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Navigating with NEMO

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Navigating with NEMO*

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Abstract

This paper describes NEMO, the main dynamic stochastic general equilibrium model used at Norges Bank for monetary policy analysis and forecasting. NEMO has been used to identify the sources of business cycle fluctuations in Norway, to conduct scenario analysis, to produce macroeconomic forecasts, and to conduct monetary policy analysis. The model has recently been re-calibrated and re-estimated to reflect economic conditions since the introduction of inflation targeting in 2001 and other structural changes. This paper presents the estimation of the model using Bayesian methods. It then evaluates its dynamic properties through examining model-based sample moments, conducting impulse response analysis as well as historical shock and forecast-error-variance decompositions, and assessing its forecasting performance against a suite of empirical models. NEMO is used in combination with a broad set of data, empirical models and judgement to make forecasts for key variables in the Norwegian economy. Re-estimation and further development of NEMO are important for the model to continue to be a useful tool for monetary policy analysis.

Keywords: *Monetary policy; DSGE; small open economy; Bayesian estimation; forecasting*

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1 Introduction

Norges Bank's main model for economic and monetary policy analysis, the Norwegian Economy Model (NEMO), has gone through continuous development since it was first introduced in 2006.[1] The global financial crisis of 2007-2009 led the first main development of NEMO as it showed that the financial sector can both be a source of shocks and that it can reinforce and weaken the effects of other shocks as well as the transmission mechanism of monetary policy. In 2013, Brubakk and Gelain (2014) introduced a banking sector as in Gerali *et al.* (2010) and a role for housing services and house prices. It was then deemed necessary to improve the model's ability to generate long cycles in house prices and credit as observed in the data. In 2015, long-term debt contracts and simple moving average forecast rules for house prices were introduced as in Gelain *et al.* (2018), replacing the standard assumptions such as one-period debt contracts and rational expectations regarding house prices. This modification also helped to further facilitate the discussion of financial stability concerns in monetary policy within the context of NEMO. Starting from 2018, the model has also been used for macro-prudential stress testing.[2]

The second main development was the introduction of an oil sector in the model after Norway experienced a sharp decline in oil prices starting from 2014. Norway is not only an oil-producing country but also a major exporter of oil supply goods as almost 25 percent of all exports excluding petroleum from Norway consist of deliveries to the oil sector abroad. In addition, as an average between 2010 and 2016, 5.3 percent of total employment is in the oil sector (mainly in the supply chain).[3] Since the model was not well-suited to capture these facts as well as the transmission channels of oil price fluctuations, an oil sector as in Bergholt *et al.* (2017) was incorporated in NEMO in 2017. With this modification, NEMO has been able to replicate some stylized facts about the oil industry in Norway as well as the macroeconomic effects of oil price shocks.[4]

Taking stock of these developments, NEMO is re-estimated to accomplish several goals. First, we estimate the model using data from the period of inflation targeting (i.e. since 2001) as sufficient data are now available. Second, we re-calibrate the long-run ratios of main macroeconomic and financial aggregates to be consistent with the data in the recent period as these ratios are changing over time. For instance, the level of household debt and housing wealth relative to mainland GDP has risen sharply over time.[5] Exports and imports of traditional goods and services are also higher now relative to mainland GDP than was the case in the 1990s.[6] Many other steady-state relationships display only small changes. Third, we aim at making the fluctuations in the model's endogenous variables as similar as possible to those in the actual data. Finally, we aim to match the macroeconomic effects of monetary policy and oil price shocks as found in empirical models. The effects of shocks to the policy rate are assessed against a suite of SVAR (structural vector autoregressive) models developed at Norges Bank. The effects of oil

[1]The first version of NEMO is documented in Brubakk *et al.* (2006).

[2]See Section 3 of Financial Stability Report 2018 in `https://www.norges-bank.no/en/Published/Publications/Financial-Stability-report/2018-finansiell-stabilitet/`

[3]See Section 3.2 for the details.

[4]See Gerdrup *et al.* (2017) for a description.

[5]The historical averages of total household debt and total corporate debt to mainland GDP ratios have increased from 74 percent and 59 percent for the 1994-2006 episode to 105 percent and 85 percent for the 2010-2016 episode, respectively. The historical average of total credit to mainland GDP has risen from 133 percent to 190 percent across those two episodes.

[6]The historical averages of total exports and imports to mainland GDP have risen from 20 percent and 27 percent for the 1990-2006 episode to 23 percent and 34 percent for the 2010-2016 episode, respectively.

price shocks are mainly based on Bergholt *et al.* (2017) and Bjørnland and Thorsrud (2016).

The estimation of NEMO is undertaken through the standard Bayesian approach as described in An and Schorfheide (2007) as well as using system priors as in the *RISE* package developed by Junior Maih and similar to Andrle and Benes (2013).[7] The latter is needed to reflect our prior beliefs about the model's features and behavior as a system and to prevent the model from having unreasonably large standard deviations for the observable variables. Moreover, in order to check for identification issues typically observed in DSGE models described by Canova and Sala (2009), we utilize the identification package developed by Ratto and Iskrev (2011). The quantitative properties of NEMO are investigated through evaluating business cycle moments, conducting impulse response analysis as well as historical and forecast-error-variance decompositions, and finally by assessing the forecasting performance of the model against a suite of empirical models.

In the re-estimated version of NEMO, the values of parameters related to the costs involved in changing prices have increased. As a result, the Phillips curves are flatter, i.e. that a given increase in capacity utilization has a somewhat smaller effect on wages and prices. This brings estimated relationships in NEMO closer to empirical models that Norges Bank uses. Moreover, in isolation, the higher steady-state levels of household debt and housing wealth suggest that an interest rate change in the model would have a somewhat stronger impact on the economy. However, since the estimated degree of real rigidities such as habit persistence in consumption and investment adjustment costs is higher relative to the previous version of the model, overall effects of a shock to the policy rate are somewhat smaller. Owing to factors such as higher export and import shares, shocks from abroad have a somewhat greater impact on the domestic economy in the re-estimated version of the model.

The remainder of the paper is organized as follows. Section 2 presents the theoretical framework of NEMO. Section 3 explains the details of the Bayesian estimation of the model. Section 4 evaluates the quantitative properties of NEMO. Section 5 concludes.

2 The model

This section provides a detailed description of the main features of the model including the key equilibrium conditions. A technical documentation of all derivations, first-order conditions, the full steady-state solution and the stationarization of the model can be found in Kravik *et al.* (n.d.).[8]

NEMO consists of households, intermediate goods and final goods producing firms, an oil sector, a government sector and the monetary authority. In addition, there are separate production sectors for housing and non-housing capital goods as well as a banking sector. All agents have rational, or model-consistent, expectations with respect to all prices and quantities, with households' house price expectations being an important exception which will be described later.

Figure 1 provides a schematic illustration of the model and displays how the different sectors and agents are linked to each other. The numeraire good of the model, *the final good*, is shown near the top of the figure. This is produced by combining inputs from the domestic firms (Q), labeled intermediate goods producers in the figure, and imports (M).

[7] See `https://github.com/jmaih/RISE_toolbox` for the details of the RISE toolbox.

[8] Kravik *et al.* (n.d.) is a live document. See the reference list for a link to the latest version.

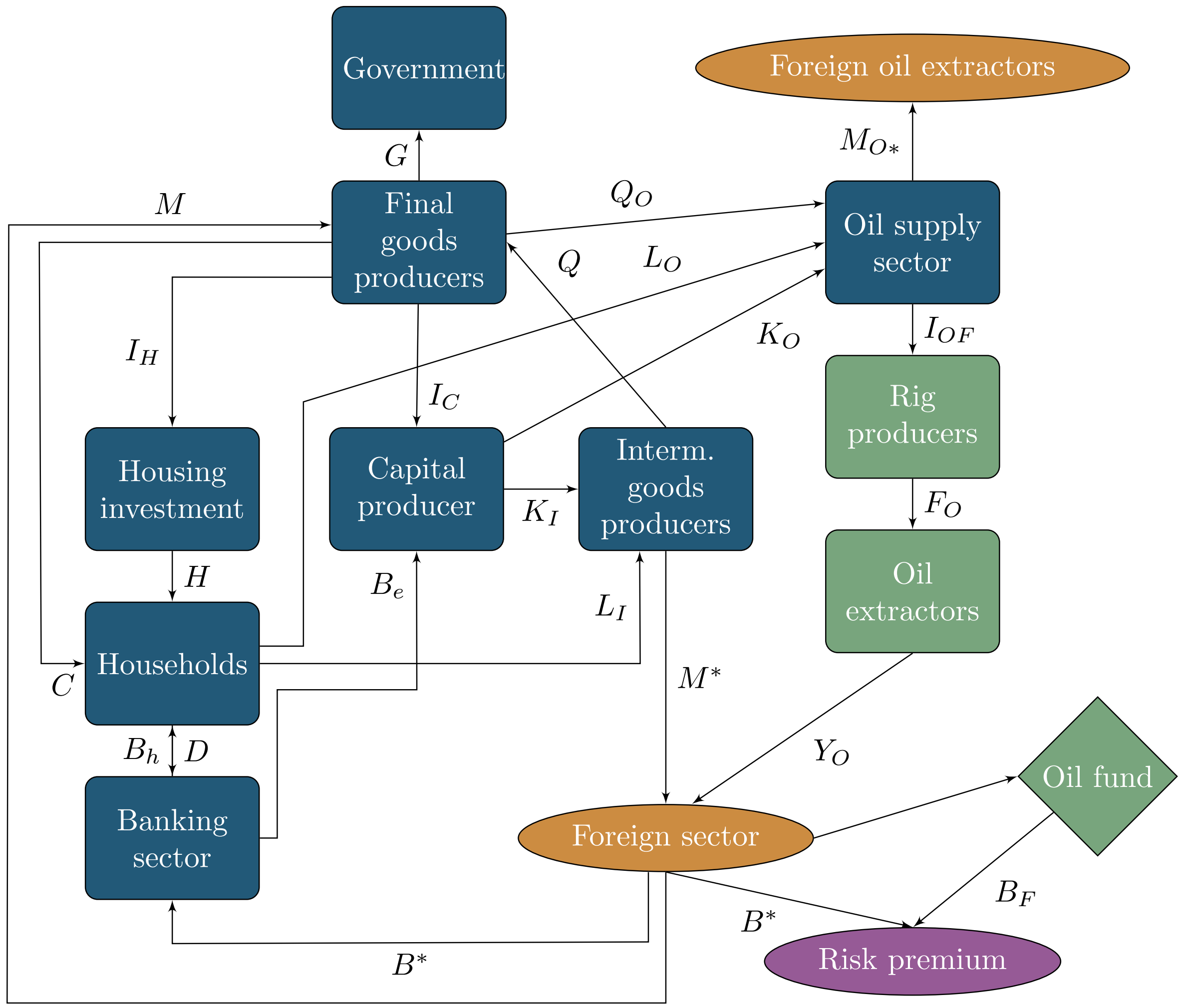

Figure 1: A bird's eye view of NEMO

The final goods are converted into household consumption (C), corporate investment (I_C), housing investment (I_H), government expenditures (G) and used as inputs in the oil sector (Q_O). The intermediate goods producers employ labor supplied by households (L_I), rent capital from entrepreneurs[9] (K_I) and sell their goods to the final goods producers (Q) and as export (M^*). The oil sector uses labor (L_O), capital (K_O) and final goods (Q_O) to produce oil supply goods which are exported (M_{O*}) or sold to the domestic rig producers (I_{OF}).[10] The rig producers invest in oil rigs (F_O) in order to extract oil (Y_O) that in turn is exported in full. The revenues are invested in the Government Pension Fund Global (GPFG), named "Oil fund" in Figure 1.

Households consume (C), work in the intermediate goods sector (L_I) and in the oil sector (L_O), buy housing services (H), and interact with banks through borrowing (B_h) and savings through deposits (D).

The banking sector lends to households (B_h) and entrepreneurs (B_e), and is funded

[9] Section 2.5 and 2.6 describe the relationship between entrepreneurs and capital producers.

[10] In this document, we refer to oil service companies, i.e. firms that provide goods and services to oil extractors, as "oil supply firms" or simply "supply firms". The goods being produced are referred to as "oil supply goods".

through deposits (D), foreign borrowing (B^*), and equity (K^B). An uncovered interest parity relationship (UIP) together with the country's net foreign debt position (private borrowing, B^*, minus government claims on foreigners, B_F) tie down the debt-elastic risk premium to ensure stationarity.[11]

2.1 Syntax and notation

Throughout this document, P_t^X denotes the nominal price of real variable X in period t. The final good is the numeraire and has the price P_t. $W_{X,t}$ is the nominal wage rate in sector X. Moreover, $R_t^X \equiv 1 + r_t^X$ is the "gross interest rate" associated with sector or variable X, where r_t^X is the net interest rate. All other variables are expressed in real terms unless otherwise stated.

Exogenous labor augmenting technological growth in the intermediate sector makes the economy grow at rate π_t^z. The housing sector is assumed to have a weaker technology growth rate of π_t^z/π_t^h to reflect increasing house prices relative to consumer prices observed in data. The stationary version of the model is available in Kravik *et al.* (n.d.). We use the notation X_{ss} to indicate variable X in steady state.

2.2 Households

Each household supplies a differentiated labor input to the intermediate goods-producing firms and the oil supply sector. Wages are set by the households under the assumption of monopolistic competition. Households obtain utility from consumption, leisure, housing services and deposits. Direct utility from deposits ensures that households are both gross lenders and gross borrowers. Preferences are additively separable. We have also separated the households problem into two maximization problems: that of the households and that of the entrepreneurs. We do this to simplify the maximization problem and to clarify the decision-making by the households in the model. The entrepreneurs' part of the problem is covered in Section 2.5.

2.2.1 The household maximization problem

Lifetime expected utility of household j at time s is represented as

$$U_s(j) = E_s \sum_{t=s}^{\infty} \beta^{t-s} \left[u\left(C_t(j)\right) + d(D_t(j)) + w(H_t(j)) - v(L_t(j)) \right], \tag{1}$$

where β is the discount factor, C_t denotes consumption, D_t is deposits, H_t is the housing stock[12] and L_t is supply of labor. The in-period utility functions are defined as:

[11] This is one of the standard ways of solving the unit problem inherent in small open economy models with incomplete markets (see Schmitt-Grohé and Uribe (2003)).

[12] The terms housing, housing services and housing stock are used interchangeably throughout this paper. In the same way as in Iacoviello and Neri (2010), one can think of H_t as both housing services and as the housing stock required to produce housing services. Consider a simple housing technology producing housing services, $\mathcal{H} = H_t^{\kappa_t}$, where κ_t is a time-varying elasticity of housing services to the housing stock. In such a setup, the total effects from the housing stock to the utility of the consumer will be captured both through the housing technology shock κ_t and the housing preference shock z_t^h. Hence, as we do not include κ_t in our model, the housing preference shock captures both pure preference shocks and changes in housing service technology.

$$u\left(C_t\left(j\right)\right)=z_t^u\left(1-\frac{b^c}{\pi_{ss}^z}\right)\ln\left[\frac{C_t\left(j\right)-b^cC_{t-1}}{1-b^c/\pi_{ss}^z}\right], \tag{2}$$

$$d\left(D_t\left(j\right)\right)=z^d\left(1-\frac{b^d}{\pi_{ss}^z}\right)\ln\left[\frac{D_t\left(j\right)-b^dD_{t-1}}{1-b^d/\pi_{ss}^z}\right], \tag{3}$$

$$v\left(L_t\left(j\right)\right)=\frac{1-b^l}{1+\zeta}\left[\frac{L_t\left(j\right)-b^lL_{t-1}}{1-b^l}\right]^{1+\zeta}, \tag{4}$$

$$w(H_t\left(j\right))=z_t^h\left(1-\frac{b^h\pi_{ss}^h}{\pi_{ss}^z}\right)\ln\left[\frac{H_t\left(j\right)-b_hH_{t-1}}{1-b^h\pi_{ss}^h/\pi_{ss}^z}\right], \tag{5}$$

where z_t's are preference parameters, of which z_t^u and z_t^h are shocks that follow AR(1) processes.[13] The b-parameters govern habit persistence and the π_{ss}^z denotes the exogenous steady-state (labor augmenting) technology growth rate.[14] As stated above, the housing sector is assumed to have a weaker technology growth rate which is equal to π_{ss}^z/π_{ss}^h in the steady state (implying that real house prices grow with the value π_{ss}^h in the steady state). The inverse of the Frisch elasticity of labor supply is given by $\zeta>0$. The Frisch elasticity captures the elasticity of hours worked to the wage rate. The log in-period utility functions for consumption, deposits and housing imply an intertemporal elasticity of substitution equal to 1, which secures a balanced growth path.

Household j's budget constraint in period t is:

$$\begin{aligned}&P_tC_t\left(j\right)+P_tD_t\left(j\right)+P_t^HH_t\left(j\right)+\left(r_{t-1}^F+\delta_t^B\left(j\right)\right)P_{t-1}B_{h,t-1}\left(j\right)\\&\quad=W_t(j)L_t\left(j\right)\left[1-\gamma_t(j)\right]+P_tI_{B,t}\left(j\right)+R_{t-1}^dP_{t-1}D_{t-1}\left(j\right)\\&\qquad+\left(1-\delta_H\right)P_t^HH_{t-1}\left(j\right)+DIV_t\left(j\right)-TAX_t\left(j\right),\end{aligned} \tag{6}$$

where P_t is the price level of final goods, P_t^H is the price level of housing services, r_t^F is the nominal net mortgage interest rate faced by households, R_t^d is the gross interest on household's deposits, $\delta_t^B(j)$ denotes household j's amortization rate (mortgage repayment share), $B_{h,t}(j)$ is real household's borrowing (or mortgage), $W_t(j)$ is the nominal wage rate (in both the intermediate goods sector and the oil sector) set by household j, $\gamma_t(j)$ is the wage adjustment cost (defined below in (11)), $L_t\left(j\right)$ is the total amount of hours worked (in both the intermediate goods sector and the oil sector), $I_{B,t}(j)$ indicates new real loans by household j, δ_H denotes the depreciation rate of the housing stock and $DIV_t(j)$ and $TAX_t(j)$ are dividends[15] (in nominal terms) disbursed to household j and lump-sum taxes payed by household j, respectively. Hence, equation (6) states that expenditures on consumption, deposits, housing services as well as interest and principal on the mortgage, need to be equal to the sum of labor income (net of adjustment costs), new mortgage, deposits from the previous period with interest income, undepreciated housing stock plus any dividends (and other lump-sum income) less taxes.

[13] Most shock processes are modeled as log-deviations from their steady state. A list of all shocks can be found in Appendix D.

[14] Including a habit formation parameter on hours worked turns out to have very limited impact on the properties of the model.

[15] Including any entrepreneurial surplus (see Section 2.5).

Household borrowing follows the process:

$$B_{h,t}(j) = \left(1 - \delta_t^B(j)\right) \frac{P_{t-1}}{P_t} B_{h,t-1}(j) + I_{B,t}(j). \tag{7}$$

Similar to Iacoviello (2005) and Gelain *et al.* (2017), we assume that households are credit constrained. Specifically, we assume that household j's new loans, $I_{B,t}$, are constrained by the expected housing wealth (the expected household's housing stock in the next period less mortgage), assumed to always be binding:[16]

$$I_{B,t}(j) = \phi_t E_t \left[\frac{P_{t+1}^H}{P_{t+1}} \frac{P_{t+1}}{P_t} H_t(j) - B_{h,t}(j) \right], \tag{8}$$

where ϕ_t is the collateral coefficient that governs the constraint on new household loans. It follows an AR(1) process and can be interpreted as a shock to the loan-to-value (LTV) ratio for household borrowing. As house prices increase, the collateral values of houses rise. This expands households' capacity to borrow more and thus create a demand for mortgages, the proceeds of which are spent on consumption goods, housing and deposits. In the steady-state solution of the model, Kravik *et al.* (n.d.) derives the relationship between ϕ_t and the LTV in the steady state.

We follow Gelain *et al.* (2017) in that the loan principal repayments share follow from an (approximated) annuity loan repayment formula:

$$\delta_{t+1}^B(j) = \left(1 - \frac{I_{B,t}(j)}{B_{h,t}(j)}\right) \left(\delta_t^B(j)\right)^{\alpha^h} + \frac{I_{B,t}(j)}{B_{h,t}(j)} \left(1 - \alpha^h\right)^{\kappa^h}, \tag{9}$$

where α^h and κ^h are exogenous parameters that govern the dynamics of amortization rate. In the case of α^h equal to 0, $\delta_t^B(j) = 1$ for all t, i.e. $B_{h,t}(j) = I_{B,t}(j)$, but if $\alpha^h > 0$, the above repayment formula captures the fact that the amortization rate is low during the first years after taking up a mortgage when interest payments are high, and thereafter increasing. We calibrate α^h and κ^h to capture the repayment schedule of a typical mortgage contract of 30 years.

The labor market is characterized by monopolistic competition. Households supply labor and set wages subject to demand from the intermediate goods sector and the oil supply sector. Real wages are set as a markup over the marginal rate of substitution of consumption for leisure (see first-order conditions below). As there is assumed to be full labor mobility between the two sectors, there is only one wage level in the economy. Household j faces the following labor demand curve from the intermediate goods sector and the oil sector:

$$L_t(j) = \left(\frac{W_t(j)}{W_t}\right)^{-\psi_t} L_t, \tag{10}$$

where W_t is the wage rate and ψ_t is the elasticity of substitution between differentiated labor, which follows an AR(1) process and can be interpreted as an inverse wage markup

[16] Our setup is inspired by and very similar to Gelain *et al.* (2017) except that the latter study assumes that the households refinance a fixed fraction of the mortgage in every period, collateralized by the same fraction of their housing wealth.

shock.[17] We further assume that there is sluggish wage adjustment due to adjustment costs that are measured in terms of the total wage bill (cf. Kim (2000)). Wage adjustment costs are specified as:

$$\gamma_t(j) = \frac{\phi^W}{2}\left[\frac{W_t\left(j\right)/W_{t-1}\left(j\right)}{W_{t-1}/W_{t-2}} - 1\right]^2. \tag{11}$$

As can be seen from (11), costs are related to changes in individual wage inflation relative to the past observed rate for the whole economy.[18] The parameter $\phi^W > 0$ determines how costly it is to change the wage inflation rate.

Combining (7) with (8), and (7) with (9) give the borrowing constraint and the repayment constraint, respectively:

$$B_{h,t}\left(j\right) = \frac{\left(1-\delta_t^B(j)\right)}{1+\phi_t}\frac{P_{t-1}}{P_t}B_{h,t-1}\left(j\right) + \frac{\phi_t}{1+\phi_t}E_t\left[\frac{P_{t+1}^H}{P_{t+1}}\frac{P_{t+1}}{P_t}H_t\left(j\right)\right], \tag{12}$$

$$\delta_{t+1}^B\left(j\right) = \left(1-\delta_t^B(j)\right)\frac{P_{t-1}}{P_t}\frac{B_{h,t-1}\left(j\right)}{B_{h,t}\left(j\right)}\left[\left(\delta_t^B\left(j\right)\right)^{\alpha^h} - \left(1-\alpha^h\right)^{\kappa^h}\right] + \left(1-\alpha^h\right)^{\kappa^h}. \tag{13}$$

Maximizing utility, (1), subject to the budget constraint, (6); the borrowing constraint, (12) and the repayment constraint, (13), letting ω_t and μ_t be the Lagrangian multipliers associated with (12) and (13), gives the first-order conditions with respect to real borrowing, $B_{h,t}$ (14); deposits, D_t (15); the wage rate, W_t (16); housing, H_t (17); and repayments, δ_t^B (18) (defining the stochastic discount factor as $\Delta_{t+1} \equiv \beta\frac{u'(C_{t+1})}{u'(C_t)}\frac{P_t}{P_{t+1}}$ and suppressing household indicator j):

$$\begin{aligned}
&1 - E_t[\Delta_{t+1}]R_t^F - \frac{\omega_t}{u'\left(C_t\right)} \\
&+E_t\left[\frac{\omega_{t+1}}{u'\left(C_{t+1}\right)}\Delta_{t+1}\frac{(1-\delta_{t+1}^B)}{1+\phi_{t+1}}\right] \\
&-\frac{\mu_t}{u'\left(C_t\right)}\frac{B_{h,t-1}}{B_{h,t}^2}\frac{P_{t-1}}{P_t}(1-\delta_t^B)\left[\left(\delta_t^B\right)^{\alpha^h} - (1-\alpha^h)^{\kappa^h}\right] \\
&+E_t\left[\frac{\mu_{t+1}}{u'\left(C_{t+1}\right)}\Delta_{t+1}\frac{(1-\delta_{t+1}^B)}{B_{h,t+1}}\left[\left(\delta_{t+1}^B\right)^{\alpha^h} - (1-\alpha^h)^{\kappa^h}\right]\right] = 0,
\end{aligned} \tag{14}$$

$$E_t\left[\Delta_{t+1}\right]R_t^d - 1 = -\frac{d'(D_t)}{u'\left(C_t\right)}, \tag{15}$$

[17] For the model to be able to replicate the importance of the oil sector for the Norwegian economy, we have added a direct impact from the oil price and the labor demand from oil supply firms to the wage markup shock. In Norway, collective wage bargaining is conducted in a way to promote competitiveness for the export-oriented sector, i.e. meaning that export-oriented industries negotiate before other labor groups and thereby set the norm for other industries. This wage bargaining system is referred to as *Frontfagsmodellen* ("leading sector model"). Frontfagsmodellen entails that the export-oriented sector has more bargaining power than their relative labor share would imply. In NEMO, we implement this feature through the wage markup shock (see Appendix D).

[18] In NEMO, the adjustment costs of wages and prices are fully indexed, which has been the case in NEMO since it was first introduced. Different specifications of adjustment costs will be explored in the future.

$$
\begin{aligned}
\frac{v'\left(L_t\right)}{u'\left(C_t\right)}\psi_t\frac{P_t}{W_t} = & \left[\left(\psi_t-1\right)\left(1-\gamma_t\right)+\phi^W\left(\frac{W_t/W_{t-1}}{W_{t-1}/W_{t-2}}-1\right)\frac{W_t/W_{t-1}}{W_{t-1}/W_{t-2}}\right] \\
& -E_t\left[\Delta_{t+1}\frac{L_{t+1}}{L_t}\phi^W\left(\frac{W_{t+1}/W_t}{W_t/W_{t-1}}-1\right)\frac{\left(W_{t+1}/W_t\right)^2}{W_t/W_{t-1}}\right],
\end{aligned}
\tag{16}
$$

$$
\frac{w'(H_t)}{u'\left(C_t\right)} = \frac{P_t^H}{P_t} - \left(1-\delta_H\right)E_t\left[\Delta_{t+1}\frac{P_{t+1}^H}{P_t}\right] - \frac{\omega_t}{u'\left(C_t\right)}\frac{\phi_t}{1+\phi_t}E_t\left[\frac{P_{t+1}^H}{P_{t+1}}\frac{P_{t+1}}{P_t}\right], \tag{17}
$$

$$
\begin{aligned}
-\mu_{t-1}+\mu_t\beta\frac{B_{h,t-1}}{B_{h,t}}\frac{P_{t-1}}{P_t}&\left[\alpha^h\left(\delta_t^B\right)^{\alpha^h-1}\left(1-\delta_t^B\right)-\left(\delta_t^B\right)^{\alpha^h}+\left(1-\alpha^h\right)^{\kappa^h}\right] \\
&-\omega_t\beta\left[\frac{B_{h,t-1}}{1+\phi_t}\frac{P_{t-1}}{P_t}\right]=0.
\end{aligned}
\tag{18}
$$

In the special case of $\delta_t^B=1$, i.e. when the full mortgage is rolled over in every period, the first-order condition with respect to $B_{h,t}$, equation (14), would simply collapse to the first three terms: $E_t[\Delta_{t+1}]R_t^F = 1-\frac{\omega_t}{u'(C_t)}$, i.e. households would take up mortgage up to a point where the effective cost of borrowing is equal to the shadow marginal benefit of mortgage. When $\delta_t^B<1$, the fourth term in (14) captures that an increased mortgage in the current period also increases the mortgage in future periods (due to the long-term debt contracts). The last two terms control how the path of the amortization rate changes when the size of the mortgage increases marginally.

The optimality condition for deposits, equation (15), states that the marginal rate of substitution between deposits and consumption must be equal to the marginal benefit of holding deposits (the interest rate). Compared to a canonical DSGE model, household faces an additional opportunity cost of consuming in the current period in the form of lost utility from deposits.

Equation (16) is the first-order equation with respect to the wage rate, which is set by households subject to the demand function in (10). In the special case without any wage adjustment costs, $\phi^W=\gamma_t=0$ (see equation (11)), (16) will simply be reduced to $\frac{W_t}{P_t}=\frac{\psi_t}{\psi_t-1}\frac{v'(L_t)}{u'(C_t)}$, i.e., real wage rate will be set as a markup over the marginal rate of substitution between leisure and consumption. The second term on the right-hand side of (16) captures the adjustment costs of a change in wages, whereas the last term reflects that increasing wages today reduces the need to increase wages in the future. Hence, the latter term means that households consider the full path of future labor demand when setting the current wage level.

The first-order condition with respect to housing, (17), equalizes the marginal rate of substitution between housing and consumption with the effective price of housing. The first term on the right-hand side is the real house price, the second part is the net-of-depreciation continuation value, and the last term captures that the increase in the household's collateral from more housing induces the household to take up more mortgage debt (from equation (8)). The increase in collateral is valued at the shadow value of additional mortgage debt.

Equation (18) is the first-order condition with respect to mortgage repayments, δ_t^B. The second term shows the impact on the amortization dynamics when the current repayment rate is increased marginally, whereas the last term includes the indirect effects through the behaviour of the mortgage.

2.2.2 House price expectations

Agents in NEMO are forward-looking and have model-consistent expectations. For instance, workers decide on wages and labor supply not only based on today's consumer prices and labor demand curves, but also based on all future expected prices and demand curves. The same is true for all agents of the model, regarding all prices. A noteworthy exception is house price expectations, where we introduce so-called hybrid expectations as in Gelain *et al.* (2013). We assume that a share b^{sa} of households expects house prices to follow a moving average process (i.e. partly backward-looking expectations), whereas a share $(1 - b^{sa})$ has rational expectations (in log-gap form). This generates house price cycles more in line with empirical observations:

$$E_t\left[\widehat{P^H_{t+1}}\right] = b^{sa}\widehat{X^H_t} + (1 - b^{sa})\widehat{P^H_{t+1}}, \tag{19}$$

where $\widehat{}$ denotes gap-form and the moving average process is defined as

$$\widehat{X^H_t} = \lambda^{sa}\widehat{P^H_{t-1}} + (1 - \lambda^{sa})\widehat{X^H_{t-1}}. \tag{20}$$

2.3 Intermediate goods sector

A continuum of firms in the intermediate goods sector uses capital and labor to produce a differentiated intermediate good which is sold under monopolistic competition to the final goods producers at home and abroad as exports. Firms choose labor and capital services to minimize factor outlays, taking wages and rental rates of capital as given. As firms in the intermediate goods sector enjoy market power, they set prices as a markup over marginal costs, and they charge different prices at home and abroad.[19] Firms are assumed to face so-called Rotemberg adjustment costs when changing nominal prices (Rotemberg, 1982), which lead firms to change their prices less in response to shocks than they otherwise would have done, i.e. prices are sticky. This assumption contributes to the non-neutrality of monetary policy. Since changing prices is costly, firms must take into account future developments when deciding on today's prices. Hence, inflation expectations influence today's inflation. Finally, capital is produced by capital producers (see Section 2.6).

2.3.1 The maximization problem

The intermediate firm n sells good $Q_t(n)$ to the final good sector and exports the amount $M^*_t(n)$, where $T_t(n) = Q_t(n) + M^*_t(n))$. It has the following CES production function:

$$T_t(n) = \left[(1-\alpha)^{\frac{1}{\xi}}\left(Z_t z^L_t L_{I,t}(n)\right)^{1-\frac{1}{\xi}} + \alpha^{\frac{1}{\xi}}\overline{K}_{I,t}(n)^{1-\frac{1}{\xi}}\right]^{\frac{\xi}{\xi-1}}, \tag{21}$$

where $\alpha \in [0, 1]$ determines the capital share and ξ denotes the elasticity of substitution between labor and capital. The variables $L_{I,t}(n)$ and $\overline{K}_{I,t}(n)$ denote, respectively, hours and effective capital used by firm n in period t. There are two exogenous shocks to productivity in the model: Z_t refers to an exogenous permanent labor augmenting process, which grows at the gross rate π^z_t, whereas z^L_t denotes a temporary (stationary) shock to productivity (or labor utilization) that follows an AR(1) process.

Total labor input to firm n is an index over used labor from all households j, i.e.

[19] Hence, we assume "local currency pricing" as in Devereux and Engel (2003) and Corsetti and Dedola (2005).

$$L_{I,t}(n)=\left[\int_0^1 L_{I,t}(n,j)^{1-\frac{1}{\psi_t}}dj\right]^{\frac{\psi_t}{\psi_t-1}}, \tag{22}$$

where ψ_t denotes the elasticity of substitution between differentiated labor.

Let $W_{I,t}$ be the wage rate, which is equal to W_t due to perfect labor mobility, and let $R_{KI,t}$ be the rental rate of capital equal to $R_{K,t}$ due to perfect capital mobility. Minimizing total factor outlays gives rise to the following conditional factor demand functions:[20]

$$L_{I,t}=(1-\alpha)\left(\frac{W_{I,t}}{MC_t}\right)^{-\xi}T_t(Z_t z_t^L)^{\xi-1}, \tag{23}$$

$$\overline{K}_{I,t}=\alpha\left(\frac{R_{KI,t}}{MC_t}\right)^{-\xi}T_t, \tag{24}$$

where we have used that marginal costs can be shown to be:

$$MC_t=\left[(1-\alpha)\left(\frac{W_{I,t}}{Z_t z_t^L}\right)^{1-\xi}+\alpha R_{KI,t}^{1-\xi}\right]^{\frac{1}{1-\xi}}. \tag{25}$$

This means, for example, that higher real wages will reduce labor demand and increase the demand for capital for a given level of production. A proportional increase in both real wages and rental prices, will have no impact on the demand for labor and capital. Firms face the following price adjustments costs in the domestic and foreign markets, respectively:

$$\gamma_{PQ,t}(n)\equiv\frac{\phi^{PQ}}{2}\left[\frac{P_t^Q(n)/P_{t-1}^Q(n)}{P_{t-1}^Q/P_{t-2}^Q}-1\right]^2, \tag{26}$$

$$\gamma_{PM^*,t}(n)\equiv\frac{\phi^{PM^*}}{2}\left[\frac{P_t^{M^*}(n)/P_{t-1}^{M^*}(n)}{P_{t-1}^{M^*}/P_{t-2}^{M^*}}-1\right]^2, \tag{27}$$

where P_t^Q and $P_t^{M^*}$ are the prices in the domestic and the foreign market (in foreign currency), respectively. The costs of changing prices are governed by the parameters ϕ^{PQ} and ϕ^{PM^*}.[21] One can show that the firms face the following demand functions from the final good sector and from abroad, respectively:

$$Q_t(n)=\left(\frac{P_t^Q(n)}{P_t^Q}\right)^{-\theta_t^H}Q_t, \tag{28}$$

$$M_t^*(n)=\left(\frac{P_t^{M^*}(n)}{P_t^{M^*}}\right)^{-\theta^{F^*}}M_t^*, \tag{29}$$

[20] Note that in symmetric equilibrium all firms make the same decisions, hence $L_{I,t}(n)=L_{I,t}$, and similarly for the capital demand.

[21] Similar to wage adjustment costs, the price adjustments costs are related to changes in inflation for firm n relative to the past observed rate for the whole economy.

where θ_t^H is the elasticity of substitution between domestic goods produced by different firms in the intermediate goods sector and follows an AR(1) process, which can be interpreted as a domestic price (inverse) markup shock. Correspondingly, θ^{F^*} is the elasticity of substitution across export goods.

Profit maximization gives rise to the following first-order condition for price-setting in the domestic market, P_t^Q:

$$\begin{aligned} &Q_t - \theta_t^H Q_t + MC_t \theta_t^H \frac{Q_t}{P_t^Q} - \phi^{PQ} \left[\frac{P_t^Q / P_{t-1}^Q}{P_{t-1}^Q / P_{t-2}^Q} - 1 \right] \frac{P_t^Q / P_{t-1}^Q}{P_{t-1}^Q / P_{t-2}^Q} Q_t \\ &+ E_t \left\{ \Delta_{t+1} \phi^{PQ} \left[\frac{P_{t+1}^Q / P_t^Q}{P_t^Q / P_{t-1}^Q} - 1 \right] \frac{(P_{t+1}^Q / P_t^Q)^2}{P_t^Q / P_{t-1}^Q} Q_{t+1} \right\} = 0, \end{aligned} \tag{30}$$

In the absence of adjustment costs, $\phi^{PQ} = 0$, prices would simply be set as a markup over marginal costs in every period $P_t^Q = \frac{\theta_t^H}{\theta_t^H - 1} MC_t$ (where $\theta_t^H > 1$). The fourth term captures the adjustment costs of the price change, whereas the last term reflects that increasing the price in the current period reduces the need to increase prices more in the future. Hence, the latter term implies that firms consider the full path of future demand when setting the prices.

Similarly, the first-order condition with respect to $P_t^{M^*}(n)$ can be written as

$$\begin{aligned} &S_t M_t^* - \theta^{F^*} S_t M_t^* + MC_t \theta^{F^*} \frac{M_t^*}{P_t^{M^*}} - \phi^{PM^*} \left[\frac{P_t^{M^*} / P_{t-1}^{M^*}}{P_{t-1}^{M^*} / P_{t-2}^{M^*}} - 1 \right] \frac{P_t^{M^*} / P_{t-1}^{M^*}}{P_{t-1}^{M^*} / P_{t-2}^{M^*}} S_t M_t^* \\ &+ E_t \left\{ \Delta_{t+1} \phi^{PM^*} \left[\frac{P_{t+1}^{M^*} / P_t^{M^*}}{P_t^{M^*} / P_{t-1}^{M^*}} - 1 \right] \frac{\left(P_{t+1}^{M^*} / P_t^{M^*}\right)^2}{P_t^{M^*} / P_{t-1}^{M^*}} S_{t+1} M_{t+1}^* \right\} = 0, \end{aligned} \tag{31}$$

where S_t is the nominal exchange rate in foreign currency per Norwegian krone (an increase in S_t implies a depreciation of the Norwegian krone). In the special case of $\phi^{PM^*} = 0$, equation (31) would become: $P_t^{M^*} = \frac{\theta^{F^*}}{\theta^{F^*} - 1} \frac{MC_t}{S_t}$.

2.4 Final goods sector

The final goods sector combines imported goods M_t and domestic goods Q_t to produce a final good A_t that is sold at a price P_t. The final good can be used for consumption, investments, government consumption and input to the oil supply firms.

The production function is given by

$$A_t = \left(\nu_t^{\frac{1}{\mu}} Q_t^{1 - \frac{1}{\mu}} + (1 - \nu_t)^{\frac{1}{\mu}} M_t^{1 - \frac{1}{\mu}} \right)^{\frac{\mu}{\mu - 1}}, \tag{32}$$

where ν_t is the domestic goods share and μ is the elasticity of substitution between domestic and imported goods. ν_t represents the degree of home bias. It follows an AR(1) process and can be interpreted as an import demand shock. The domestic good Q_t is a composite of domestic goods produced by the different firms in the intermediate goods sector. The imported good M_t is a composite of imported goods produced by the different firms in the intermediate goods sector abroad.

Minimizing costs gives rise to the following conditional demand functions:

$$Q_t = \nu_t \left(\frac{P_t^Q}{P_t} \right)^{-\mu} A_t, \tag{33}$$

$$M_t = (1-\nu_t) \left(\frac{P_t^M}{P_t} \right)^{-\mu} A_t, \tag{34}$$

where $P_t \equiv \left[\nu_t (P_t^Q)^{1-\mu} + (1-\nu_t)(P_t^M)^{1-\mu} \right]^{\frac{1}{1-\mu}}$ is the numeraire of the model.

2.5 Entrepreneurs

2.5.1 The maximization problem

In this sector we focus on the maximization problem for entrepreneurs. Entrepreneurs are households, but this section considers a separate part of households' budget constraint to simplify the exposition.[22] We could alternatively have modeled this sector as a firm owned by households.

Entrepreneurs rent capital to the intermediate goods sector and the oil sector gaining the rental rate $R_{K,t}$ $(= R_{KI,t} = R_{KO,t}$ due to perfect capital mobility). They rent out $\overline{K}_{I,t}$ to the intermediate goods sector and $\overline{K}_{O,t}$ to the oil supply sector. $\overline{K}_t$ is then the aggregate utilized capital rented out by entrepreneurs. At the beginning of period t they sell the undepreciated capital $(1-\delta) K_{t-1}$ at price P_t^K to the capital producers. The latter combines it with investment goods to produce K_t to be sold back to entrepreneurs at the same price. To finance their activity, entrepreneurs borrow $B_{e,t}$ (referred to as corporate credit) from banks at gross rate R_t^e, providing capital goods as collateral. They enter in a multi-period loan contract. Finally, entrepreneurs also decide the capital utilization rate u_t.

We define effective capital input in period t as

$$\overline{K}_t = u_t K_{t-1}. \tag{35}$$

Entrepreneurs are subject to the following real budget constraint:

$$\begin{aligned} &\frac{R_{K,t}}{P_t} \overline{K}_t + \frac{P_t^K}{P_t} (1-\delta) K_{t-1} + I_{B,t}^e = \\ &\frac{P_t^K}{P_t} K_t + (r_{t-1}^e + \delta_t^e) \frac{P_{t-1}}{P_t} B_{e,t-1} + \gamma(u_t) K_{t-1} + C_t + \frac{1}{P_t} \Xi_t, \end{aligned} \tag{36}$$

where the first term is the income from renting out capital to the intermediate goods sector and the oil supply sector, the second term is the income generated from the sale of undepreciated capital to the capital producers (see Section 2.6), and $I_{B,t}^e$ is new loans. The first term on the expenditure side of (36) is capital bought back from the capital producers, the second term represents the interest and principal payments to banks on outstanding debt, the third term are costs associated with a given level of the utilization

[22] We suppress index j in this section.

rate of capital (see below), and C_t is household consumption. The last term, Ξ_t, represents all other terms that enter into the household budget constraint (6).[23]

The unit utilization cost is defined as

$$\gamma\left(u_t\right)=\frac{R_{K,ss}}{P_{ss}\phi_u}\left[e^{\phi_u\left(u_t-1\right)}-1\right], \tag{37}$$

where ϕ_u governs the cost of adjusting the utilization rate, and the subscript ss denotes steady-state values. Note that total utilized capital rented out must be equal to the utilized capital demanded by the intermediate goods sector and by the oil supply sector, $\overline{K}_t=\overline{K}_{I,t}+\overline{K}_{O,t}$.

Whereas households used housing capital as collateral, the entrepreneurs can borrow against their real capital $(1-\delta)\,K_t$. Similar to the household constraint (12) and (13), we have:

$$B_{e,t}=\frac{\left(1-\delta_t^e\right)}{1+\phi_t^{ent}}\frac{P_{t-1}}{P_t}B_{e,t-1}+\frac{\phi_t^{ent}}{1+\phi_t^{ent}}E_t\left[\frac{P_{t+1}^K}{P_{t+1}}\frac{P_{t+1}}{P_t}\left(1-\delta\right)K_t\right], \tag{38}$$

$$\delta_{t+1}^e=\left(1-\delta_t^e\right)\frac{P_{t-1}}{P_t}\frac{B_{e,t-1}}{B_{e,t}}\left[\left(\delta_t^e\right)^{\alpha^e}-\left(1-\alpha^e\right)^{\kappa^e}\right]+\left(1-\alpha^e\right)^{\kappa^e}, \tag{39}$$

where ϕ_t^{ent} is the collateral coefficient that governs the constraint on new corporate debt. It follows an AR(1) process and can be interpreted as a shock to the loan-to-value (LTV) ratio for business credit. δ_t^e is the loan repayment share and α^e and κ^e are exogenous parameters that govern entrepreneurs' annuity loan repayment formula (analogous to the household case in equation (9)).

Maximizing utility (equation (1)) subject to (36), (38) and (39) with respect to K_t, B_t^e, δ_t^e and u_t gives the following first-order conditions (where ω_t^e and μ_t^e are the Lagrangian multipliers associated with (38) and (39), respectively):

$$\begin{aligned}\frac{P_t^K}{P_t}&=E_t\left[\frac{\omega_t^e}{u'\left(C_t\right)}\frac{\phi_t^{ent}}{1+\phi_t^{ent}}\frac{P_{t+1}^K}{P_{t+1}}\frac{P_{t+1}}{P_t}\left(1-\delta\right)\right]\\&+E_t\left[\Delta_{t+1}\frac{P_{t+1}}{P_t}\left(\frac{P_{t+1}^K}{P_{t+1}}\left(1-\delta\right)+\frac{R_{K,t+1}}{P_{t+1}}u_{t+1}-\gamma\left(u_{t+1}\right)\right)\right],\end{aligned} \tag{40}$$

$$\begin{aligned}&B_{e,t}-B_{e,t}E_t\left[\Delta_{t+1}\right]R_t^e-\frac{\omega_t^e}{u'\left(C_t\right)}B_{e,t}\\&+E_t\left[\frac{\omega_{t+1}^e}{u'\left(C_{t+1}\right)}\Delta_{t+1}\frac{\left(1-\delta_{t+1}^e\right)}{1+\phi_{t+1}^{ent}}B_{e,t}\right]\\&-\frac{\mu_t^e}{u'\left(C_t\right)}\frac{B_{e,t-1}}{B_{e,t}}\frac{P_{t-1}}{P_t}\left(1-\delta_t^e\right)\left[\left(\delta_t^e\right)^{\alpha^e}-\left(1-\alpha^e\right)^{\kappa^e}\right]\\&+E_t\left[\frac{\mu_{t+1}^e}{u'\left(C_{t+1}\right)}\Delta_{t+1}\frac{B_{e,t}}{B_{e,t+1}}\left(1-\delta_{t+1}^e\right)\left[\left(\delta_{t+1}^e\right)^{\alpha^e}-\left(1-\alpha^e\right)^{\kappa^e}\right]\right]=0,\end{aligned} \tag{41}$$

[23] Since households and entrepreneurs technically are the same, one can think of all terms in (36) (except C_t and Ξ_t) as part of DIV_t in (6).

$$
\begin{aligned}
-\mu_{t-1}^{e}+\mu_{t}^{e}\beta\frac{B_{e,t-1}}{B_{e,t}}\frac{P_{t-1}}{P_{t}}\left[\alpha^{e}\left(\delta_{t}^{e}\right)^{\alpha^{e}-1}\left(1-\delta_{t}^{e}\right)-\left(\delta_{t}^{e}\right)^{\alpha^{e}}+\left(1-\alpha^{e}\right)^{\kappa^{e}}\right]& \\
-\omega_{t}^{e}\beta\left[\frac{B_{e,t-1}}{1+\phi_{t}^{ent}}\frac{P_{t-1}}{P_{t}}\right]=0,&
\end{aligned}
\tag{42}
$$

$$
\frac{R_{K,t}}{P_{t}}=\gamma'\left(u_{,t}\right)=\frac{R_{K,ss}}{P_{ss}}e^{\phi_{u}(u_{t}-1)}. \tag{43}
$$

Equation (40), the first-order condition with respect to K_t, states that entrepreneurs choose capital so that the marginal utility of capital (right side of (40)) equals marginal costs (the left side). The first term on the right side represents the benefit of increased collateral whereas the second term is the income from selling and renting out capital net of utilization costs.

The optimality conditions for corporate credit, (41), and for loan repayments, (42), are fully analogues to (14) and (18) in the household section, respectively.

Equation (43) is the first-order condition with respect to the utilization rate, u_t, which states that the marginal benefit of utilizing an additional unit of capital is equal to the cost of utilizing it. The second equality follows from (37).

2.6 Capital producers

Capital goods, K_t, are produced by separate producers. At the beginning of period t the capital goods producers buy undepreciated capital $(1-\delta)K_{t-1}$ at price P_t^K from entrepreneurs, and combines it with (gross) investment goods $I_{C,t}$ to produce K_t to be sold back to entrepreneurs at the same price. The capital producers operate in a perfectly competitive market, and therefore earn no profit. $I_{C,t}$ is bought from the final goods sector at a price P_t.

The representative capital producer h maximizes the following function

$$
\max_{\{I_{C,t}(h)\}}\left[P_{t}^{K}K_{t}(h)-P_{t}^{K}\left(1-\delta\right)K_{t-1}(h)-P_{t}I_{C,t}(h)\right],
$$

s.t. the capital accumulation equation:

$$
K_{t}(h)=(1-\delta)K_{t-1}(h)+\kappa_{t}(h)K_{t-1}(h). \tag{44}
$$

The last term, $\kappa_t(h)K_{t-1}(h)$, can be thought of as "net investments", i.e. investments net of adjustment costs:

$$
\kappa_{t}(h)=\frac{I_{C,t}(h)}{K_{t-1}(h)}-\frac{\phi_{I1}}{2}\left[\frac{I_{C,t}(h)}{K_{t-1}(h)}-\frac{I_{C,ss}\pi_{ss}^{z}}{K_{ss}}z_{I,t}\right]^{2}-\frac{\phi_{I2}}{2}\left[\frac{I_{C,t}(h)}{K_{t-1}(h)}-\frac{I_{C,t-1}}{K_{t-2}}\right]^{2}. \tag{45}
$$

The parameters ϕ_{I1} and ϕ_{I2} govern the degree of adjustment costs, and $z_{I,t}$ is a shock to investment adjustment costs, that follows an AR(1) process. Note that there are two terms in the adjustment cost equation. The first cost term stems from the deviation of today's level of investment from its (stationary) steady-state value (where π_{ss}^z is steady-state technology growth (see page 5)), whereas the second cost term originates from the deviation of today's level of investment from the level in the previous period (for the whole economy). Because of these adjustments costs, net investments are smaller than gross investments, $\kappa_t K_{t-1} \leq I_{C,t}$ (holds with equality in the steady state).

Maximization with respect to $I_{C,t}$ gives the following first-order condition, suppressing indicator h:

$$\frac{P_t^K}{P_t} = \left\{ 1 - \phi_{I1} \left[\frac{I_{C,t}}{K_{t-1}} - \frac{I_{C,ss}\pi_{ss}^z}{K_{ss}} z_{I,t} \right] - \phi_{I2} \left[\frac{I_{C,t}}{K_{t-1}} - \frac{I_{C,t-1}}{K_{t-2}} \right] \right\}^{-1}. \tag{46}$$

Based on the movements in the adjustment costs in the two bracketed terms in (46), the real price of capital fluctuates around its steady-state level of 1.

2.7 Housing producers

The housing producers' production function and housing capital accumulation constraint are similar to those of the capital producers. At the beginning of period t the housing producers buy the undepreciated housing stock $(1-\delta_H)\, H_{t-1}$ at price P_t^H from households, and combine it with housing investment goods $I_{H,t}$ to produce H_t to be sold back to households at the same price. The housing producers also operate in a perfectly competitive market, and earns no profit. $I_{H,t}$ is bought from the final goods sector at a price P_t.

Consistent with the historical trend in real house prices, the housing sector is assumed to have a weaker technology growth rate than the rest of the economy of π_t^z/π_t^h, where $\pi_t^z \equiv Z_t/Z_{t-1}$ and $\pi_t^h \equiv Z_t^h/Z_{t-1}^h$.

The representative housing producer f maximizes

$$\max_{\{I_{H,t}(f)\}} \left[P_t^H H_t(f) - P_t^H (1-\delta_H)\, H_{t-1}(f) - P_t I_{H,t}(f) \right],$$

s.t. the housing accumulation equation:

$$H_t(f) = (1-\delta_H) H_{t-1}(f) + \gamma_{H,t}(f) H_{t-1}(f), \tag{47}$$

where $\gamma_{H,t}(f)H_{t-1}(f)$ is "net housing investments" and $\gamma_{H,t}(f)$ is defined as

$$\begin{aligned} \gamma_{H,t}(f) = \frac{I_{H,t}(f)}{H_{t-1}(f)Z_t^h} &- \frac{\phi_{H1}}{2}\left[\frac{I_{H,t}(f)}{H_{t-1}(f)Z_t^h} - \frac{I_{H,ss}\pi_{ss}^z}{H_{ss}\pi_{ss}^h} z_{IH,t} \right]^2 \\ &- \frac{\phi_{H2}}{2}\left[\frac{I_{H,t}(f)}{H_{t-1}(f)Z_t^h} - \frac{I_{H,t-1}}{H_{t-2}Z_{t-1}^h} \right]^2. \end{aligned} \tag{48}$$

The parameters ϕ_{H1} and ϕ_{H2} govern the degree of adjustment costs, and $z_{IH,t}$ is a shock to housing investment adjustment costs, that follows an AR(1) process. The interpretation of the investment adjustment cost function is similar to the one in the previous section.

The first-order condition with respect to $I_{H,t}$ becomes, analogously to (46) (suppressing index f):

$$\frac{P_t^H}{P_t} = Z_t^h \left(1 - \phi_{H1}\left[\frac{I_{H,t}}{H_{t-1}Z_t^h} - \frac{I_{H,ss}\pi_{ss}^z}{H_{ss}\pi_{ss}^h} z_{IH,t} \right] - \phi_{H2}\left[\frac{I_{H,t}}{H_{t-1}Z_t^h} - \frac{I_{H,t-1}}{H_{t-2}Z_{t-1}^h} \right] \right)^{-1}. \tag{49}$$

2.8 Banking sector

The structure of the banking sector builds on Gerali *et al.* (2010). There is an infinite number of banks in the economy, indexed by $i \in [0,1]$. Each bank consists of two retail branches and a wholesale branch. One retail branch is responsible for providing differentiated loans to households and to entrepreneurs, while the other retail branch specializes in deposits. Both branches set interest rates in a monopolistically competitive fashion (Hafstead and Smith, 2012), subject to adjustment costs, which leads to imperfect and sluggish interest rate pass-through from the policy rate to loan and deposit rates. The wholesale branch manages the capital position of the bank. It chooses the overall level of operations regarding deposits and lending, adhering to Gerali *et al.* (2010)-type capital requirements adjusted with asset specific risk-weights. Banks incur a cost if they fail to meet their capital-to-asset ratio target. Bank capital plays an important role for credit supply in the model through a feedback loop between the real and the financial sides of the economy.

The balance sheet of bank i (in real terms) is:

$$B_t(i) = B_{F,t}^{TOT}(i) + K_t^B(i), \tag{50}$$

where $B_t(i)$ is total assets (total lending). On the liability side, $B_{F,t}^{TOT}(i)$ is total external bank funding and $K_t^B(i)$ is bank capital (equity). Total external bank funding is the sum of household deposits and foreign debt, i.e

$$B_{F,t}^{TOT}(i) = D_t(i) + B_t^*(i). \tag{51}$$

Make note that $P_t B_t^*(i)$ measures nominal foreign bank debt in domestic currency. Total lending is the sum of lending to entrepreneurs and households:

$$B_t(i) = B_{e,t}(i) + B_{h,t}(i). \tag{52}$$

If banks fail to meet their target level of risk-weighted capital requirements, ϖ_t, they incur a penalty cost. The target level of risk-weighted capital requirements consists of two elements: "hard" capital requirements, γ_t^b and a countercyclical capital buffer, CCB_t^b, hence $\varpi_t = \gamma_t^b + CCB_t^b$.[24] In addition, they face linear operational costs. Profits in period t for bank i as a whole is then given by:

$$\begin{aligned} J_t(i) &= r_t^F(i) B_{h,t}(i) + r_t^e(i) B_{e,t}(i) - r_t^d(i) D_t(i) \\ &- \left(\left[1-\gamma_t^{B^*}\right] R_t^* \frac{S_{t+1}}{S_t} - 1 \right) B_t^*(i) - \chi_o B_t(i) - \frac{\chi_c}{2} \left[\frac{K_t^B(i)}{B_t^{RW}(i)} - \varpi_t \right]^2 K_t^B(i), \end{aligned} \tag{53}$$

where $r_t^F(i)$ is the net interest rate on loans to households, $r_t^e(i)$ is the net interest rate on loans to entrepreneurs and $r_t^d(i)$ is the net deposit interest rate. The bank pays a risk premium on foreign funding. The "full" net interest rate for foreign funding hence becomes $\left[1-\gamma_t^{B^*}\right] R_t^* \frac{S_{t+1}}{S_t} - 1$, where $1-\gamma_t^{B^*}$ is the debt-elastic risk premium. R_t^* is the foreign

[24]The risk-weighted capital requirements, γ_t^b and CCB_t^b, are either shocks that follow AR(1) processes or policy rules that respond to financial variables such as credit or spreads, depending on the policy experiment. They are normally only active when the model is used for financial stability analysis. Otherwise, they are set to their steady-state values.

money market rate and S_t is the nominal exchange rate. χ_o governs the operational costs, and χ_c governs the capital target costs. $B_t^{RW}(i)$ denotes risk-weighted assets:

$$B_t^{RW}(i) = \varsigma^e B_{e,t} + \varsigma^h B_{h,t}, \tag{54}$$

where ς^e and ς^h are the risk-weights associated with credit to entrepreneurs and households, respectively. Bank capital accumulates according to:

$$K_t^B(i) = (1-\delta^b)\frac{P_{t-1}}{P_t}K_{t-1}^B(i) + \frac{P_{t-1}}{P_t}J_{t-1}(i), \tag{55}$$

where δ^b is the dividend share of the bank capital paid out to shareholders (households).

2.8.1 The wholesale branch

The wholesale branch lends to the loan branch at the interest rate $R_t^{b,e}(i) = 1 + r_t^{b,e}(i)$ for corporate credit (entrepreneurial loans) and $R_t^{b,h}(i) = 1 + r_t^{b,h}(i)$ for household loans. It is funded through borrowing from the deposit branch and from abroad. The "wholesale deposit rate" is assumed to be equal to the money market rate $R_t = 1 + r_t$, which follows from a no-arbitrage condition since we assume that banks have access to unlimited financing at the money market rate. The foreign funding rate, $\left[1-\gamma_t^{B^*}\right] R_t^* \frac{S_{t+1}}{S_t}$, is explained above.

The wholesale branch takes these funding costs as given and solves the following profit maximization problem:

$$\begin{aligned}\max_{\{B_{h,t}(i),B_{e,t}(i),B_t^*(i),D_t(i)\}} & E_t\Big[R_t^{b,e}(i)\,B_{e,t}(i) + R_t^{b,h}(i)\,B_{h,t}(i) \\ & -R_t D_t(i) - \left[1-\gamma_t^{B^*}\right] R_t^* \frac{S_{t+1}}{S_t} B_t^*(i) - \chi_o B_t(i) - \frac{\chi_c}{2}\left[\frac{K_t^B(i)}{B_t^{RW}(i)} - \varpi_t\right]^2 K_t^B(i)\Big],\end{aligned} \tag{56}$$

subject to (50) - (52) and (54).

The first-order conditions for the wholesale bank become:[25]

$$R_t^{b,e} = R_t + \chi_o - \chi_c\varsigma^e\left[\frac{K_t^B}{B_t^{RW}} - \varpi_t\right]\left(\frac{K_t^B}{B_t^{RW}}\right)^2, \tag{57}$$

$$R_t^{b,h} = R_t + \chi_o - \chi_c\varsigma^h\left[\frac{K_t^B}{B_t^{RW}} - \varpi_t\right]\left(\frac{K_t^B}{B_t^{RW}}\right)^2, \tag{58}$$

$$R_t = E_t\left[\left[1-\gamma_t^{B^*}\right] R_t^* \frac{S_{t+1}}{S_t}\right]. \tag{59}$$

Hence, the wholesale loan rates, $R_t^{b,e}$ and $R_t^{b,h}$ are set as markups over the money market rate, where the markups are increasing in the linear operational cost and the cost of deviating from the capital target. The first-order conditions with respect to $D_t(i)$ and $B_t^*(i)$ give equation (59), which is this model's version of the uncovered interest parity (UIP). It says that the money market rate needs to be equal to the "full" interest rate for foreign funding. It is assumed that the risk premium depends positively on the country's net foreign debt position (see Section 2.12).

[25] Since all banks behave the same, we have removed the index i from the first-order conditions in the Banking sector section.

2.8.2 The loan branch

The loan branch lends to households and entrepreneurs (at net rates $r_t^F(i)$ and $r_t^e(i)$, respectively) and borrows from the wholesale branch at the net interest rates $r_t^{b,h}(i)$ and $r_t^{b,e}(i)$. It faces costs when changing the loan rates, governed by the parameters ϕ^F and ϕ^e.

The maximization problem for the loan branch becomes:

$$\max_{\left\{r_t^F(i), r_t^e(i)\right\}} E_s \sum_{t=s}^{\infty} \Delta_{s,t} \left[\begin{array}{c} r_t^F(i) B_{h,t}(i) + r_t^e(i) B_{e,t}(i) - r_t^{b,h}(i) B_{h,t}(i) - r_t^{b,e}(i) B_{e,t}(i) \\ -\frac{\phi^F}{2}\left(\frac{r_t^F(i)}{r_{t-1}^F(i)} - 1\right)^2 r_t^F B_{h,t} - \frac{\phi^e}{2}\left(\frac{r_t^e(i)}{r_{t-1}^e(i)} - 1\right)^2 r_t^e B_{e,t} \end{array} \right],$$

subject to

$$B_t(i) = B_{e,t}(i) + B_{h,t}(i), \tag{60}$$

$$B_{h,t}(i) = \left(\frac{r_t^F(i)}{r_t^F}\right)^{-\theta_t^{IH}} B_{h,t}, \tag{61}$$

$$B_{e,t}(i) = \left(\frac{r_t^e(i)}{r_t^e}\right)^{-\theta_t^e} B_{e,t}. \tag{62}$$

Equation (61) and (62) are the demand functions from households and entrepreneurs respectively, and $\theta_t^{IH} > 0$ and $\theta_t^e > 0$ are the elasticities of substitution between household loans and corporate credit from all loan branches. They follow AR(1) processes and can be interpreted as markup shocks to the lending rates for household and business loans, respectively.

The first-order condition for the loan rate to households reads as (suppressing i):

$$1-\theta_t^{IH}+\theta_t^{IH}\frac{r_t^{b,h}}{r_t^F}-\phi^F\left(\frac{r_t^F}{r_{t-1}^F}-1\right)\frac{r_t^F}{r_{t-1}^F}+E_t\left[\Delta_{t+1}\phi^F\left(\frac{r_{t+1}^F}{r_t^F}-1\right)\left(\frac{r_{t+1}^F}{r_t^F}\right)^2\frac{P_{t+1}}{P_t}\frac{B_{h,t+1}}{B_{h,t}}\right]=0. \tag{63}$$

In the absence of adjustment costs, $\phi^F = 0$, the mortgage loan rate collapses to a markup over the wholesale lending rate (which is again a markup over the money-market rate (see (57))), $r_t^F = \frac{\theta_t^{IH}}{\theta_t^{IH}-1} r_t^{b,h}$. The third term in (63) ensures that the loan branch also takes into account future prices when setting today's price.

In a similar fashion, the first-order condition for the loan rate to entrepreneurs, $r_t^e(i)$, becomes:

$$1-\theta_t^e+\theta_t^e\frac{r_t^{b,e}}{r_t^e}-\phi^e\left(\frac{r_t^e}{r_{t-1}^e}-1\right)\frac{r_t^e}{r_{t-1}^e}+E_t\left[\Delta_{t+1}\phi^e\left(\frac{r_{t+1}^e}{r_t^e}-1\right)\left(\frac{r_{t+1}^e}{r_t^e}\right)^2\frac{P_{t+1}}{P_t}\frac{B_{e,t+1}}{B_{e,t}}\right]=0. \tag{64}$$

2.8.3 The deposit branch

The deposit branch lends to the wholesale branch at money market net rate r_t and pays out interest on household deposits at rate $r_t^d(i)$. It faces costs when changing the deposit rate, governed by parameter ϕ^D. The maximization problem becomes

$$\max_{\{r_t^d(i)\}} E_s \sum_{t=s}^{\infty} \Delta_{s,t} \left[r_t D_t(i) - r_t^d(i) D_t(i) - \frac{\phi^D}{2} \left(\frac{r_t^d(i)}{r_{t-1}^d(i)} - 1 \right)^2 r_t^d D_t \right],$$

subject to deposit demand from households:

$$D_t(i) = \left(\frac{r_t^d(i)}{r_t^d} \right)^{\theta_t^D} D_t, \tag{65}$$

where $\theta^D > 0$ is the elasticity of substitution between deposit services.

The first-order condition with respect to $r_t^d(i)$ becomes:

$$-(1+\theta^D)+\theta^D \frac{r_t}{r_t^d} - \phi^D \left(\frac{r_t^d}{r_{t-1}^d} - 1 \right) \frac{r_t^d}{r_{t-1}^d} + E_t \left[\Delta_{t+1} \phi^D \left(\frac{r_{t+1}^d}{r_t^d} - 1 \right) \left(\frac{r_{t+1}^d}{r_t^d} \right)^2 \frac{P_{t+1}}{P_t} \frac{D_{t+1}}{D_t} \right] = 0. \tag{66}$$

In the absence of adjustment costs the deposit rate collapses to a mark-down on the money-market rate ($r_t^D = \frac{\theta^D}{1+\theta^D} r_t$).

2.9 Oil sector

To take into account the significance of the oil sector for the Norwegian economy, an explicit oil sector is incorporated in NEMO. The oil sector builds on Bergholt *et al.* (2017). The sector consists of supply firms as well as a domestic and a foreign extraction firm. The supply firms combine labor, capital and final goods to produce oil supply goods that are used for oil investment by the domestic extraction firm, and are exported to a foreign oil extraction firm. The representative domestic oil extraction firm undertakes two activities: (i) it invests in rigs, using solely oil supply goods as inputs, and (ii)) it extracts and exports oil, using rigs and oil in the ground as inputs.

2.9.1 Supply firms

A continuum of oil supply firms, indexed r, combines final goods $Q_{O,t}(r)$ (priced at $P_t^{QO} = P_t$), labor from households $L_{O,t}(r)$ and capital rented from entrepreneurs $\overline{K}_{O,t}(r)$ to produce a good $Y_{R,t}(r)$ that is used for oil investments by an extraction firm and exports to a foreign oil extraction firm. The wage earned by households working in the oil supply sector is $W_{O,t}$, equal to W_t because of perfect labor mobility, while the rental price of utilized capital is $R_{KO,t}$, equal to $R_{K,t}$ due to perfect mobility of capital.

The production function for supply firm r is:

$$Y_{R,t}(r) = Z_R Q_{O,t}^{\alpha_q}(r) (Z_t L_{O,t}(r))^{\alpha_l} \overline{K}_{O,t}^{1-\alpha_q-\alpha_l}(r), \tag{67}$$

where Z_R is oil supply productivity, α_q is the final goods share in production, α_l is the labor share and $1 - \alpha_q - \alpha_l$ is the capital share in production. Including final goods as inputs ensures that imports indirectly enter the production function. Minimizing costs, subject to (67), gives rise to the following conditional demand functions and marginal cost function:

$$Q_{O,t}(r) = \alpha_q \left(\frac{P_t^{QO}}{MC_{R,t}} \right)^{-1} Y_{R,t}(r), \tag{68}$$

$$L_{O,t}(r) = \alpha_l \left(\frac{W_{O,t}}{MC_{R,t}}\right)^{-1} Y_{R,t}(r), \tag{69}$$

$$\overline{K}_{O,t}(r) = (1-\alpha_q-\alpha_l)\left(\frac{R_{KO,t}}{MC_{R,t}}\right)^{-1} Y_{R,t}(r), \tag{70}$$

$$MC_{R,t} = \frac{1}{Z_R}\left(\frac{P_t^{QO}}{\alpha_q}\right)^{\alpha_q}\left(\frac{W_{O,t}}{\alpha_l}\right)^{\alpha_l}\left(\frac{R_{KO,t}}{1-\alpha_q-\alpha_l}\right)^{1-\alpha_q-\alpha_l}. \tag{71}$$

Oil supply firms sell their goods under monopolistic competition. Each firm r charges different prices at home and abroad, $P_t^R(r)$ in the domestic market and $P_t^{R^*}(r)$ abroad, where the latter is denoted in foreign currency. Dividends (which are paid out to households) becomes:

$$\Psi_t(r) = P_t^R(r)\, I_{OF,t}(r) + P_t^{R*}(r)\, S_t M_{O*,t}(r) - MC_{R,t} Y_{R,t}(r), \tag{72}$$

where $I_{OF,t}(r)$ are goods delivered to the domestic extraction firm, $M_{O,t}^*(r)$ are supply goods for exports and S_t is the nominal exchange rate. Total production of supply goods must satisfy: $Y_{R,t} = I_{OF,t}(r) + M_{O*,t}(r)$.

It can be shown that supply firm r faces the following demand functions from the domestic and foreign extraction sectors, respectively:

$$I_{OF,t}(r) = \left(\frac{P_t^R(r)}{P_t^R}\right)^{-\theta^R} I_{OF,t}, \tag{73}$$

$$M_{O*,t}(r) = \left(\frac{P_t^{R*}(r)}{P_t^{R*}}\right)^{-\theta^{R^*}} M_{O*,t}, \tag{74}$$

where θ^R and θ^{R^*} are the elasticities of substitution between goods in the two markets respectively. Additionally, the costs of adjusting prices in the domestic and the foreign markets are given by:

$$\gamma_{PR,t}(r) \equiv \frac{\phi^{PR}}{2}\left[\frac{P_t^R(r)/P_{t-1}^R(r)}{P_{t-1}^R/P_{t-2}^R} - 1\right]^2, \tag{75}$$

$$\gamma_{PR^*,t}(r) \equiv \frac{\phi^{PR^*}}{2}\left[\frac{P_t^{R^*}(r)/P_{t-1}^{R^*}(r)}{P_{t-1}^{R^*}/P_{t-2}^{R^*}} - 1\right]^2, \tag{76}$$

respectively, where ϕ^{PR} and ϕ^{PR^*} govern the costs of adjusting prices.

Profit maximization with respect to P_t^R and $P_t^{R^*}$ leads to the following first-order conditions in symmetric equilibrium (index r removed), respectively:

$$\begin{gathered} I_{OF,t} - \theta^R I_{OF,t} + MC_{R,t}\theta^R \frac{I_{OF,t}}{P_t^R} - \phi^{PR}\left[\frac{P_t^R/P_{t-1}^R}{P_{t-1}^R/P_{t-2}^R} - 1\right]\frac{P_t^R/P_{t-1}^R}{P_{t-1}^R/P_{t-2}^R} I_{OF,t} \\ + E_t\left\{\Delta_{t+1}\phi^{PR}\left[\frac{P_{t+1}^R/P_t^R}{P_t^R/P_{t-1}^R} - 1\right]\frac{(P_{t+1}^R/P_t^R)^2}{P_t^R/P_{t-1}^R} I_{OF,t+1}\right\} = 0, \end{gathered} \tag{77}$$

$$S_t M_{O*,t} - \theta^{R^*} S_t M_{O*,t} + MC_{R,t}\theta^{R^*}\frac{M_{O*,t}}{P_t^{R^*}} - \phi^{PR^*}\left[\frac{P_t^{R^*}/P_{t-1}^{R^*}}{P_{t-1}^{R^*}/P_{t-2}^{R^*}} - 1\right]\frac{P_t^{R^*}/P_{t-1}^{R^*}}{P_{t-1}^{R^*}/P_{t-2}^{R^*}} S_t M_{O*,t}$$
$$+E_t\left\{\Delta_{t+1}\phi^{PR^*}\left[\frac{P_{t+1}^{R^*}/P_t^{R^*}}{P_t^{R^*}/P_{t-1}^{R^*}} - 1\right]\frac{\left(P_{t+1}^{R^*}/P_t^{R^*}\right)^2}{P_t^{R^*}/P_{t-1}^{R^*}} S_{t+1}M_{O*,t+1}\right\} = 0. \tag{78}$$

Because of the adjustment costs, the supply firms take into account the full future path of expected prices when setting current prices. In the case without any adjustment costs, prices would be set as markups over marginal costs in every period: $P_t^R = \frac{\theta^R}{\theta^R - 1} MC_{R,t}$ and $P_t^{R^*} = \frac{\theta^{R^*}}{\theta^{R^*}-1}\frac{1}{S_t} MC_{R,t}$.

2.9.2 The domestic extraction firm

Domestic oil extraction ($Y_{O,t}$) requires oil reserves (O_t) and oil rig services ($\overline{F}_{O,t}$) so that

$$Y_{O,t} = Z_O \overline{F}_{O,t}^{\alpha_o} O_t^{1-\alpha_o}, \tag{79}$$

where Z_O is oil extraction productivity and α_o is the rigs share. As we abstract from issues of depletion and discovery of new oil fields, O_t is treated as a parameter, $O_t = O$. Hence, $\alpha_o \in [0, 1)$ implies decreasing returns to scale. Effective oil rig services are determined by oil rig capacity, $F_{O,t-1}$, and a utilization rate of that capacity, $U_{F,t}$:

$$\overline{F}_{O,t} = F_{O,t-1} U_{F,t}. \tag{80}$$

In (80) it is assumed that the rig capacity for period t is set in period $t-1$. Hence, to increase effective oil production in period t, the oil extraction firm must increase the utilization rate, which comes at a cost. Due to this endogenous utilization rate, there will be a tradeoff between raising the utilization rate to increase production in the current period, or to increase investment that will increase production capacity in future periods. The unit cost of increasing the utilization rate in terms of oil supply goods is represented by the function $a(U_{F,t})$:

$$a(U_{F,t}) = \gamma^O(U_{F,t} - 1) + \frac{\gamma^O \phi^{uf}}{2}(U_{F,t} - 1)^2. \tag{81}$$

The cost of changing the utilization rate is governed by the parameters γ^O and ϕ^{uf}.[26] The extraction firm can invest in rig capacity, using oil supply goods as the investment good. Hence, the dynamics of oil rig capacity is characterized by:

$$F_{O,t} = (1-\delta_O)F_{O,t-1} + Z_{IOIL,t}\left[1 - \Psi_O\left(\frac{I_{O,t}}{I_{O,t-1}}\right)\right] I_{O,t}, \tag{82}$$

where δ_O is the rigs depreciation rate and $\Psi_O(\frac{I_{O,t}}{I_{O,t-1}}) = \frac{\phi^{RI}}{2}(\frac{I_{O,t}}{I_{O,t-1}} - \pi_t^z)^2$ represents the costs of changing investment levels, governed by the parameter ϕ^{RI}. The parameter π_t^z is the growth rate of the economy and $Z_{IOIL,t}$ is an oil-specific technology shock, that follows an AR(1) process. A positive innovation leads to more operative oil rigs in future

[26] By using $U_{F,ss} = 1$, it can easily be shown that $\gamma^O = a'(U_{F,ss})$. Kravik *et al.* (n.d.) show in their steady-state solution (by combining steady-state versions of equation (84) and (86)) that $\gamma^O = a'(U_{F,ss}) = (\delta_O + \frac{\pi_{ss}^z}{\beta} - 1)$.

periods for any given level of investment activity in the current period. Total demand for supply goods from the domestic extraction firms is given by the sum of gross investments and the cost associated with the utilization rate of rigs: $I_{OF,t} = I_{O,t} + a(U_{F,t})F_{O,t-1}$.

Oil production is given by $Y_{O,t}$, which is exported at a price P_t^{O*} in foreign currency. Consequently, the oil price in domestic currency is given by $S_t P_t^{O*}$, where S_t is the nominal exchange rate. The extraction firm maximizes the discounted expected stream of cash flows, subject to extraction technology and rig accumulation:

$$\max_{\{F_{O,t}, I_{O,t}, U_{F,t}\}} \sum_{t=s}^{\infty} \Delta_{s,t} \left[S_t P_t^{O*} Y_{O,t} - P_t^R I_{OF,t} \right], \tag{83}$$

where $\Delta_{s,t}$ is the stochastic discount factor between period s and t.

The intertemporal first-order conditions with respect to $F_{O,t}$ and $I_{O,t}$ become:[27]

$$\Omega_{O,t} = E\left[\Delta_{t+1} \left(\alpha_o S_{t+1} P_{t+1}^{O*} Y_{O,t+1} F_{O,t}^{-1} - P_{t+1}^R a(U_{F,t+1}) + (1-\delta_O)\Omega_{O,t+1} \right) \right], \tag{84}$$

$$\begin{aligned} P_t^R = \Omega_{O,t} Z_{IOIL,t} & \left[1 - \Psi_O^{'} \left(\frac{I_{O,t}}{I_{O,t-1}} \right) \frac{I_{O,t}}{I_{O,t-1}} - \Psi_O \left(\frac{I_{O,t}}{I_{O,t-1}} \right) \right] \\ + E & \left[\Delta \Omega_{O,t+1} Z_{IOIL,t+1} \Psi_O^{'} \left(\frac{I_{O,t+1}}{I_{O,t}} \right) \left(\frac{I_{O,t+1}}{I_{O,t}} \right)^2 \right]. \end{aligned} \tag{85}$$

Equation (84) determines the present marginal value of oil rig capacity, $\Omega_{O,t}$ (the shadow price of rig capacity). The first term on the right-hand side is the net income from installing more rigs at the margin. The second term is the utilization cost associated with more rigs, while the third term represents the net-of-depreciation continuation value.

Equation (85) aligns the marginal cost of new investments (P_t^R) with the marginal gain from increased rig capacity. The first term on the right is the marginal gain from more capacity, net of adjustment costs. The second term reflects that more investment in period t reduces the need for costly investment adjustments in the future. The optimality conditions imply the oil company bases its investment decisions on the entire expected future oil price path.

The first-order condition with respect to the utilization rate $U_{F,t}$ becomes:

$$\alpha_o S_t P_t^{O*} \frac{Y_{O,t}}{U_{F,t}} = P_t^R a^{'}(U_{F,t}) F_{O,t-1}. \tag{86}$$

In optimum, the marginal revenues from a higher rig utilization rate is equated to the marginal utilization costs.

2.9.3 The foreign extraction firm

The foreign extraction firm is modeled in a simpler fashion. It extracts oil, $Y_{O*,t}$, invests, $I_{O*,t}$, and imports oil supply goods from the home country's oil supply sector, $M_{O*,t}$, with the following production function:[28]

[27] These are identical to equation (8) and (9) in Bergholt *et al.* (2017).

[28] One can think of the product $M_{O*,t}^{\alpha_{o*}} I_{O*,t}^{\alpha_{io*}}$ as the foreign rigs production function, corresponding to $\overline{F}_{O,t}^{\alpha_o}$ in (79).

$$Y_{O*,t} = M_{O*,t}^{\alpha_{o*}} I_{O*,t}^{\alpha_{io*}} (O_*)^{1-\alpha_{io*}-\alpha_{o*}}. \tag{87}$$

O_* is oil in the ground abroad, set to a constant and α_{o*} is the share of domestically produced oil supply goods used as inputs. Maximizing profits leads to the following demand function for oil supply goods from abroad:

$$M_{O*,t} = \alpha_{o*} \left(\frac{P_t^{R*}}{P_t^{O*}} \right)^{-1} Y_{O*,t}. \tag{88}$$

Note that $Y_{O*,t}$ follows an AR(1) process and can be interpreted as a foreign oil production shock in the model (making $I_{O*,t}$, O_* and α_{io*} superfluous and not determined).

2.9.4 The Government Pension Fund Global

In Norway, the Government Pension Fund Act stipulates that the government's cash flow from the petroleum industry shall be transferred to the "Government Pension Fund Global" (GPFG). A fiscal rule specifies that the transfers from the GPFG to the central government's fiscal budget shall follow the expected real return on the GPFG over time. In NEMO, this relationship is simplified, as the GPFG and fiscal policy are independently treated. The full sales revenue is transferred to the GPFG in every period. Hence, the GPFG, $B_{F,t}$, accumulates according to:

$$B_{F,t} = (1 - \rho_{G_F}) \left[R_{t-1}^* \frac{P_{t-1}}{P_t} \frac{S_t}{S_{t-1}} B_{F,t-1} \right] + S_t \frac{P_t^{O*}}{P_t} Y_{O,t}, \tag{89}$$

where the amount (in real terms) transferred from the pension fund is given by:

$$G_{F,t} = \rho_{G_F} \left[R_{t-1}^* \frac{P_{t-1}}{P_t} \frac{S_t}{S_{t-1}} B_{F,t-1} \right]. \tag{90}$$

The transfer, $G_{F,t}$, ensures that the pension fund, $B_{F,t}$ is stationary. For instance, following an oil price shock, the fund will never return back to its steady state when $\rho_{G_F} = 0$.

In the model, we assume that the transfer from the fund goes to the banking sector (and not to the government sector). This assumption deemed necessary to be able to replicate (in the steady state of the model) the fact that mainland Norway has positive net imports as well as a negative (private) asset position (held by the banking sector) (see Section 2.12 for the mainland debt accumulation equation (B_t^*) and further details).

2.10 Foreign sector

The foreign sector in NEMO is split into two parts. The first part derives the optimality condition for the price setting of the imported good that enters into the final good sector as well as export demand for the domestic intermediate good. The second part, starting with (93) below, is a block exogenous system of equations based on a standard New Keynesian model that links foreign output, foreign money market rates, foreign inflation and the international oil price. We adopt the small open economy assumption, implying that the foreign economy (rest of the world) is fully exogenous from the point of view of the Norwegian economy. Hence, economic developments in Norway have no effects on its trading partners. The two parts are linked since export demand depends on trading partners' output level.

The intermediate sector abroad is assumed to be symmetric to the domestic intermediate sector. Foreign exporters enjoy market power and face price adjustment costs. The optimal price setting rule for the imported price P_t^M in domestic currency (that enters into the domestic final good sector as inputs) will therefore be (cf. (31)):

$$M_t - \theta^F M_t + S_t MC_t^* \theta^F \frac{M_t}{P_t^M} - \phi^{PM}\left[\frac{\pi_t^M}{\pi_{t-1}^M} - 1\right]\frac{\pi_t^M}{\pi_{t-1}^M} M_t$$
$$+E_t\left\{\Delta_{t+1}^* \phi^{PM}\left[\frac{\pi_{t+1}^M}{\pi_t^M} - 1\right]\frac{(\pi_{t+1}^M)^2}{\pi_t^M} M_{t+1}\frac{S_t}{S_{t+1}}\right\} = 0, \tag{91}$$

where Δ_{t+1}^* is the foreign stochastic discount factor (assumed equal to $(R_t^*)^{-1}$ for simplicity), ϕ^{PM} is a parameter that captures the cost of changing the price of imported goods, MC_t^* denotes foreign marginal costs that follow a shock process and θ^F is the substitution elasticity between imported goods. Note that we have defined $\pi_t^M \equiv P_t^M / P_{t-1}^M$. In the absence of adjustment costs, $\phi^{PM} = 0$, prices would simply be set as a markup over marginal costs in every period $P_t^M = \frac{\theta^F}{\theta^F - 1} S_t MC_t^*$ with full exchange rate pass-through.

Turning to exports, the export demand for the intermediate good is given by (symmetric to (34)):

$$M_t^* = (1 - \nu_t^*)\left(\frac{P_t^{M*}}{P_t^*}\right)^{-\mu^*} Y_{NAT,t}^*, \tag{92}$$

where ν_t^* follows an AR(1) process and can be interpreted as an export demand shock. $Y_{NAT,t}^*$ is output abroad.

The second part of the foreign sector is modeled as a block-exogenous set of equations, linking the foreign inflation gap, the foreign output gap, the foreign interest rate gap and the oil price gap.[29] Moreover, the foreign sector is divided into two groups: Trading partners and non-trading partners. The former is a group of Norway's largest export and import partners; the latter is the foreign sector minus trading partners. The model for the foreign sector is based on a standard New Keynesian model, with a dynamic IS curve representing the relationship between output and the real interest rate, and a Phillips curve linking inflation to output, both with added backward-looking terms to add more dynamics and realism.

The oil price has been added to the system of equations to negatively affect trading partners' output and positively affect their rate of inflation. A rise in global demand will increase international oil prices, but oil prices can also increase due to reduced international supply. The effects of a demand-driven change in the oil price are stronger on the Norwegian economy than the effects of a supply-driven change, since the latter weakens exports from the domestic non-oil sector, dampening the positive effect on GDP (see Section 4). The effects of oil prices on the Norwegian economy is further discussed in Gerdrup *et al.* (2017).

Output for trading partners is given by equation (93) and (94), the latter being the traditional IS curve (with the parameter ψ^{R*} relating the real interest rate to output):

[29] In the remainder of this section, all variables are in gap-form (deviation from steady state). The gap indicator $\widehat{\ }$ is suppressed for readability.

$$Y^*_{NAT,t} = \phi^{Y*} Y^*_{NAT,t-1} + (1 - \phi^{Y*}) Y^*_{FNAT,t} - \phi^{O*} P^{O*}_t + \phi^{YNTP*} Y^{NTP}_{NAT,t} + z_{U*,t}, \tag{93}$$

where $Y^*_{FNAT,t}$ is defined as:

$$Y^*_{FNAT,t} = Y^*_{FNAT,t+1} - \psi^{R*}(R^*_t - \pi^*_{t+1}). \tag{94}$$

Trading partners' output is affected negatively by the oil price gap, P^{O*}_t, as Norway's trading partners are net oil importers, and positively by the output gap among non-trading partners, $Y^{NTP}_{NAT,t}$. ϕ^{O*} and ϕ^{YNTP*} are positive parameters. ϕ^{Y*} is the lag operator, and $z_{U*,t}$ follows an AR(1) process and can be interpreted as a trading partner demand shock.

The output gap for non-trading partners, $Y^{NTP}_{NAT,t}$, is assumed to follow:

$$Y^{NTP}_{NAT,t} = \lambda^{YNTP} Y^{YNTP}_{NAT,t-1} - \phi^{ONTP} P^{O*}_t + \phi^{YNTP} Y^*_{NAT,t} + z_{YNTP,t}, \tag{95}$$

where $z_{YNTP,t}$ can be interpreted as a global demand shock (equal to its innovation as there is no corresponding persistence parameter), and λ^{YNTP}, ϕ^{ONTP} and ϕ^{YNTP} are parameters. Total global output is given by a weighted sum of trading partners' and non-trading partners' output:

$$Y^{GLOB}_{NAT,t} = \alpha^{GLOB} Y^*_{NAT,t} + (1 - \alpha^{GLOB}) Y^{NTP}_{NAT,t}, \tag{96}$$

where α^{GLOB} is the trading partners' output share of total global output.

Inflation for trading partners is given by equations (97) and (98), the latter being the traditional Phillips curve:

$$\pi^*_t = \phi^{P*} \pi^*_{t-1} + (1 - \phi^{P*}) \pi^*_{F,t} + \phi^{OP*} P^{O*}_t, \tag{97}$$

where $\pi^*_{F,t}$ is defined as:

$$\pi^*_{F,t} = \alpha^{P*} \pi^*_{F,t+1} + \alpha^{Y*} Y^*_{NAT,t} + z_{\theta^{H*},t}. \tag{98}$$

α^{Y*} is the traditional Phillips curve parameter, whereas ϕ^{OP*} is a positive parameter picking up the positive effect of real oil prices on marginal costs for trading partner firms. ϕ^{P*} is the lag operator and $z_{\theta^{H*},t}$ is a foreign price markup shock following an AR(1) process.

The oil price is forward-looking and assumed positively affected by global demand:

$$P^{O*}_t = \beta^O P^{O*}_{t+1} + \kappa^O Y^{GLOB}_{NAT,t} + z_{PO*,t}, \tag{99}$$

where $z_{PO*,t}$ can be interpreted as an international oil supply shock, following an AR(1) process, and β^O and κ^O are parameters.

Lastly, the foreign monetary policy rate (equal to the foreign money market rate) is given by a simple policy rule with smoothing:

$$R^*_t = \omega^{R*} R^*_{t-1} + (1 - \omega^{R*}) \left[\omega^{P*} \pi^*_t + \omega^{Y*} Y^*_{NAT,t}\right] + z_{R*,t}, \tag{100}$$

where $z_{R*,t}$ follows an AR(1) process and can be interpreted as a trading partner monetary policy shock, the parameter ω^{R*} governs interest rate smoothing, and ω^{P*} and ω^{Y*} are weights on inflation and output, respectively.

2.11 Market clearing conditions

The following set of equilibrium conditions needs to hold in order to close the model. In the intermediate goods market, total production needs to equal goods for domestic use and exports:

$$T_t = Q_t + M_t^*. \tag{101}$$

Total production of final goods needs to equal the sum of the following demand components: Consumption, investment, housing investment, government expenditure and inputs into the oil supply sector:

$$A_t = C_t \ + I_{C,t} + I_{H,t} + G_t + Q_{O,t}. \tag{102}$$

Total investments must equal the sum of business and housing investment (note that it does note include oil supply investments):

$$I_t = I_{C,t} + I_{H,t}. \tag{103}$$

Total production of capital goods must equal capital usage in the oil and traditional sector combined:

$$\overline{K}_t = \overline{K}_{O,t} \ + \overline{K}_{I,t}. \tag{104}$$

Equilibrium in the labor market is characterized by:

$$L_t = L_{O,t} \ + L_{I,t}. \tag{105}$$

For the oil supply firms, total production must equal use by the domestic extraction firm and oil supply exports.

$$Y_{R,t} = I_{OF,t} + M_{O*,t}. \tag{106}$$

Lastly, we define output for mainland Norway as:

$$Y_{NAT,t} = \left(C_t + G_t + I_t + P_t^R I_{O,t} + S_t P_t^{M*} M_t^* + S_t P_t^{R*} M_{O*,t} - P_t^M M_t\right) \frac{1}{\log(z_{x,t})}, \tag{107}$$

where the four first terms on the right hand side are household and government consumption, investments and oil supply investments, respectively. The following two terms are traditional and oil supply exports and $P_t^M M_t$ represents imports. Finally, $z_{x,t}$ is an inventory shock to the mainland economy that follows an AR(1) process. Total output is given by:

$$Y_{NAT,t}^{TOTAL} = Y_{NAT,t} + S_t P_t^{O*} Y_{O,t}^*, \tag{108}$$

i.e. mainland output plus production from oil extraction (which is exported).

2.12 Resource constraints, UIP and the current account

The division of the Norwegian economy into a mainland share and a non-mainland share entails that foreign debt for the country as a whole is equal to mainland private foreign debt (held by banks) less government claims:

$$B_t^{TOT*} = B_t^* - B_{F,t}. \tag{109}$$

Taking the household budget constraint as the point of departure and inserting for profits, dividends and lump-sum taxes, it is possible to derive mainland Norway's resource constraint, i.e. the private foreign debt accumulation equation, as:

$$B_t^* = \frac{P_{t-1}}{P_t} R_{t-1} B_{t-1}^* + \left[\frac{P_t^M}{P_t} M_t - S_t \frac{P_t^{R*}}{P_t} M_{O*,t} - S_t \frac{P_t^{M*}}{P_t} M_t^* - \frac{P_t^R}{P_t} I_{OF,t} - G_{F,t} \right], \tag{110}$$

where the bracketed term is the current account for mainland Norway, i.e. positive net imports imply increased external debt for mainland Norway. The first term in the brackets is imports, the second term is oil supply exports, the third term is traditional exports and the fourth term is "exports" of oil supply goods from mainland Norway to non-mainland Norway.[30] The fifth term, $G_{F,t}$, represents transfers from the pension fund to the mainland economy.

The accumulation equation for government claims and the size of transfers ($G_{F,t}$) were derived in Section 2.9.4. Note that $G_{F,t}$ is included both in B_t^* and $B_{F,t}$ and hence cancels out (except for the interest rate differential (see equation (89))). In reality, the annual transfers from the oil fund go to the government. As this mechanism is not modelled in NEMO and we do not wish transfers from the pension fund to drive banking sector net worth, we set $G_{F,t}$ to its steady-state value in (110) when we operate the model.

The uncovered interest rate parity was derived in Section 2.8.1 and is repeated here:

$$E_t \left[\left[1 - \gamma_t^{B^*} \right] R_t^* \frac{S_{t+1}}{S_t} \right] = R_t. \tag{111}$$

In (111), $1 - \gamma_t^{B^*}$ is the debt-elastic risk premium, R_t^* is the foreign money market interest rate and S_t is the nominal exchange rate (NOK per foreign currency unit). It is assumed that the risk premium depends positively on the country's net foreign debt position (B_t^{TOT*}) and the anticipated growth rate of the exchange rate:[31]

$$1 - \gamma_t^{B^*} = exp\left[\phi^B (B_t^{TOT*} - B_{ss}^{TOT*}) - \phi^S (E_t S_{t+1} S_t - S_{ss}^2) \right] + z_t^B, \tag{112}$$

where z_t^B is an exogenous exchange rate risk premium shock following an AR(1) process and ϕ^B and ϕ^S are non-negative parameters.

The assumption of a financial friction is necessary to ensure stationarity in small open economy models like NEMO. Augmenting the risk premium with the anticipated growth rate of the exchange rate tend to give a more hump-shaped exchange rate response following a risk premium shock (see Adolfson *et al.* (2013) for a discussion).[32]

[30] The latter term is ignored in the model file, in accordance with the national accounts.

[31] Technically, the risk premium is defined in terms of stationary variables. Hence, in equation (112) the B_t^{TOT*} refers to the stationary version and S_t is the *real* exchange rate.

[32] As discussed in Section 3, ϕ^S is weakly identified in the model and set to 0.

The relationship between the net foreign asset position, the risk premium and the UIP is summarized in Figure 2.

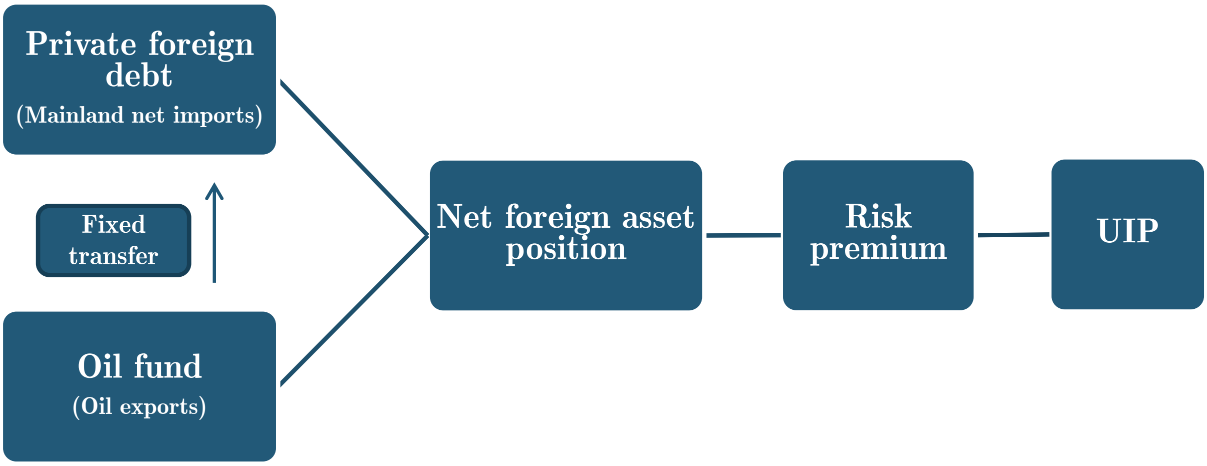

Figure 2: The relationship between the net foreign asset position, the risk premium and the UIP in NEMO.

2.13 Monetary policy

The central bank controls the policy rate ($R_{P,t}$), equal to the product of the money market rate and the exogenous money market risk premium ($R_{P,t} = R_t Z_{prem,t}$), where $Z_{prem,t}$ is the risk premium and a shock (following an AR(1) process). The central bank conducts optimal monetary policy, i.e. setting the interest rate to minimize a loss function. The loss function consists of the discounted (weighted) sum of future expected quadratic deviations from steady-state values of inflation, output, the level of the policy rate and changes in the policy rate. More specifically, the central bank minimizes the following loss function, using the policy rate as instrument (either under commitment or discretionary policies), where $\widehat{x}_t$ denotes variable x's log-deviation from the steady state:

$$\min_{\{\widehat{R}_{P,t}\}} \sum_{t=s}^{\infty} \beta_p^{t-s} \left[\left(\widehat{\pi}_{pol,t}\right)^2 + \lambda_y \left(\widehat{Y}_{NAT,t}\right)^2 + \lambda_{dr} \left(\triangle R_{P,t}\right)^2 + \lambda_{lr} \left(\widehat{R}_{P,t}^{YEAR}\right)^2 \right], \tag{113}$$

where β_p is the central bank's discount factor, $\widehat{R}_{P,t}$ is the policy rate gap, $\widehat{Y}_{NAT,t}$ is the mainland output gap (defined in Section 2.11), $\widehat{\pi}_{pol,t}$ is the 4-quarter consumer price inflation as a deviation from the inflation target, $\triangle R_{P,t}$ is the annualized change in the policy rate and $\widehat{R}_{P,t}^{YEAR}$ is the annualized policy rate gap. The definitions of the three latter variables are:

$$\widehat{\pi}_{pol,t} = \widehat{\pi}_t + \widehat{\pi}_{t-1} + \widehat{\pi}_{t-2} + \widehat{\pi}_{t-3} + \log\left(\frac{z_{inf,t}}{z_{inf,ss}}\right), \tag{114}$$

$$\triangle R_{P,t} = 4\left(R_{P,t} - R_{P,t-1}\right), \tag{115}$$

$$\widehat{R}_{P,t}^{YEAR} = 4\widehat{R}_{P,t}. \tag{116}$$

where $z_{inf,t}$ is a shock to the inflation target that follows an AR(1) process, which can be interpreted as a monetary policy shock. λ_y, λ_{dr} and λ_{lr} are the corresponding weights in the loss function.

Monetary policy in NEMO can alternatively be solved under a Taylor type rule of the following kind:[33]

$$\widehat{R}_t = \omega_R \widehat{R}_{t-1} + (1-\omega_R)(\omega_P \widehat{\pi}_t + \omega_Y \widehat{Y}_{NAT,t}) + Z_{RN3M,t}, \tag{117}$$

where R_t is the money market rate, ω_R governs interest rate persistence and ω_P and ω_Y are the weights on inflation and output respectively, while $Z_{RN3M,t}$ represents a monetary policy shock that follows an AR(1) process.

3 Estimation

We estimate the parameters of NEMO using Bayesian techniques, as outlined in An and Schorfheide (2007). Computations are done by using the *RISE* toolbox[34] and *NB Toolbox*.[35]. In this chapter we describe the data used for the estimation, give an account of how the model's steady state is calibrated and report on our prior and posterior distributions. A full list of all parameters in NEMO is provided in Appendix C.

3.1 Data

The data set used for estimation of NEMO is quarterly and runs from 2001Q1, the year Norges Bank officially introduced (flexible) inflation targeting, to 2017Q4. The macroeconomic time series cover Norwegian and international variables. Real domestic variables include GDP, consumption, exports, imports, government expenditures, investment and hours worked. Financial variables include household and corporate credit. Price variables include wages, consumer prices, house prices, lending rates to households, lending rates to corporations, money market interest rates and the policy rate. Lastly, international variables include the exchange rate, the international oil price and foreign GDP, money market rates and inflation. The data sources include Statistics Norway, Norges Bank's own calculations, and international sources, particularly the IMF and Thomson Reuters. The data for the real variables are in constant prices from the national accounts, whereas credit and house prices are deflated by consumer prices. In total, there are 26 observable variables used in the estimation of NEMO.

3.1.1 Data transformation and the steady state

NEMO is linearized around a steady state when solved. As with most DSGE models, NEMO assumes that the economy has one balanced-growth path, and that the different demand components of GDP grow at the same pace over time.[36] There is also a close relationship between the steady-state real interest rate and the balanced-growth path. However, actual data are not as well-behaved. Different variables exhibit different trends within the time span we have available, but we have to choose only one set of steady-state values that are both deemed relevant for the recent past and the economy going forward and that in addition are model-consistent.

[33] Section 3.3 describes the particular monetary policy rule used in the estimation.

[34] "Rationality In Switching Environments" (*RISE*) is an object-oriented Matlab toolbox for solving and estimating nonlinear Regime-Switching DSGE models. The toolbox is developed by Junior Maih and freely available for downloading at `https://github.com/jmaih/RISE_toolbox`.

[35] NB Toolbox is internally developed at Norges Bank. It will be released for public use in the future.

[36] NEMO has a separate growth rate for the housing sector.

Even though business cycle dynamics can be influenced by the calculated gradients around the steady state, most of the business cycles dynamics are determined by the dynamic parameters and shock processes in the model. Consequently, since the model is too simple to explain multiple, time-varying trends in the data, we use pre-filtered gap series (i.e. log-deviations from trend) when we estimate dynamic parameters, estimate shock processes, calculate business cycle moments, do shock decomposition and perform variance decompositions. There is therefore no data transformations taking place within NEMO and no measurement equations. A future goal is to solve the model around multiple time-varying states, so as to bring the model closer to actual trend developments in the data.

For the demand components (consumption, housing investment, business investment, oil investment, government consumption, imports, traditional exports and oil supply exports) we use the model DORY[37] to filter the series and create the gaps. DORY ensures that the demand component gaps sum up to the output gap. Statistical filters (e.g. the Hodrick-Prescott filter) and sector expert judgement are used to estimate the trend for hours worked, house prices, credit variables, the oil price and foreign output. For some series, a three-quarter central moving average procedure is utilized in order to remove noise.

Inflation is detrended with the inflation target of 2.5 percent.[38] The trend in imported inflation is assumed to be lower than that in overall inflation because of the continuous terms of trade gains from low import price inflation that Norway has enjoyed over the sample period. These gains have been slightly smaller in the latter years and are expected to be so going forward. An upward trend shift in imported inflation is therefore assumed after 2012.

Due to lower growth rates of trend productivity in recent years, downward shifts in the trend growth rate of real wages were added in 2012 and 2013.[39] The trend shifts in the money market rate are consistent with Norges Bank's published estimates of the neutral interest rate (see Norges Bank's *Monetary Policy Report* (MPR) 3/16, MPR 1/14, MPR 1/12 and MPR 1/10). Norges Bank's estimates are usually expressed as intervals, but NEMO requires point estimates in order to compute the interest rate gap. The point estimate in NEMO has been in the lower end of the estimated interval for the neutral interest rate in recent years.

The neutral foreign money market rate is assumed to be 0.5 percentage point lower than in Norway, reflecting the differences in the inflation target between Norway and our main trading partners in the sample period. The neutral level of market interest rates are calculated based on Norges Bank's internal estimates of various risk premiums.

Appendix A plots levels, trends and gaps for each observable variable.[40]

[37]DORY is developed by Ørjan Robstad and Kenneth S. Paulsen and will be documented in a forthcoming staff memo.

[38]The inflation target was reduced in March 2018 to 2 percent. However, as we calibrate and estimate the model using historical data from 2001 to 2017, the new target is not considered in the detrending exercise.

[39]See the Special Feature on low productivity growth in Norges Bank's *Monetary Policy Report* (MPR) 2/16. All Norges Bank's *Monetary Policy Reports* are available at http://www.norges-bank.no/en/Published/Publications/Monetary-Policy-Report-with-financial-stability-assessment/.

[40]In Appendix A, 27 variables are graphed. However, as the risk premium is equal to the money market interest rates minus the policy rate, only two of these are fed to the model, i.e. making it 26 observable variables.

3.2 Calibration of the steady state

The steady-state solution of the model is derived recursively and is publicly available in Kravik *et al.* (n.d.). We calibrate the steady state of the model by matching real and financial "great ratios". Specifically, we aim at matching 14 macroeconomic aggregates and 12 financial targets. As some of these ratios are trending over time, we aim to match data over the relatively recent time period 2010-2016 (see Appendix B for how a subsample of macroeconomic aggregates has evolved over time). Table 1 lists the empirical ratios and the model's steady-state counterparts.

Table 1: Data targets and steady-state calibration values

Target	Data	Steady state
Macroeconomic aggregates		
Consumption to mainland GDP (MGDP)	0.51	0.52
Corporate investment to MGDP	0.09	0.09
Housing investment to MGDP	0.06	0.07
Oil investment to MGDP	0.08	0.06
Government spending to MGDP	0.34	0.34
Traditional exports to MGDP	0.16	0.16
Oil supply exports to MGDP	0.07	0.07
Imports to MGDP	0.34	0.39
Physical capital to MGDP	1.66	1.66
Physical capital in oil supply sector to MGDP	0.04	0.04
Physical capital in oil extraction sector to MGDP	0.42	0.28
Housing capital to MGDP	1.24	1.25
Labor in oil sector to total labor	0.07	0.05
Oil production to MGDP	0.20	0.16
Financial sector		
Household lending to total assets	0.55	0.56
Corporate lending to total assets	0.45	0.44
Household deposits to total assets	0.51	0.49
Foreign funding to total assets	0.42	0.42
Bank capital to total assets	0.07	0.09
Total assets to MGDP	1.90	1.90
Bank capital to risk-weighted assets	0.16	0.16
Real return on bank equity	0.10	0.10
Average business credit spread (%)	2.37	2.37
Average mortgage credit spread (%)	2.12	2.12
Average money market-deposit rate spread (%)	0.5	0.5
Average money market premium (%)	0.5	0.5

Reflecting the assumption of a small open economy, the nominal interest rate in Norway in the steady state is determined by the foreign sector and the inflation target in Norway. The foreign inflation rate and the discount factor are set to 2 percent and 0.996, respectively, on an annual basis. The foreign sector and Norway are assumed to share a steady-state productivity growth rate of 1 percent on annual basis, which is in line with recent estimates for the Norwegian economy. Together with the foreign inflation rate and the discount factor, this pins down the nominal and real interest rates for the foreign sector in the model at 3.44 percent and 1.41 percent, respectively, on an annual basis. Accordingly, the real interest for Norway is also 1.41 percent on an annual basis. In the data, the real interest rate has been close to zero over the sample period.

Although the Norwegian inflation rate has been 1.92 percent on average for our sample period, we set the inflation rate in steady state to the (previous) inflation target for Norway of 2.5 percent, which yields a money market rate of 3.94 percent annually.[41] Parameters determining interest rate markups are set to match market spreads from the data, i.e. 2.37 percent, 2.12 percent, and 0.5 percent for the business credit spread, the mortgage credit spread and money market-deposit rate spread, respectively on an annual basis. The money market premium is set to 0.5 percent as found in the data, giving a steady-state policy rate of 3.44 percent on an annual basis.

We treat the final good as the model's numéraire good and accordingly set the price of this good to 1. The price of the intermediate good and the import good are also set to 1 in the steady state. Although markups internationally have shown an increasing trend (Diez *et al.*, 2018), we set markups for the domestic good, the imported good and the exported good to 1.2, following the standard calibration in the literature. In order to match the observed capital to mainland GDP ratio of 1.66, we set the capital share parameter, α, to 0.256 and the elasticity of substitution between capital and labor, ξ, to 0.929. This gives a wage income share of about 67 percent both for the intermediate goods sector and for the total mainland economy in the steady state. This is on the lower side of what is found in the data of around 70 to 75 percent for Norway.[42]

The elasticity of substitution for labor services, ψ, can be interpreted as the inverse of the degree of market power of the workers (or unions) in the wage setting process, and reflects the deviation from free competition in the labor market. A relatively high union coverage ratio in Norway implies a low number, whereas low structural unemployment suggest the opposite. We set $\psi = 2.5$, which is on the lower side of empirical estimates. We set ζ, the inverse of the Frisch elasticity of labor supply, to 3, which implies a Frisch elasticity of 0.33.

Because of its large petroleum revenues, Norway has since the mid-1990s accumulated a sovereign wealth fund of more than 2.5 times mainland GDP. However, combining net positive exports with a positive net foreign asset position in the steady state would violate the transversality condition. To circumvent this, we fix the net foreign asset position, and hence net exports, to zero in the steady state. We reach these targets partly by reducing the target for the oil exports to mainland GDP ratio from the empirical observation of around 20 percent to 16 percent and partly by increasing the corresponding import share from 34 to 39 percent.[43] To match export and import ratios, we set the domestic share parameter, ν_{ss}, and the export share parameter, ν^*_{ss}, to 0.65 and 0.21 respectively.[44]

[41] As the steady state of NEMO is calibrated to match the Norwegian economy in the period 2010-2016, we did not let the announcement of the new inflation target of 2 percent affect the parameterization of the model. However, when the model is used for forecasting in MPRs, different parameter values may be used.

[42] The wage share of 67 percent is calculated based on market values ("WL/GDP"). However, if one instead does the calculation based on the production functions – assuming competitive markets (i.e. the wage rate is equal to the marginal product of labor) – the wage income share comes out at around 83 percent in the steady state.

[43] The oil production share (import share) has shown a decreasing (increasing) trend over time.

[44] A zero net foreign asset position in the steady state also eliminates large wealth effects from interest rate shocks through the risk premium in the UIP condition.

Continuing with the oil sector, we set the factor share parameters in the oil supply production function to match this sector's labor share of total labor and its capital to mainland GDP ratio. We fix the labor share parameter, α_l, to 0.28 and the final goods share parameter, α_q, to 0.69, giving a labor share in the oil sector to total labor of 5.3 percent and a capital to mainland GDP ratio of 4 percent. These numbers are somewhat on the lower side of the empirical counterparts of 7 percent and 4.2 percent, respectively. This is partly due to the fact that the oil extraction sector is lower in our steady state than in the calibration target period, reflecting the need for a zero trade balance in steady state, as discussed above.

We have little empirical information on markups and elasticities in the oil supply sector. We fix the rig depreciation rate (δ_O), the rig share parameter in oil extraction (α_o), the substitution elasticities of supply goods (θ^R and θ^{R^*}) and the size of the oil reserves (O, which enters as a factor of production for the domestic oil extraction company) in order to match the size of the oil production industry, oil supply goods used for oil investments, oil supply exports and capital in the oil extraction sector to mainland GDP. Due to the lower oil extraction share in the steady state compared to data, the sub-targets also become a little lower than empirical counterparts.

Turning to the banking sector, we use the regulatory capital risk weights of 0.4 and 0.8 on household and corporate loans, respectively. In accordance with Norwegian financial regulations, we set capital requirements for banks to 15.6 percent, of which 2 percent is the countercyclical capital buffer.[45] The internal rates of the banking sector are determined by the linear cost parameter χ_o. We calibrate this and the dividend parameter δ^b to jointly achieve the empirical observation of a return on equity in the Norwegian banking sector at around 10 percent. Households' principal repayments are assumed to follow from an approximated annuity loan repayment formula (see equation (9)). The amortization rate dynamics parameters α^h and κ^h are set in order to capture the repayment schedule of a 30-year mortgage contract, in line with Norwegian household mortgage data. We set the collateral constraint parameter, ϕ_{ss}, to match a household debt to mainland GDP ratio of 105 percent. This gives an average loan-to-value (LTV) ratio for households of 84.5 percent in the model, which is broadly consistent with a 15 percent downpayment requirement in Norway. For corporate credit demand, we assume that loans are rolled over in every period ($\alpha_e = 0$).

To match the corporate credit-to-mainland GDP ratio at 85 percent, we set the entrepreneurial collateral constraint parameter, ϕ_{ss}^{ent}, to 0.9917 in steady state, giving a loan-to-value rate for the entrepreneurs at around 50 percent. We use the household deposit preference parameter, z^d, to match the deposit ratio.

House prices have over time grown more rapidly than other prices in Norway. We capture this by assuming a negative technology trend growth in housing production of 3.4 percent annually, matching the observed real house price growth rate of 1.046 annually.

The quarterly capital depreciation rate, δ, is set to 0.0108 in order to match the business investment to mainland GDP ratio of 9 percent. We set the housing depreciation rate, δ_H, to target the housing stock to mainland GDP ratio of about 124 percent. This gives a housing investment to mainland GDP ratio of 7 percent – the empirical target being 6.15 percent.

The current steady state uses a few restrictions to pin down some of the great ratios: The oil production share and the government expenditure share relative to final goods

[45]When the model is used for monetary policy analysis, the countercyclical capital buffer is set to its steady-state value of 2 percent.

are exogenously determined in steady state to match empirical data. For future work, we aim to solve the steady state of the model in a fully flexible way, i.e. solely determined by structural parameters of the model.

3.3 Monetary policy in the estimation

When we use NEMO for monetary policy analyses and forecasting in MPRs, the model is solved under optimal, discretionary, monetary policy. The weights in the operational loss function are model-dependent and calibrated to achieve reasonable responses and trade-offs between, e.g., output and inflation stabilization, when the economy is hit by different shocks.

Using optimal policy in the estimation process would be too time-consuming and computationally demanding. Instead, we estimate a "mimicking" policy rate rule based on some state variables to replicate optimal monetary policy. The simple rule is estimated to match impulse responses under optimal policy to a number of selected shocks on a number of selected variables for 10 periods. The procedure is iterative since an estimated policy rule changes the main estimation, which again calls for an updated mimicking rule and so forth. Note that the procedure implies that the policy rule parameters are not estimated simultaneously with the other model parameters (as this would not necessarily have generated a rule that would replicate optimal policy).

The simple rule together with the estimation results are displayed in equation (118) and Table 2. The variables in the mimicking rule include (in gap terms) annual inflation ($\widehat{\pi}_t$), expected annual inflation one quarter ahead ($\widehat{\pi}_{t+1}$), wage inflation ($\widehat{\pi}_t^W$), output ($\widehat{Y}_{NAT,t}$), the real exchange rate ($\widehat{S}_t$), the money market premium ($\widehat{Z}_{prem,t}$), the foreign monetary policy rate ($\widehat{R}_t^*$), a monetary policy shock ($Z_{RN3M,t}$) and a lagged term.

The matching shocks comprise the monetary policy shock, money market premium shock, oil price shock, price markup shock, trading partner demand shock, risk premium shock, wage markup shock, labor supply shock, foreign marginal cost shock and the foreign interest rate shock.

The evaluated variables are household credit, corporate credit, inflation, business investment, housing investment, oil investment, hours worked, imports, exports, output, house prices, exchange rate, real wage and the policy rate.

When estimating the mimicking rule, we put higher weights on responses on output, inflation and the policy rate to a monetary policy shock and an international oil price shock.

$$\begin{aligned}\widehat{R}_{P,t} = \omega_R \widehat{R}_{P,t-1} + (1-\omega_R)\big(&\omega_P \widehat{\pi}_t + \omega_{P1}\widehat{\pi}_{t+1} + \omega_W \widehat{\pi}_t^W + \omega_Y \widehat{Y}_{NAT,t} \\ &+\omega_S \widehat{S}_t + \omega_{PREM}\widehat{Z}_{prem,t} + \omega_{RF}\widehat{R}_t^*\big) + Z_{RN3M,t}.\end{aligned} \tag{118}$$

Table 2: Estimated mimicking rule

ω_R	ω_P	ω_{P1}	ω_W	ω_Y	ω_S	ω_{PREM}	ω_{RF}
0.67	0	0.29	0.87	0.24	0.02	0	0

Note: Estimation results from an estimated policy rule that mimics optimal policy. The estimation hits the boundaries for ω_P, ω_{PREM} and ω_{RF}.

The estimated mimicking rule puts a relatively high weight on wage inflation. This finding is consistent with Levin *et al.* (2006) who find that an interest rule responding to wage inflation yields a welfare outcome that nearly matches that under optimal policy, as well as Justiniano *et al.* (2011) who show that the stability of the output gap is consistent with a significant reduction in the volatility of price and, especially, wage inflation.

Appendix E shows impulse responses to a monetary policy shock under optimal policy and the mimicking rule. Judging from the impulse response functions, the estimated rule does a nice job in replicating optimal monetary policy.

3.4 Identification of dynamic parameters

Estimating large simultaneous systems often involves identification problems. For parameters of a model to be identified, "the objective function must have a unique extremum at the true parameter vector and display 'enough' curvature in all relevant dimensions" (Canova and Sala, 2009).

Detecting identification problems is difficult since the mapping between the parameters of the model and the objective function is highly nonlinear. To check for identification issues we utilize the identification package developed at the Joint Research Centre, European Commission, for the Dynare environment (see Ratto and Iskrev (2011) for a description). Figure 3 shows the identification-strength plot of all the dynamic parameters in NEMO. The bar charts depict the identification strength of the parameters based on the Fischer information matrix normalized by the parameter values at their prior mean (blue bars) and by their standard deviation at the prior mean (yellow bars). Intuitively, the bars represent the normalized curvature of the log-likelihood function at the prior mean in the direction of the parameter.[46] The larger the value, the stronger is the identification.[47]

Looking at the graph, all parameters are identified as none of them exhibit a zero identification strength. Theoretically, all parameters could therefore be identified. Many of the parameters related to the foreign sector (ending in "TP" or "OIL" in Figure 3) are however only weakly identified. Nonetheless, we include them in the estimation, but with particularly tight priors. We exclude the risk premium parameter ϕ^S ("PHI_S_NW") in the estimation due to the low identification strength.

Appendix F shows collinearity plots between parameters. These graphs show "which linear combination of parameters shown in the columns best replicates/replaces the effect of the parameter depicted in the row on the moments of the observables" (Pfeifer, 2017). The darker red the squares are, the more critical the collinearity is between parameters. In addition to shocks displaying collinearity with their own persistence parameters, a few other parameter combinations also showed sign of being weakly identifiable. This includes adjustment costs to business investments (ϕ_{I1} with ϕ_{I2}) and housing investments (ϕ_{H1} with ϕ_{H2})[48]. We experimented with excluding two of these from the estimation, but this did not have a substantial impact on the estimation results and behaviour of the model.

[46] This description is taken directly from Pfeifer (2017).

[47] See Appendix Q for a translation of the parameter text names in Figure 3 and their model names in Section 2.

[48] There are two parameters that govern these adjustment costs (see equations (45) and (48)).

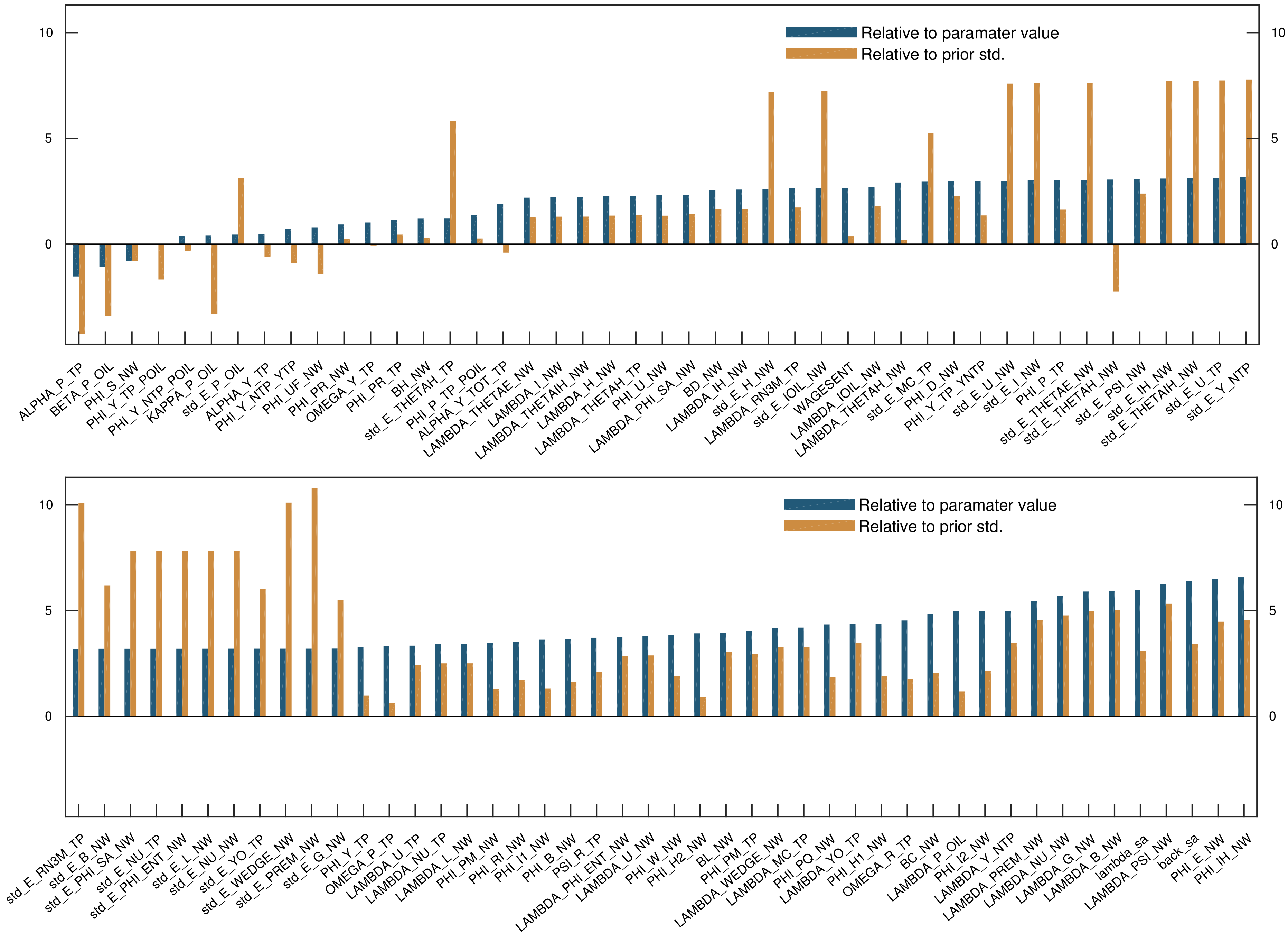

Figure 3: Identification strength-plot (log-scale)

3.5 Choice of priors

In total, we estimate 89 parameters, of which 24 are domestic dynamic non-shock-related parameters, 16 are non-shock-related parameters in the foreign block sector, 25 are shock standard errors (of which 5 are in the foreign block), and finally there are 24 shock-persistence parameters. Computations are done using the *RISE* toolbox (see footnote 34). We use two types of priors in estimating the model: system priors and marginal priors.

3.5.1 System priors

The *RISE* toolbox allows for augmenting marginal priors (below) with *system priors*.[49] In contrast to marginal priors that deal with parameters independently, system priors are priors about the model's features and behavior as a system and are modelled with a density function conditional on the model parameters. In theory, the system priors can either substitute or be combined with marginal priors. In our estimation setup, we choose to augment our marginal priors with specific beliefs about the variances of the observed variables. Specifically, we specify our system priors as normal distributions over the variances of the observed variables, $N(\mu, \sigma)$, where we set μ equal to the second-order moment from the data set that is used in the estimation, and a not too restrictive standard deviation (given the magnitude of the variances of the observed variables), σ, equal to 0.01. We did not set prior beliefs about co-variances. The standard deviations of the observables are listed in Table 5 in Section 4.

3.5.2 Marginal priors

We use a mixed approach in setting the marginal priors. For some parameters, we use the existing literature, empirical analysis and comparable models to find suitable prior values. Additionally, for some parameters, we calibrate the model to match the targeted model moments referred to in the previous section on system priors, and set these values as the prior means. Finally, as NEMO primarily is a tool for conducting monetary policy and forecasting, some priors are set based on model users' and sector experts' assessments and judgements of the model's properties, including impulse responses to specific shocks, correlation patterns, and the overall forecasting abilities of the model. This is especially true for the foreign block of the model, where several of the parameters were only weakly identifiable. Table 3 and 4 display the marginal priors.

We choose a beta distribution for the habit persistence parameters with a prior mean of 0.5 and a standard deviation of 0.2. For the habit formation parameter in consumption we set a tighter prior around 0.8 due to the low consumption volatility observed in the data.

We calibrate the parameters regarding house price expectations and housing investment adjustment costs in order to match the volatilities of housing investment and household credit and to get empirically relevant effects of a monetary policy shock on house prices and housing investment. Similarly, we calibrate the prior mean on investment adjustment costs parameters to match investment volatility. As in Adolfson *et al.* (2013), we set the prior mean of the curvature parameter in the capital utilization cost, ϕ_u, to

[49] This is somewhat similar to the framework laid out in Andrle and Benes (2013) and Del Negro and Schorfheide (2008). See the *RISE* website (`https://github.com/jmaih/RISE_toolbox`) for the particular codes.

0.2 to allow for a varying degree of utilization of the capital stock. Prior means for price and wage adjustment costs are calibrated to be broadly in line with the moments on price and wage inflation rates, but prior standard deviations are set to give room for flexibility in the estimation.

In the banking sector, we estimate the adjustment costs related to changing the deposit, mortgage and corporate lending rates. We calibrate the prior means to match observed interest pass-through observed in Norwegian data, i.e. close to 1-to-1 for deposit rates and 1-to-0.8 for corporate and household lending rates.

The oil sector in NEMO builds on Bergholt *et al.* (2017) which forms the basis for our oil related parameter priors. In particular, we set the prior mean of the rig investment adjustment cost parameter to 6 and the curvature parameter in the rig utilization cost to 18, both being close to posterior modes in Bergholt *et al.* (2017). To create sluggishness in the price setting of oil supply goods, we augment the model with adjustment costs. We set high prior means and large standard deviations.

As evident from Figure 3 regarding the identification strength, most of the foreign sector parameters are weakly identified. This might be due to two reasons: (i) The foreign sector is currently modelled as reduced-form (semi-structural) and may not be a good description of the data and (ii) having a considerable number of parameters (25) given only 5 observable variables related to the foreign sector. We therefore estimated this part of the model based on relatively tight priors. In doing so, we rely on sector experts' judgement and in particular we aim to match key relationships from shocks to the international oil price and global activity found in Bergholt *et al.* (2017) and Bjørnland and Thorsrud (2016). We also use system priors on the volatilities of foreign sector variables.

DSGE models tend to be sensitive to the external debt-elastic risk premium parameters in the sense that small changes in these parameters can have large effects on the model's behaviour. We estimate ϕ^B based on a tight prior that was set to obtain empirically relevant effects of a shock to real oil prices on the dynamics of the real exchange rate and the Norwegian economy in general (see Section 4.2). The second risk premium parameter, ϕ^S, was excluded from our estimation due to the low identification strength. We set ϕ^S to 0 to be consistent with the empirically observed response of the real exchange rate to a monetary policy shock.

Shocks There are 26 shocks in NEMO, equal to the number of observable variables. All shocks are assumed to follow first-order autoregressive processes, except for the non-trading-partner output shock which is a pure innovation. Hence, there are 25 persistence parameters. The shock equations are listed in Appendix D.

All shocks are assumed to have an inverse gamma distribution with a standard deviation of 2. Most shocks have a prior mean of 0.01, but some prior means have been somewhat calibrated to better fit some moments. Due to the wide priors on the standard deviations, the shock calibration is expected to have limited impact on the estimation result. The persistence parameters are given a beta distribution with a prior mean of 0.5 and a standard deviation of 0.2.

There is one exception to the above paragraph. The model showed some tendencies in giving the price markup shock a "too high" explanatory power in explaining inflation in the historical shock decomposition. To push the model to use other shocks, we tighten the prior standard deviations of this particular shock and its persistence parameter.

3.6 Posterior results

Table 3 and 4 summarise the estimation results. While we here briefly comment on a few parameter values, Section 4 will assess the model's empirical properties and forecasting abilities at the posterior mode.

The posterior modes show strong habit persistence in consumption (0.94) and housing (0.99), reflecting a large degree of inertia in these variables (although the housing habit parameter is only weakly identifiable). The parameters regarding Rotemberg price adjustment costs have increased compared to the earlier versions of NEMO, indicating a flatter Phillips curve. A relatively flat Phillips curve is also found in the estimation of other DSGE models (see e.g. Adolfson *et al.* (2013), Dorich *et al.* (2013) and Rees *et al.* (2016)).

The posterior modes on the parameters regarding corporate and housing investment adjustment costs move relatively little compared to their prior means in spite of relatively loose prior distributions. This is likely to be a sign of some identification issues (but it may also be due to prior means that correspond well with data and the system priors). In the banking sector, the posterior modes of the interest rate adjustment costs indicate a somewhat lower pass-through of corporate and household interest rates and a higher pass-through for deposit rates, compared to prior means.

Foreign sector parameters move relatively little compared to their prior means. As mentioned above, this is expected as most of these parameters were only weakly identified in the identification analysis and we set quite tight priors.

Most shock persistence parameters came out on the high side. Important exceptions include the price markup shock (for which we set a tight prior) and the wage markup shock, the latter being a sign of wage fluctuations being more transitory than other shocks. Interestingly, similar to the finding in Rees *et al.* (2016), the foreign inflation shock is much more transitory (0.05) than shocks to foreign output (0.78) and foreign monetary policy (0.32).

The posterior distributions are shown in Appendix H. We use 30 Markov chains, each of which contains 2,400,000 draws generated by the Random Walk Metropolis-Hastings algorithm with an acceptance rate tuned to 0.25. After thinning by a factor of 10 (i.e. keeping every 10th draw), posterior moments were computed from 7,200,000 draws, where the first 1,200,000 were used as burn-in.[50]

We thin again to keep every remaining 100th draw before calculating the potential scale reduction factor (PSRF) for each parameter as well as the so-called multivariate potential scale reduction factor (MPSRF), which are displayed in Appendix G. The PSRFs for almost all estimated parameters get close to 1, implying that convergence is achieved. The MPSRF is close to 1.4.

[50]To cover a large part of the surface of the log-likelihood function and to obtain the needed variation in the posterior draws, we used 900 Markov chains. Each of the 900 chains included 80000 draws. We then concatenated these different chains to obtain 30 chains with 2.4 million draws each. The resulting posterior densities looked well-behaved.

Table 3: Marginal prior and posterior distributions, dynamic parameters

			Prior		Posterior			
		Distr.	Mean	S.d.	Mode	Mean	5%	95%
Habit formations								
b^c	Consumption	β	0.8	0.05	0.938	0.945	0.93	0.957
b^h	Housing	β	0.5	0.2	0.987	0.989	0.987	0.99
b^l	Labor	β	0.5	0.2	0.586	0.57	0.535	0.605
b^d	Deposits	β	0.5	0.2	0.481	0.389	0.278	0.49
Adjustment costs etc.								
b^{sa}	House price expect.	β	0.65	0.025	0.639	0.621	0.606	0.635
λ^{sa}	House price expect.	β	0.9	0.05	0.949	0.964	0.95	0.98
ϕ^{PM}	Imports[a]	Γ	9	1	8.301	7.966	7.585	8.334
ϕ^{PM^*}	Exports[a]	Γ	3	1	2.856	2.883	2.693	3.054
ϕ^{PQ}	Domestic goods[a]	Γ	12	1	6.69	6.767	6.7	6.863
ϕ^W	Wage inflation[b]	Γ	0.7	0.1	0.667	0.68	0.646	0.713
ϕ_u	Capital util., entrep.	Γ	0.2	0.075	0.219	0.22	0.201	0.24
ϕ_{I1}	Business investment	Γ	10	2	12.543	12.714	11.838	13.57
ϕ_{I2}	Business investment	Γ	170	10	165.662	163.034	158.858	166.972
ϕ_{H1}	Housing investment	Γ	60	5	60.728	61.748	59.614	63.98
ϕ_{H2}	Housing investment	Γ	200	10	199.655	196.241	187.099	205.43
ϕ^D	Deposit rate	Γ	0.1	0.05	0.073	0.087	0.076	0.099
ϕ^e	Loan rate, entrep.	Γ	15	2	18.501	19.581	18.149	21.096
ϕ^F	Loan rate, househ.	Γ	15	2	18.36	18.661	17.828	19.525
ϕ^{RI}	Oil investment	Γ	6	1	8.215	8.149	7.639	8.624
ϕ^{uf}	Oil rigs util.	Γ	18	2	17.795	17.27	16.752	17.71
ϕ^{PR}	Oil supply, dom.[b]	Γ	2	1	1.246	1.182	1.061	1.292
ϕ^{PR^*}	Oil supply, abr.[b]	Γ	2	1	1.723	1.468	0.827	2.167
ϕ^B	Risk Prem.	N	0.0015	0.0002	0.00156	0.00159	0.00153	0.00166
Foreign block								
ϕ^{Y*}	Lag, output	N	0.5	0.05	0.615	0.619	0.596	0.643
ψ^{R*}	IS curve	N	1	0.2	0.757	0.724	0.615	0.832
ω^{R*}	Lag, Taylor	β	0.8	0.05	0.841	0.812	0.787	0.835
ω^{P*}	Infl. weight, Taylor	N	1.5	0.1	1.461	1.408	1.366	1.444
ω^{Y*}	Outp. weight, Taylor	N	0.03	0.01	0.04	0.046	0.039	0.054
α^{P*}	Infl. Expectations	N	0.15	0.01	0.15	0.15	0.149	0.15
α^{Y*}	Infl. $\leftarrow$ output	N	0.15	0.05	0.046	0.046	0.039	0.053
ϕ^{P*}	Lag, inflation	N	0.8	0.2	0.886	0.884	0.873	0.894
ϕ^{OP*}	Infl. $\leftarrow$ oil price	N	0.003	0.001	0.001	0	0	0.001
ϕ^{O*}	Output $\leftarrow$ oil price	N	0.005	0.001	0.005	0.005	0.004	0.005
ϕ^{YNTP*}	Output $\leftarrow$ NTP output	N	1	0.2	1.099	1.137	1.04	1.244
λ^{YNTP}	Lag, NTP output	N	0.9	0.2	0.926	0.947	0.914	0.971
ϕ^{ONTP}	NTP output $\leftarrow$ oil price	N	0.002	0.001	0.001	0.002	0.001	0.003
ϕ^{YNTP}	NTP output $\leftarrow$ output	N	0.01	0.002	0.011	0.011	0.011	0.012
β^O	Oil price expectations	N	0.2	0.02	0.203	0.202	0.197	0.206
κ^O	Oil price demand	N	4	0.1	4.003	3.998	3.983	4.015

Note: After thinning by a factor of 10, posterior moments are computed from 7,200,000 draws generated by the Random Walk Metropolis-Hastings algorithm using 30 chains with an acceptance rate tuned to 0.25, where the first 1,200,000 are used as burn-in.

[a] Parameter is multiplied by 100 in the model.

[b] Parameter is multiplied by 1000 in the model.

Table 4: Marginal prior and posterior distributions, shock parameters

			Prior		Posterior			
		Distr.	Mean	S.d.	Mode	Mean	5%	95%
Shock persistence								
λ_B	Risk prem.	β	0.5	0.2	0.737	0.732	0.686	0.774
λ_G	Gov. exp.	β	0.5	0.2	0.914	0.948	0.933	0.964
λ_h	Househ. pref.	β	0.5	0.2	0.694	0.658	0.599	0.711
λ_{IH}	Housing investment	β	0.5	0.2	0.861	0.869	0.849	0.888
λ_{IOIL}	Oil investment	β	0.5	0.2	0.834	0.853	0.806	0.894
λ_I	Business investment	β	0.5	0.2	0.646	0.661	0.618	0.703
λ_{z^L}	Productivity (temp.)	β	0.5	0.2	0.804	0.815	0.794	0.835
λ_{MC*}	Marginal costs, abr.	β	0.5	0.2	0.097	0.065	0.034	0.094
λ_ν	Import share	β	0.5	0.2	0.934	0.964	0.949	0.976
λ_{ν_*}	Export share	β	0.5	0.2	0.924	0.927	0.9	0.953
λ_ϕ	LTV, househ.	β	0.5	0.2	0.783	0.716	0.646	0.776
$\lambda_{\phi^{ent}}$	LTV, entrep.	β	0.5	0.2	0.91	0.884	0.836	0.927
λ_{prem}	Money market risk prem.	β	0.5	0.2	0.817	0.837	0.806	0.868
λ_ψ	Wage markup	β	0.5	0.2	0.28	0.241	0.2	0.279
λ_{θ^e}	Lending rate, entrep.	β	0.5	0.2	0.964	0.966	0.957	0.974
λ_{θ^H}	Price markup	β	0.3	0.02	0.435	0.432	0.428	0.434
$\lambda_{\theta^{IH}}$	Lending rate, househ.	β	0.5	0.2	0.89	0.874	0.848	0.898
λ_u	Consump. pref.	β	0.5	0.2	0.725	0.691	0.641	0.739
λ_{wedge}	Inventories	β	0.5	0.2	0.838	0.868	0.824	0.912
λ_{YO*}	Oil prod., abroad	β	0.5	0.2	0.746	0.741	0.716	0.767
λ_{PO*}	Oil price	β	0.9	0.02	0.874	0.872	0.865	0.879
λ_{R*}	Mon. pol., TP	β	0.5	0.2	0.322	0.342	0.283	0.408
$\lambda_{\theta^{H*}}$	Price markup, TP	β	0.5	0.2	0.052	0.066	0.033	0.104
λ_{U*}	Demand, TP	β	0.5	0.2	0.782	0.816	0.782	0.85
Shock st.dev. (multiplied by 100)								
σ_B	Risk prem.	Γ^{-1}	5	200	0.618	0.633	0.519	0.767
σ_G	Gov. exp.	Γ^{-1}	10	200	0.381	0.401	0.381	0.44
σ_h	Household pref.	Γ^{-1}	1	200	28.677	47.065	36.776	57.85
σ_{IH}	Housing investment	Γ^{-1}	1	200	2.575	2.522	2.356	2.688
σ_{IOIL}	Oil investment	Γ^{-1}	1	200	2.612	2.507	2.021	3.08
σ_I	Business investment	Γ^{-1}	1	200	23.018	24.665	22.951	26.403
σ_{z^L}	Productivity (temp.)	Γ^{-1}	1	200	0.598	0.587	0.545	0.631
σ_{MC*}	Marg. costs, abr.	Γ^{-1}	10	200	34.629	37.145	34.876	39.747
σ_ν	Import share	Γ^{-1}	1	200	0.428	0.485	0.417	0.565
σ_{ν_*}	Export share	Γ^{-1}	1	200	4.238	4.419	3.825	5.101
$\sigma_{\phi^{ent}}$	LTV, entrep.	Γ^{-1}	1	200	2.59	2.757	2.377	3.203
σ_ϕ	LTV, househ.	Γ^{-1}	1	200	25.423	26.756	23.2	30.894
σ_{prem}	Money market risk prem.	Γ^{-1}	0.05	200	0.037	0.037	0.035	0.038
σ_ψ	Wage markup	Γ^{-1}	200	200	63.31	52.133	46.675	57.846
σ_{θ^e}	Lending rate, entrep.	Γ^{-1}	1	200	84.858	97.346	84.03	112.26
σ_{θ^H}	Price markup	Γ^{-1}	20	0.1	20.145	20.155	20.13	20.183
$\sigma_{\theta^{IH}}$	Lending rate, househ.	Γ^{-1}	1	200	167.942	185.12	174.699	196.939
σ_u	Consump. pref.	Γ^{-1}	1	200	3.021	3.356	2.847	3.91
σ_{wedge}	Inventories	Γ^{-1}	0.1	200	0.184	0.19	0.18	0.201
σ_{YO*}	Oil prod., abroad	Γ^{-1}	6	200	3.409	3.31	3.052	3.546
σ_{PO*}	Oil price	Γ^{-1}	7	200	7.918	8.055	7.864	8.253
σ_{R*}	Mon. pol., TP	Γ^{-1}	0.1	200	0.084	0.086	0.08	0.093
$\sigma_{\theta^{H*}}$	Price markup, TP	Γ^{-1}	1	200	0.833	0.822	0.797	0.844
σ_{U*}	Demand, TP	Γ^{-1}	1	200	1.115	1.104	0.991	1.229
σ_{YNTP}	Global demand	Γ^{-1}	1	200	0.183	0.198	0.17	0.231
Other								
ρ_{ffm}	Oil price $\leftarrow$ wage bargaining	N	0.5	0.05	0.527	0.532	0.516	0.55

Note: See notes to Table 3.

4 Model properties

This section assesses the empirical properties of NEMO computed at the posterior mode. We first study the model-implied business cycle moments of the observed variables used in the estimation. Second, we examine the impulse responses of main macroeconomic variables to selected structural shocks to understand the transmission mechanisms in the model. We then interpret the historical and forecast-error-variance decompositions of inflation, mainland output and policy rate gaps to evaluate the contributions of estimated structural shocks to each variable. Finally, we investigate the forecasting performance of the model for inflation rate, per-capita real mainland output growth and the policy rate.

4.1 Business cycle moments

In this section, we present the model-implied theoretical standard deviations of the observable variables used in the estimation of NEMO together with their empirical counterparts for the estimation period from 2001Q1 to 2017Q4, which are displayed in Table 5. The model-implied theoretical standard deviations are computed at the posterior mode.

Table 5 shows that the variations of model-implied observable gap variables are broadly in line with the data, which is partly due to using system priors on the standard deviations of observable gaps. Regarding the real variables, we see that mainland output is a bit less volatile than the data while consumption is more volatile. Business and housing investment expenditures are a little more volatile than the data while the volatility of oil investment is a bit lower. Concerning housing investment, we intentionally allow the model to have a higher volatility in this series in order to match a change of nearly similar magnitude in real house prices and housing investment in response to macro shocks. Finally, the standard deviation of hours worked is broadly consistent with the data.

When we inspect the financial variables, we see that the household credit gap is less volatile than the data while the business credit gap is more volatile.[51] The standard deviation of real house prices is higher than its empirical counterpart, as it proves to be challenging for the model to jointly replicate the volatilities of household credit and real house prices. Regarding household and corporate lending rates, the variations in these two variables are also in line with the data.[52]

Concerning the external variables, the fluctuations in the real exchange rate in the data are higher than those in the model. Instead of specifically focusing on this moment, we aim to match the magnitude of the change in the real exchange rate in response to a monetary policy shock. Exports and oil supply goods exports are more volatile in the data while imports, and trading partners' and global output gaps are less volatile. Since the real oil price in the model is mostly driven by an exogenous shock process, its volatility is in line with the data.

[51]This result might partly be due to the fact that household loans in the model are long-term while business loans are one-period loans.

[52]The degree of interest rate pass-through from the policy rate to household and corporate lending rates are also targeted to be consistent with the data.

Table 5: Standard deviations of data vs. model variables (%)

Variable	Data	NEMO
Real variables		
Mainland output	1.33	1.24
Consumption	1.23	1.82
Business investment	10.17	11.62
Housing investment	5.70	6.56
Oil investment	11.29	10.91
Government spending	0.77	0.94
Hours worked	1.51	1.45
Financial variables		
Household credit	7.50	7.18
Business credit	4.95	5.72
Real house prices	4.28	6.06
Household lending rate	0.39	0.38
Corporate lending rate	0.37	0.39
External variables		
Real exchange rate	5.40	4.65
Exports	2.81	3.43
Oil supply goods exports	5.16	5.74
Imports	3.36	2.72
Real oil prices	19.68	19.25
Trading partners' output	3.91	3.33
Global output	1.04	0.77
Nominal variables		
Aggregate inflation	0.29	0.24
Imported price inflation	0.45	0.48
Inflation abroad	0.16	0.23
Wage inflation	0.35	0.30
Policy rate	0.46	0.36
Money market rate abroad	0.48	0.35

The standard deviations of model-implied gaps of the observable variables are computed at the posterior mode.

Finally, the volatilities of nominal variables are broadly consistent with the data. The standard deviations of aggregate inflation and wage inflation are a bit lower than the data while import price inflation and foreign inflation are more volatile. Concerning the policy rate and money market rate abroad, they seem to be less volatile than the data. Since we use a Taylor-type interest rate rule that mimics the optimal policy in terms of matching the impulse responses of some key macro shocks, we do not estimate the coefficients in this interest rate rule. That might lead to the discrepancy between the data and the model moment in the policy rate.

4.2 Impulse responses of selected structural shocks

This section demonstrates the impulse responses of main macroeconomic variables to a number of selected structural shocks in order to understand the key propagation mechanisms of NEMO. The selected structural shocks are a shock to the inflation target (i.e., a shock to monetary policy preferences in an optimal policy setting), which equivalently represents a standard shock to the short-term nominal interest rate, a shock to the external risk premium (i.e. a shock to the exchange rate), a shock to households' preferences for consumption, a shock to the degree of competition in the labor market (i.e. a wage markup shock), a shock to global demand and finally a shock to the oil supply, of which the two latter increase real oil prices. Figures 4 to 9 show these impulse responses computed at the posterior mode, respectively. All impulse responses are displayed as percentage deviations from the model's non-stochastic steady state, except for those of inflation and interest rates which are displayed as annualized percentage point deviations. We also include the 70 percent and 90 percent confidence intervals that are calculated using 3000 posterior draws in Appendix I. Finally, a comparison of the impulse responses to the same set of shocks between the old and the new version of the model is provided in Appendix P.

4.2.1 Shock to the inflation target (monetary policy shock)

Figure 4 depicts impulse responses to a shock to the inflation target. In order to obtain an increase in the policy rate in response to the shock, the economy is hit by a negative shock to the inflation target leading to a positive inflation gap which the central bank aims to stabilize by raising the short-term interest rate. The shock is normalized so that the policy rate increases by 1 percentage point on an annualized basis at its peak.

A change in the policy rate affects the macroeconomy through two main channels: aggregate demand and real exchange rate. A rise in the policy rate leads to a reduction in the domestic aggregate demand and a stronger real exchange rate. The increase in the short-term interest rate is transmitted to the real economy through the banking sector via a gradual pass-through from the policy rate to the household and corporate lending rates. As household and corporate lending rates elevate, households' consumption and firms' investment expenditures decline, leading a fall in the aggregate demand and thus in the mainland output. The reductions in housing investment and households' consumption are reinforced by the fall in house prices, which tightens households' borrowing constraint for new mortgage loans more (since it depends on the value of the housing stock). Since house prices are partly determined by backward-looking expectations, it takes some time for them to return back to their steady-state levels, which results in a quite persistent decline in private consumption and housing investment. Non-financial firms reduce their demand for labor due to the fall in the aggregate demand and this generates a reduction in both wages and hours worked. Since wages are one of the main components of the intermediate firms' marginal costs, a fall in wages reduces their marginal costs, resulting in lower domestic prices. Moreover, the stronger exchange rate generates a reduction in exports and a fall in imported prices. It takes 5 quarters for mainland output to reach its trough while it takes a bit longer time for inflation. Overall, an increase in the policy rate generates a decline in inflation mainly caused by a lower aggregate demand and a stronger exchange rate.

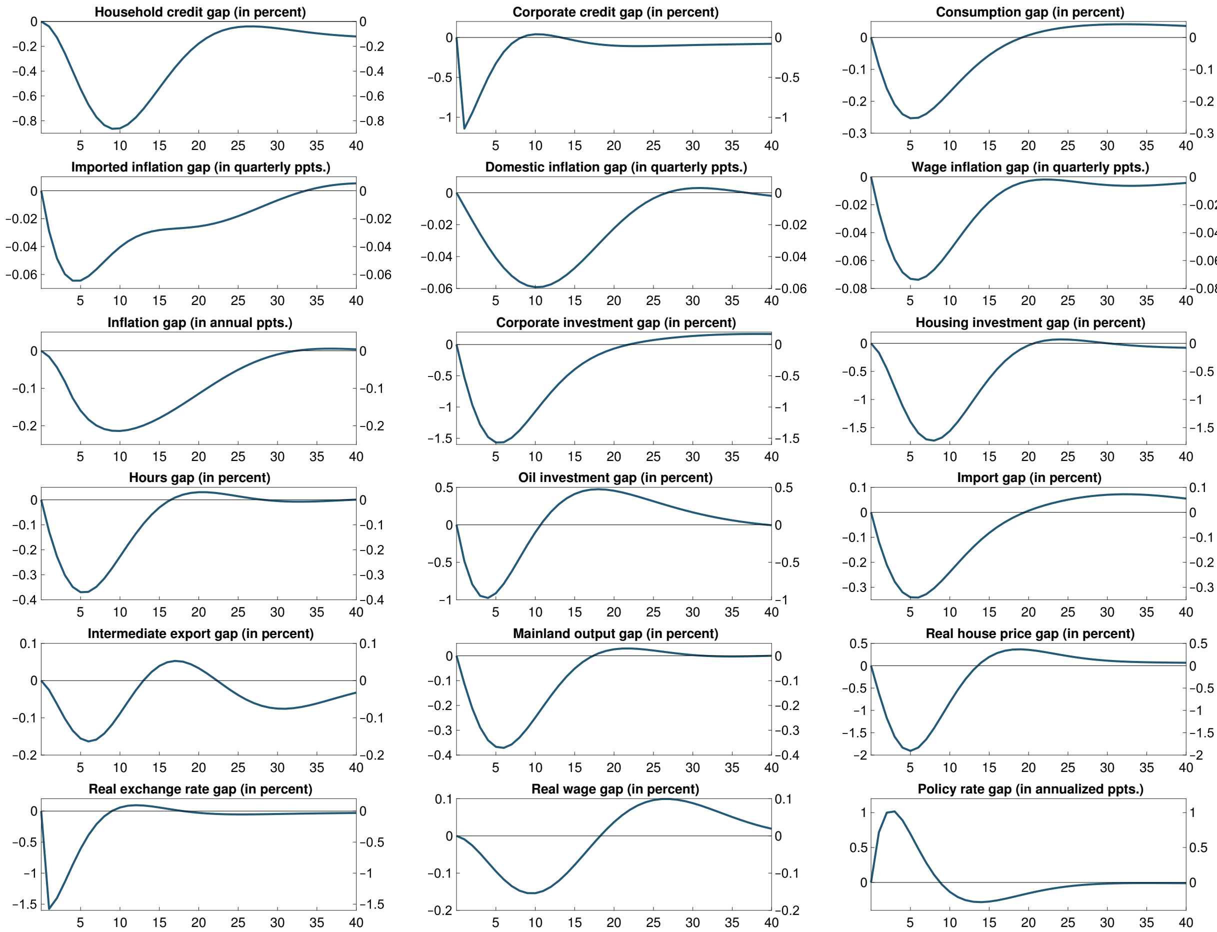

Figure 4: Impulse responses to a monetary policy shock

4.2.2 Shock to the external risk premium

Figure 5 shows impulse responses to a shock to the external risk premium (i.e. a shock to the exchange rate). The shock is normalized to obtain a real exchange rate depreciation of 1 percent on impact. A positive shock to the external risk premium induces private agents to hold fewer Norwegian kroner than before. The depreciation in the krone generates higher imported inflation. Since higher imported inflation increases aggregate inflation, the central bank raises its policy rate. The rise in the short-term interest rate reduces the aggregate demand through the same channels mentioned in the previous section. Household consumption, business and housing investment expenditures as well as real house prices all decrease. In addition, we observe that a depreciation in the exchange rate also leads to higher exports, which results in a rise in mainland output in initial periods followed by a fall. To sum up, the inflation rate is higher in response to the exchange rate risk premium shock mainly due to the depreciation it generates.

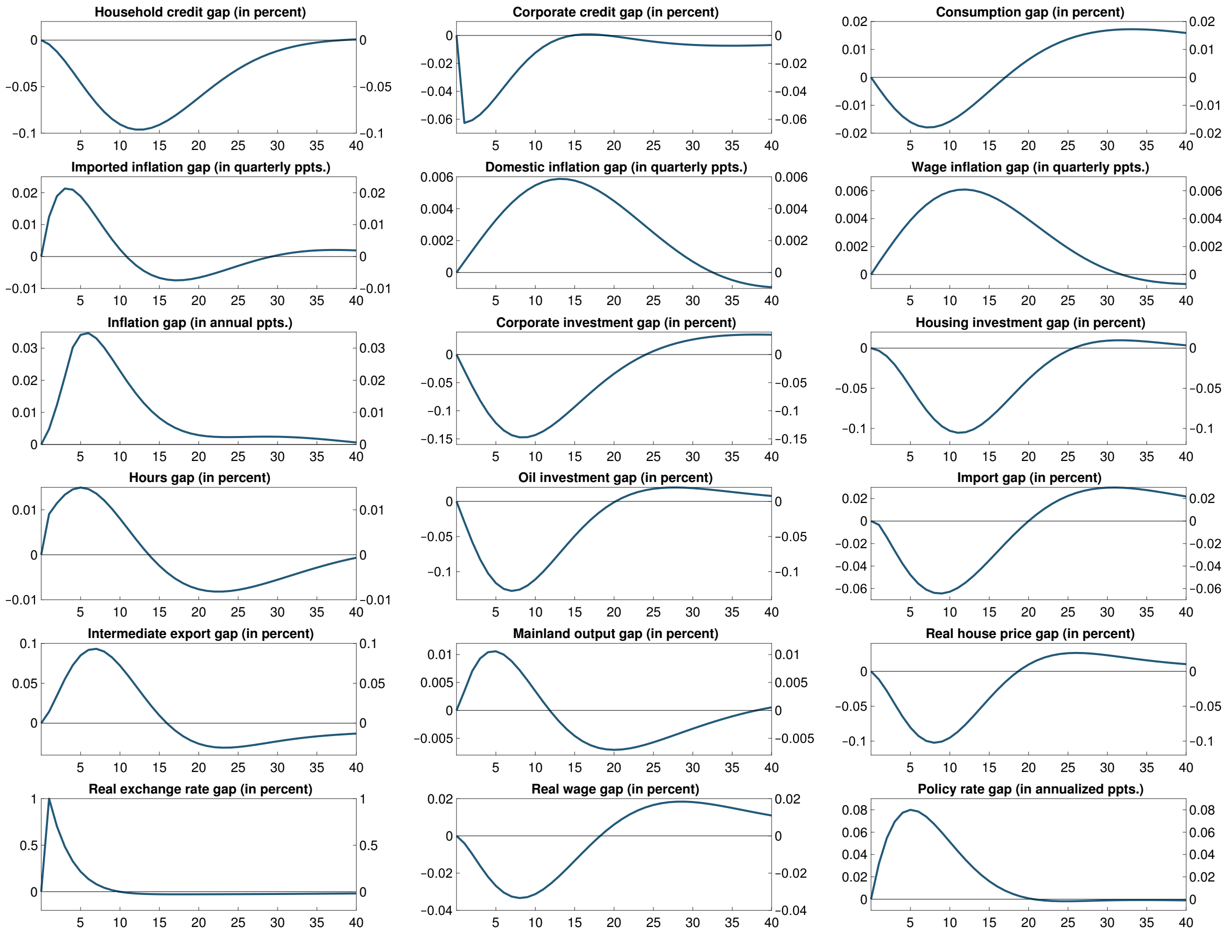

Figure 5: Impulse responses to an external risk premium shock

4.2.3 Shock to households' preferences for consumption

Figure 6 displays impulse responses to a shock to households' consumption preferences. The shock is normalized so that private consumption increases by 1 percent at its peak. Owing to a positive shock to consumption preferences, households value today's consumption more compared to tomorrow's, resulting in higher consumption expenditures today. The latter raises domestic demand although corporate and housing investments as well as house prices fall altogether due to the crowding-out effect of higher consumption. In order to finance this higher consumption, households work more, and hence supply more labor. This is also caused by the relative shift in household preferences towards more consumption away from leisure. Although demand for labor increases due to higher domestic demand, households seem to require smaller compensation to supply more labor. Overall, the latter effect dominates, leading to lower real wages and falling wage inflation. Lower wage inflation causes domestic inflation to fall. As the real exchange rate appreciates due to the hike in the policy rate, imported inflation declines. Overall, the joint impact of lower domestic and imported prices on aggregate inflation is negative by a small margin. The appreciated real exchange rate triggers an increase in imports and a fall in exports initially. As wage inflation falls and the exchange rate reverses after a few periods, exports pick up.

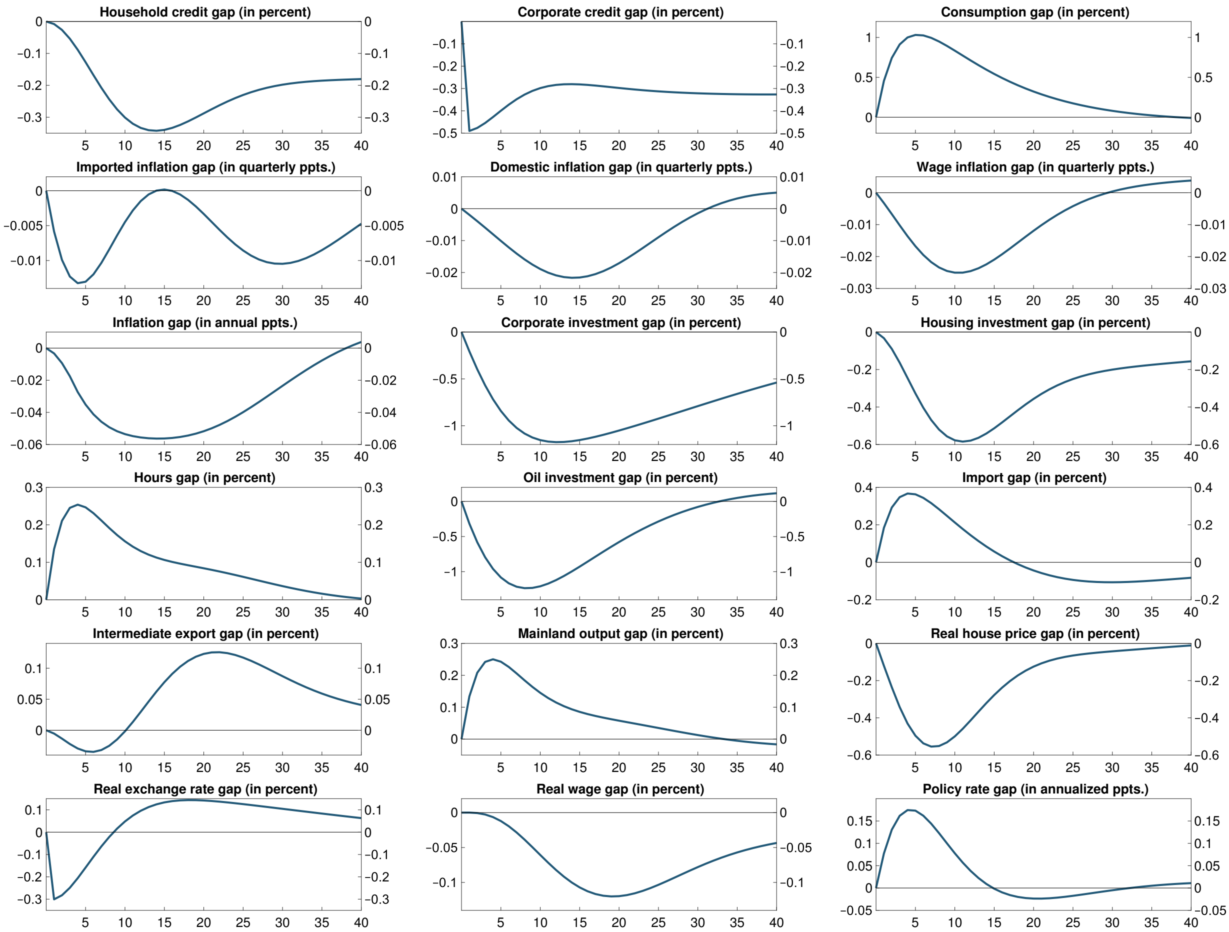

Figure 6: Impulse responses to a consumption preference shock

4.2.4 Shock to the wage markup

Figure 7 shows impulse responses to a shock to the degree of competition in the labor market (i.e. a shock to the wage markup). The shock is normalized to obtain an annualized wage inflation of 1 percentage point. A negative shock to the degree of competition in the labor market raises the market power of employees and leads to an increase in workers' ability to exercise more market power generating upward pressure on wages. The rise in wages causes firms' marginal costs and prices to increase. In response to the hike in the inflation rate, the central bank raises the short-term policy rate. Despite a temporary increase in real wages, consumption declines due to higher interest rates. The latter also causes investment expenditures to go down, lowering aggregate demand. The hike in the policy rate also generates a real exchange rate appreciation. This results in a lower volume of exports. Although the real exchange rate appreciation is expected to increase imports, lower consumption demand dominates this effect and leads to lower imports.

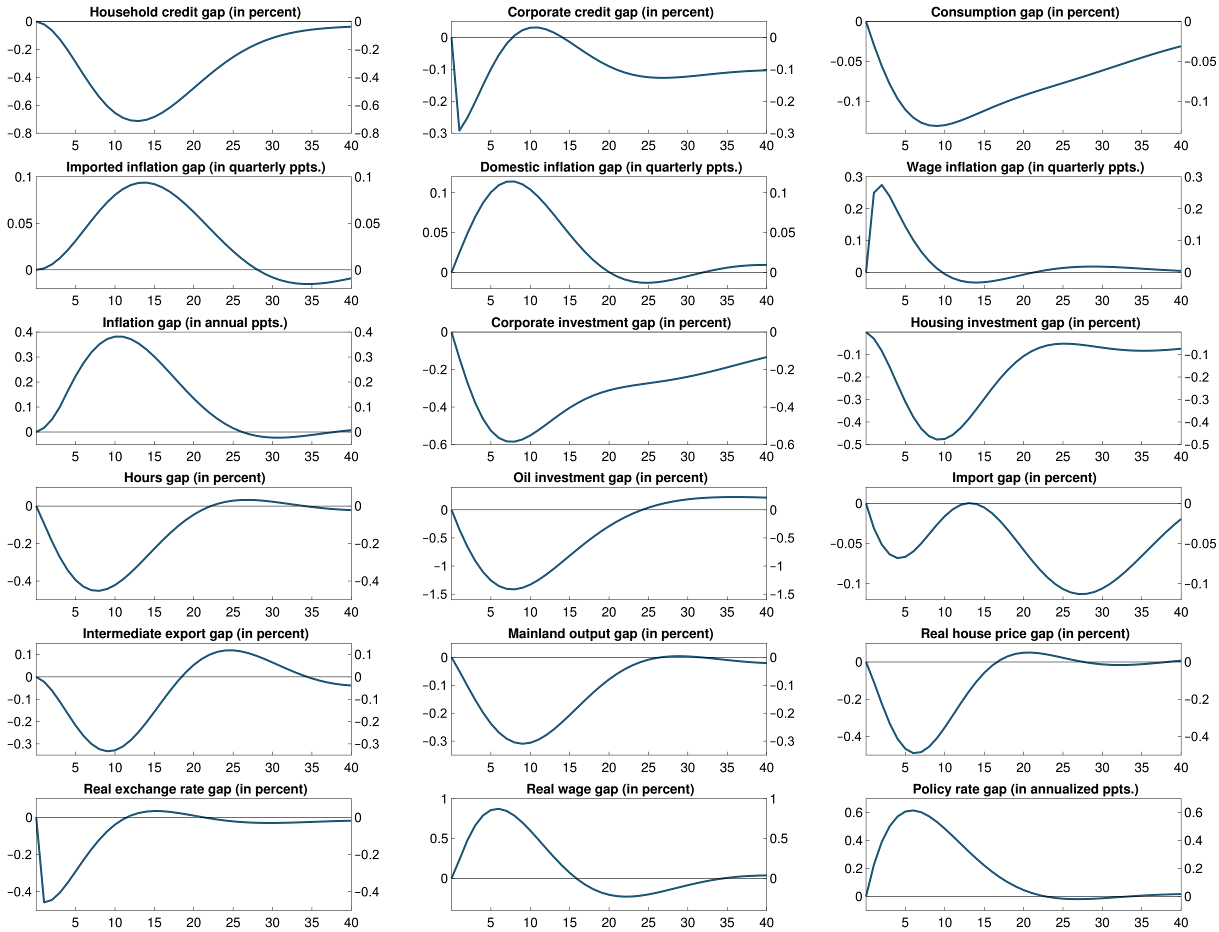

Figure 7: Impulse responses to a wage markup shock

4.2.5 Shocks to the real oil price and to the global demand

Figures 8 and 9 depict impulse responses to a shock to the real oil price and a shock to the global demand, both of which are normalized to increase real oil prices by 10 percent on impact. Starting with the first shock, an increase in real oil prices raises production by oil extractors abroad, leading to higher demand for exported goods from the oil sector supply chain in Norway. The rise in oil prices also stimulates domestic oil investment. This expansionary effect increases mainland output somewhat and real wages increase. From the perspective of Norway's trading partners, higher real oil prices generate higher inflation and lower demand. This causes the demand for traditional export goods from Norway to decline. The central bank hikes the policy rate somewhat. The rise in the policy rate as well as better terms of trade result in a real exchange rate appreciation generating a fall in imported inflation in early periods. The latter leads to a reduction in inflation in initial periods. However, inflation rises after around two years due to higher domestic demand. Overall, a positive shock to the real oil price increases real economic activity in Norway.

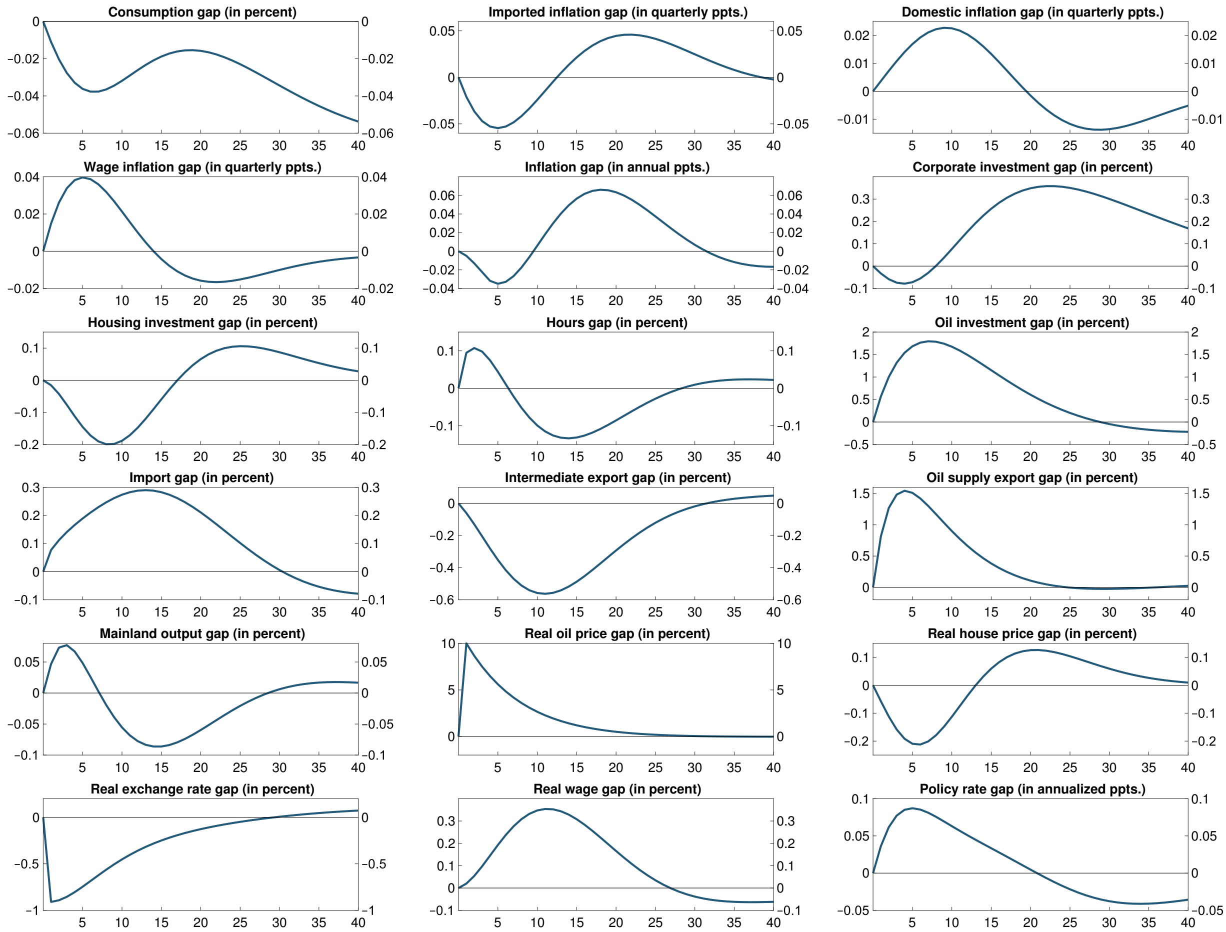

Figure 8: Impulse responses to a real oil price shock

Compared to the shock to the real oil prices, a positive global demand shock that raises real oil prices by a similar magnitude (see Figure 9) boosts the Norwegian economy much more. Since higher global demand also leads to higher real economic activity among Norway's trading partners as opposed to the aforementioned shock to the real oil price, it also leads to a higher demand for traditional export goods from Norway in addition to a higher demand for goods from the oil sector supply chain. The shock also causes the central bank of trading partners to hike their policy rates. The higher real economic activity in Norway together with the positive contribution from higher policy rates abroad leads the central bank in Norway to increase its policy rate. This generates a fall in household consumption and real house prices. The hike in the policy rate causes the real exchange rate to appreciate and this contributes to a decline in imported inflation in early periods. The aggregate inflation declines initially due to a negative contribution from imported inflation and then rises due to higher domestic demand.

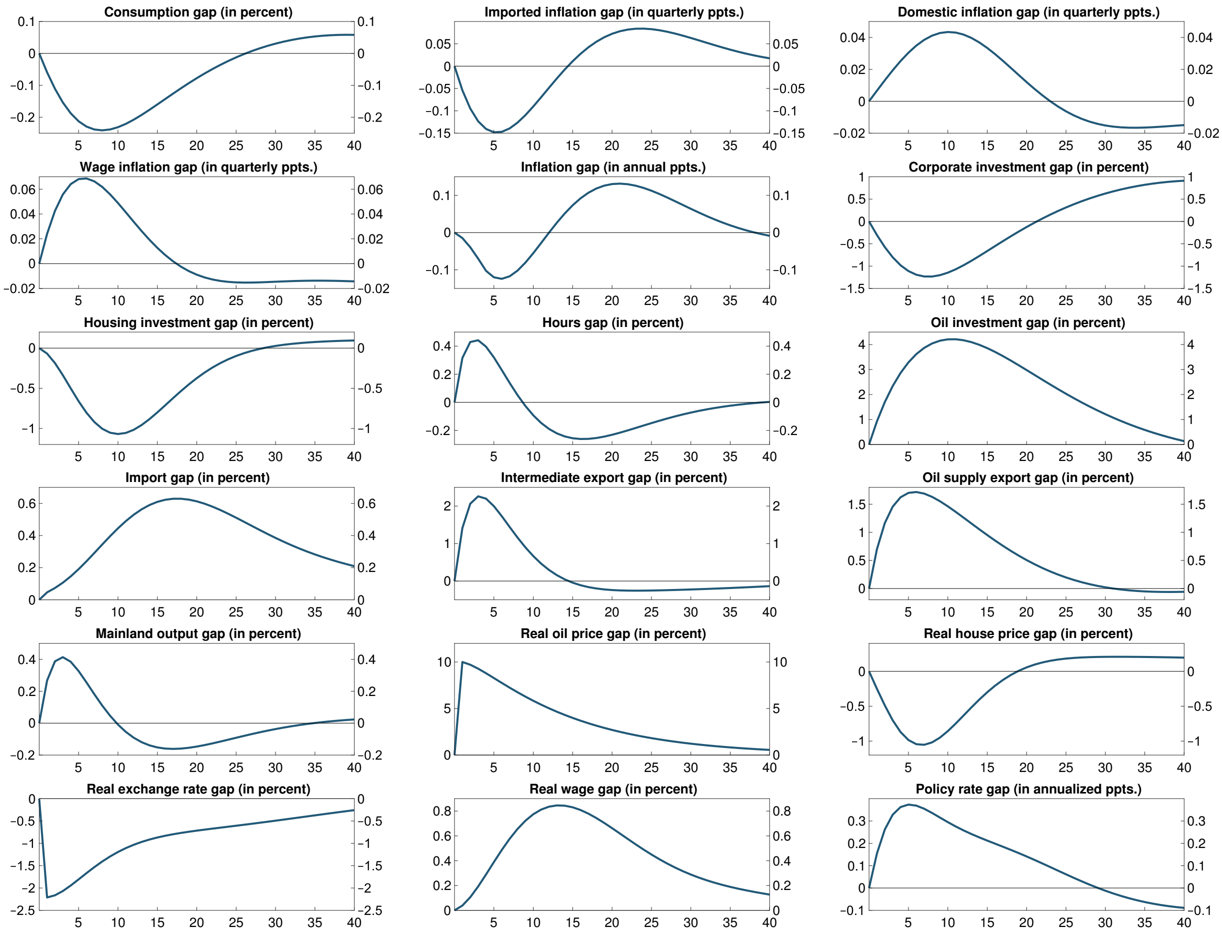

Figure 9: Impulse responses to a global demand shock

4.3 Historical shock decomposition of main macro variables

We use historical shock decompositions to quantitatively assess the main drivers of selected macroeconomic variables by looking at the contributions of the estimated shocks from 2001, the year Norges Bank switched to an explicit inflation targeting regime.[53] In order to facilitate the interpretation of the estimated structural shocks, we categorize them into seven groups: domestic demand shocks, domestic supply shocks, shocks related to the foreign sector, a shock to the exchange rate, financial shocks (shocks related to the banking sector), shocks related to the oil sector and a monetary policy shock.[54] The categorization of the shocks is given in Table 6.

[53]See Norges Bank (2017) for Norges Bank's assessment of its experience with the monetary policy framework since 2001. Moreover, in the model, we filter the shocks starting from 1994 to eliminate the effects of initial conditions on shock decompositions.

[54]Reader can refer to Appendix K to see the historical shock decomposition of all shocks separately.

Table 6: Categorization of estimated structural shocks

Domestic demand	Domestic supply	Foreign
Consumption preference	Temporary productivity	Foreign marg. costs
Housing preference	Firm inv. adj. costs	Global demand
Government spending	Housing inv. adj. costs	Export demand pref.
Import demand	Price markup	Foreign interest rate
	Wage markup	Foreign inflation
		Trading partners' output
Exchange rate	**Banking sector**	**Oil sector**
External risk premium	Money market risk premium	Real oil price
	Household LTV ratio	Oil investment
Monetary policy	Entrepreneur LTV ratio	Oil production abroad
Inflation target	Markup of mortgage loan rate	
	Markup of business loan rate	

Note: The exchange rate shock is an external risk premium shock in the UIP condition. The monetary policy shock under the optimal policy setup is implemented as a shock to the inflation target, which is equivalent to unanticipated deviations of the policy rate from the optimal monetary policy prescription.

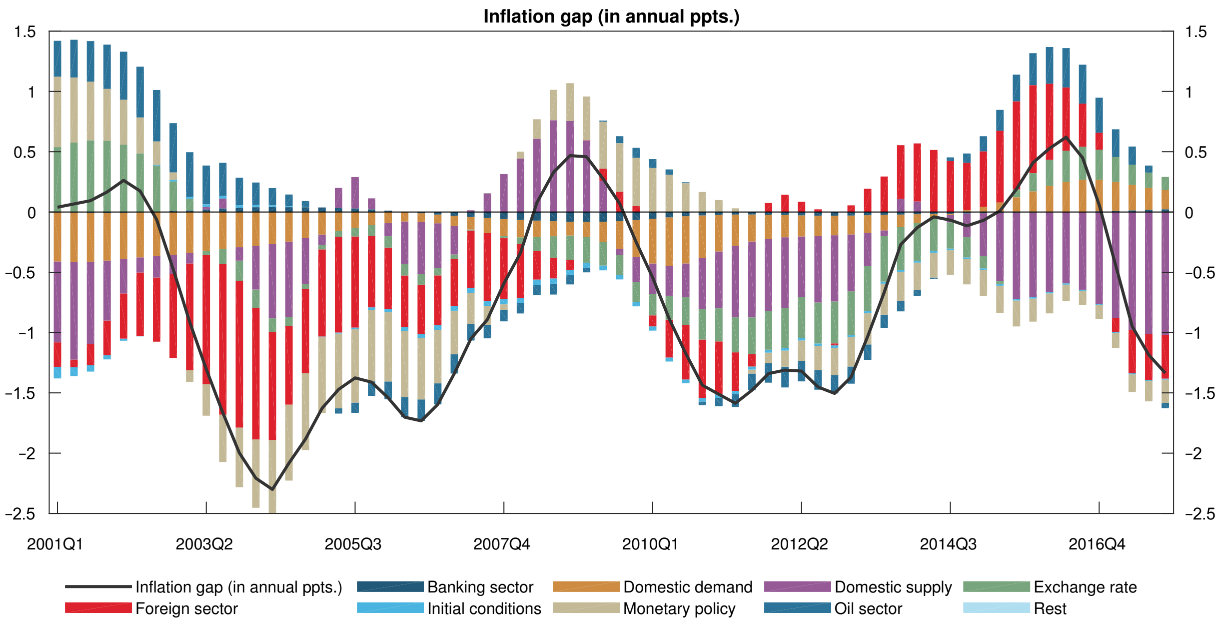

Figure 10: Historical shock decomposition of the inflation gap

Figures 10, 11 and 12 display the historical shock decompositions of the annual inflation rate gap, the mainland output gap and the policy rate gap from 2001 to 2017 computed at the posterior mode. Figure 10 shows that the initial small increase in inflation rate from 2001 to 2002 was explained by the positive contributions of the external risk premium, monetary policy and oil sector shocks as well as receding negative contributions of price markup shocks. Starting with the end of 2002, there was a sharp decline in inflation and a fall in mainland output which, according to the model, were caused mostly by negative external shocks due to an international economic downturn at the time. Domestic demand shocks contributed positively to mainland output during 2001 and 2002. Receding negative external shocks contributed to the recovery of mainland output during 2003. Inflation rate remained low in this period.

After 2003, although mainland output started to recover, an increase in the inflation rate was still lagging, partly due to negative external shocks. According to Norges Bank (2017), the period starting from 2004 was also influenced by an increase in labor immigration following the EU enlargement, leading to structural changes in the supply side of the economy. Immigration reduced wage growth in some sectors and increased supply side flexibility. These developments might have contributed to the low inflation between 2004 and 2006. However, inflation started to recover after 2006 due to declining effects of the negative external shocks. Figure 11 also indicates that mainland output continued its strong recovery from 2004 until the Lehman Brother's collapse in September 2008 thanks to the positive contributions from domestic demand and supply shocks.

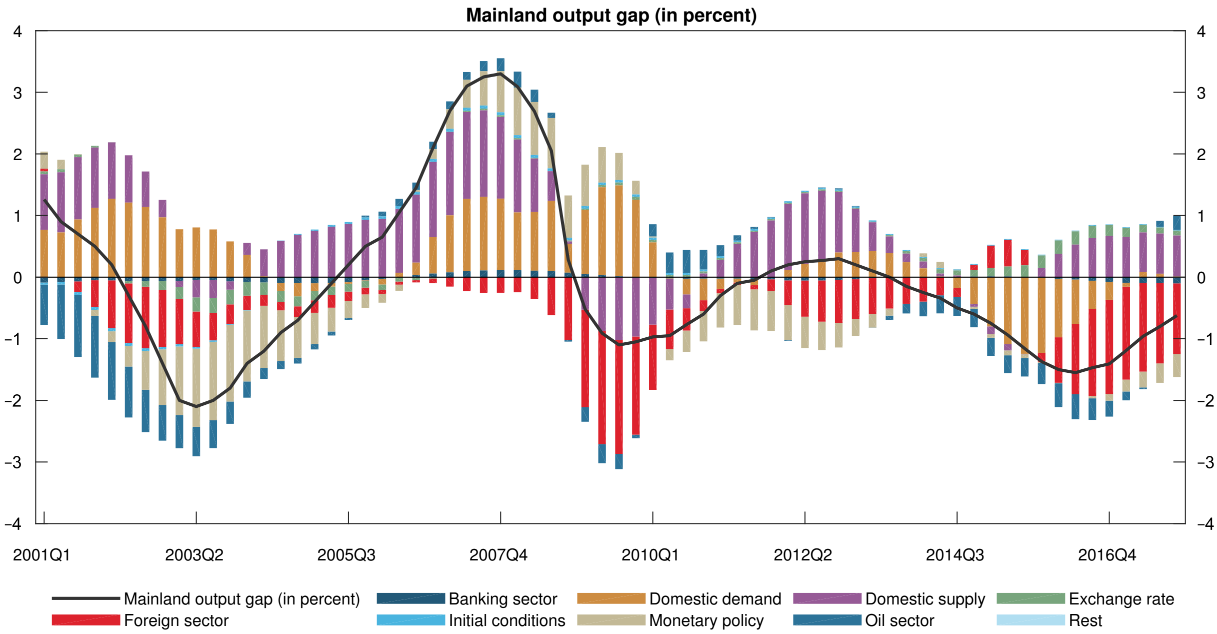

Figure 11: Historical shock decomposition of the mainland output gap

In September 2008, the U.S. investment bank Lehman Brothers announced its bankruptcy, which led to a severe worldwide recession. Uncertainty about future international economic developments rose markedly and generated negative spill-over effects on the Norwegian economy as well. Oil prices declined substantially and the krone depreciated. As Figure 11 shows, the model attributes the fall in mainland output from 2009 to 2010 to the negative macroeconomic shocks from abroad although the domestic demand shocks contributed positively at the time. The global financial crisis affected the Norwegian economy less than most of the other advanced economies since the oil price quickly returned to elevated levels. Another reason why the Norwegian economy did not experience a severe recession is that the Norwegian banks were not heavily affected. Similar to other advanced economies' central banks, Norges Bank sharply reduced the policy rate from 5.75 percent in September 2008 to 1.25 percent in June 2009. Furthermore, the Bank also deployed some other measures to ease banks' access to liquidity. Together with the declining negative effects from external shocks and domestic supply shocks, the real economic activity started to recover through 2010. Even though mainland economy began to rebound, the model indicates that inflation remained low due to negative domestic and foreign shocks as well as negative external risk premium shocks which led to a stronger exchange rate.

The Eurozone debt crisis in 2010-2012 resulted in a weaker global economic recovery after the global financial crisis. In addition to negative domestic and external risk premium shocks, the model finds that negative foreign shocks also contributed to lower inflation during these years, as Figure 10 suggests. Since the policy rates in the euro area and in other advanced economies were already at their effective lower bounds, the central banks in those countries started deploying quantitative easing programmes (large-scale asset purchases) to stimulate aggregate demand by keeping long-term rates low for extended periods. The policy rate in Norway also remained low due to negative external shocks.

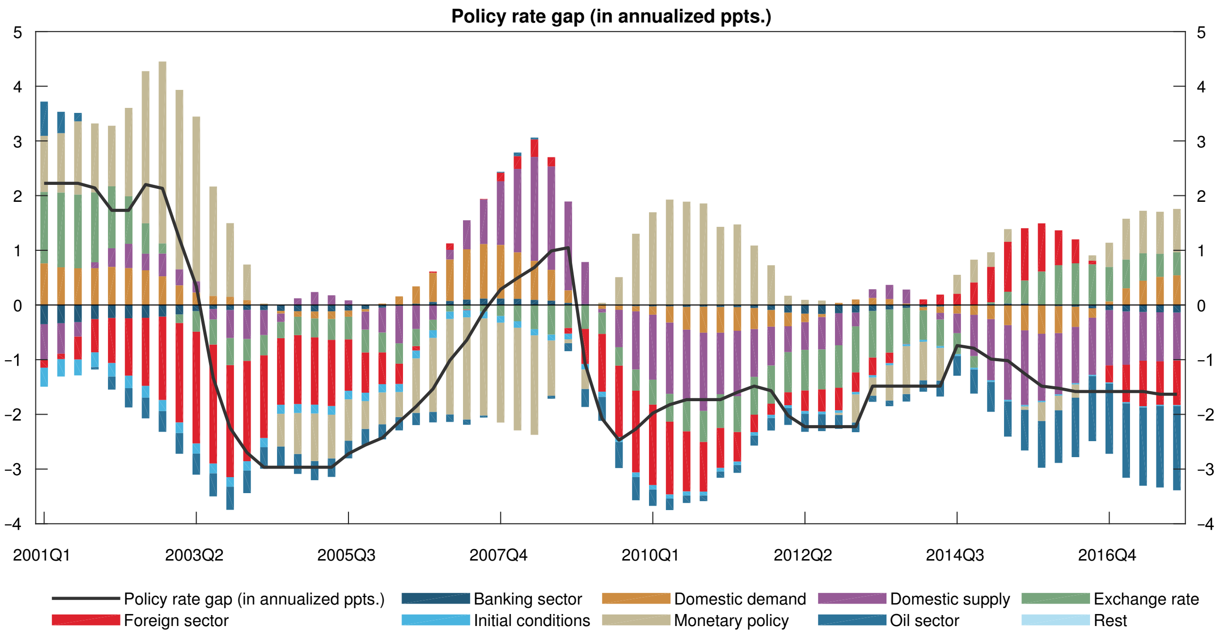

Figure 12: Historical shock decomposition of the policy rate gap

From the beginning of 2014, oil prices started to fall substantially until they reached their lowest level in the beginning of 2016. This marked fall in oil prices was explained by the positive contributions from oil price shocks in the model (see Figure 82. The model also indicates that oil investment declined due to both negative real oil price and negative oil investment shocks (see Figure 76). According to the model, the fall in mainland output was further aggravated by negative domestic demand shocks, which can be seen from Figure 11. The limited negative contribution to mainland output from the real oil price shock at the time can be attributed to the accommodative monetary policy, which is apparent from Figure 12. Starting with mid-2015, mainland output started to recover thanks to smaller negative domestic demand shocks and positive contributions from domestic supply shocks although negative external shocks weighed on the downside.

During 2015, inflation increased somewhat with the positive contributions from domestic demand, foreign, and external risk premium shocks. Later in 2016, it again started to fall because of increasing negative contributions from price and wage markup shocks as well as negative external shocks despite the positive effects from domestic demand, external and oil sector shocks. Monetary policy was also tighter than that derived from the model from 2016. One explanation for this is that financial stability concerns against the backdrop of high house price inflation gained a more prominent role in monetary policy considerations.[55] Another explanation is that Norges Bank put more weight on moving with caution as the uncertainty surrounding the effects of monetary policy increases when the interest rate approaches a lower bound.[56]

4.4 Forecast-error-variance decomposition for macro variables

This section presents forecast-error-variance decompositions (FEVD), which summarize the individual contributions of the estimated structural shocks in explaining the fluctuations in the variables in the model. Figures 13, 14, and 15 show the FEVDs of inflation, mainland output and policy rate gaps for 40 quarters computed at the posterior mode, respectively. For the ease of the exposition, we still use the same grouping for the structural shocks as in the previous section: domestic demand shocks, domestic supply shocks, shocks related to foreign sector, shock to the exchange rate, financial shocks, oil sector shocks and a monetary policy shock.[57]

4.4.1 Inflation gap

In the short run (at the 1-year horizon), the shocks related to foreign sector explain more than 67 percent of the observed fluctuations of the inflation gap while domestic supply shocks contribute to 25 percent of the movements as can be seen from Figure 13. Foreign marginal costs, which feed into imported prices, are the main driver of the inflation gap in the short run with a share of 65 percent, followed by the domestic price markup shock with a share of 19 percent. The external risk premium shock to the exchange rate and the domestic demand shock group in total account for a little more than 5 percent of the variations in the inflation gap in the short run.

In the medium term (at the 3-year horizon), the observed fluctuations in the inflation gap are primarily explained by the domestic supply (51 percent) and foreign sector related shocks. The shock to foreign marginal costs is still the most important part of the foreign shocks group (34 percent) followed by the shock to inflation abroad (2 percent) and to export demand preferences (1 percent). The domestic supply shocks mainly comprise the wage markup shock (27 percent) and the price markup shock (15 percent) followed by the temporary technology shock (9 percent). The domestic demand shocks (mainly the shock to import demand) and the shock to the exchange rate each explain 4 percent of inflation in the medium term. The shocks related to the oil sector drive a bit more than 1 percent of the observed fluctuations in inflation both in the short and the medium terms.

Finally, in the long run (at the 10-year horizon), the domestic supply shock group is the most important contributor to inflation gap (about 50 percent), which is primarily driven by the wage markup shock (30 percent), the price markup shock (10 percent) and the temporary technology shock (7 percent). The impact of the foreign sector related shocks

[55] In Monetary Policy Report 4/17, it was also explicitly stated, "*Persistently low interest rates add to the vulnerabilities in the financial system. In the interest of long-term economic stability, the key policy rate has been set somewhat higher in recent years than the projections for inflation and the output gap in the coming years would in isolation imply*". See page 36 of Monetary Policy Report 4/17 in `https://www.norges-bank.no/en/Published/Publications/Monetary-Policy-Report-with-financial-stability-assessment/2017/417-monetary-policy-report/`

[56] See Gerdrup *et al.* (2017).

[57] Reader can refer to Appendix M to see the forecast-error-variance decomposition of all shocks separately.

somewhat diminished to 30 percent, with the shares of the shock to foreign marginal costs and of the shock to inflation abroad as 24 percent and 2.5 percent of the total variation in the inflation gap, respectively. Moreover, the shocks to oil prices and to oil investment adjustment costs explain 8 percent of the observed variation in inflation in the long term. The domestic demand shock group contributes to 7 percent of the fluctuations in inflation, with the share of the shock to import demand as 6 percent of the total variation. The monetary policy shock drives only 1 percent of the movements in inflation at all horizons.

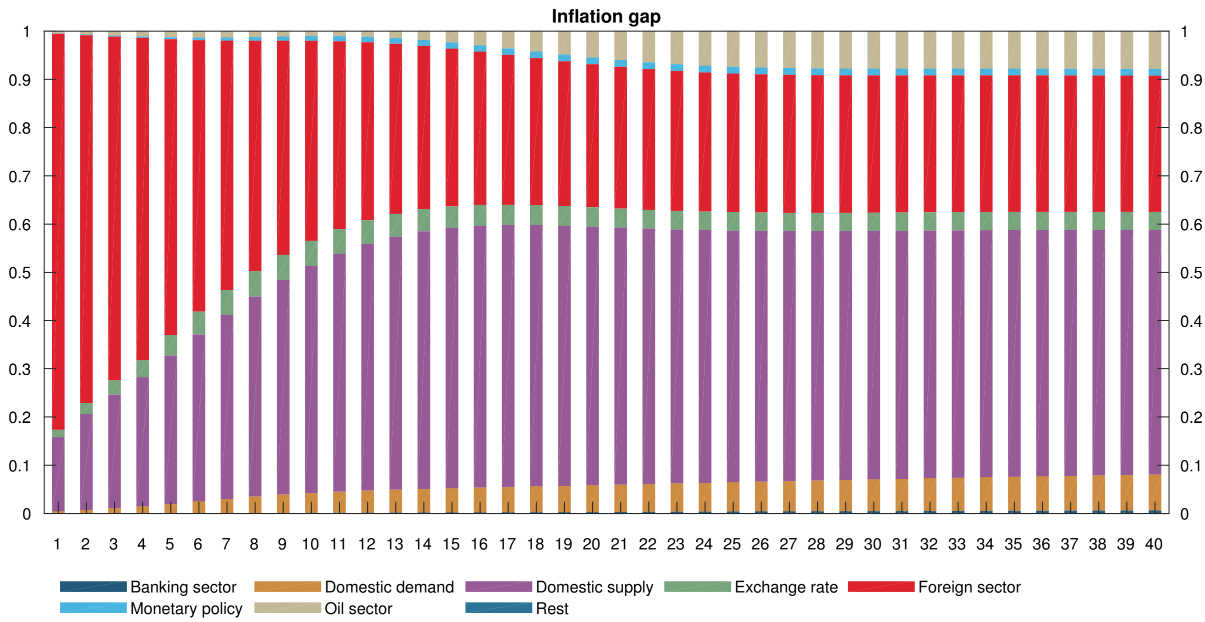

Figure 13: Forecast-error-variance decomposition of the inflation gap

4.4.2 Mainland output gap

Figure 14 shows that in the short run, the observed movements in mainland output are primarily explained by the domestic demand shocks (54 percent) and the foreign sector shocks (30 percent) followed by the domestic supply (9 percent) and oil sector shocks (6 percent). The shock to import demand is the main contributor to driving output gap with a share of 36 percent of the total variation. The shock to output abroad accounts for 16 percent of the observed fluctuations in output while the shock to export demand preferences explain 13 percent of those fluctuations. In addition, the shock to the firm investment adjustment costs in the domestic supply shock group drives 6 percent of the variation in output and the shocks to oil prices and oil production account for another 6 percent of it.

In the medium term, the domestic demand shocks still dominate by explaining 47 percent of the fluctuations in output, mostly driven by the shock to import demand (32 percent). While the impact of the domestic supply shocks increase to 20 percent in the medium term compared to 9 percent in the short run, that of foreign sector shocks is a bit lower (26 percent vs. 30 percent). The oil sector related shocks still contribute to driving 6 percent of the output variation as in the short-term. 13 percent of the observed fluctuations in output gap is driven by the shock to foreign output. The shock to export demand preferences accounts for 11 percent of the variation in mainland GDP. Regarding the domestic supply shock group, the wage markup and the corporate investment shocks drive 9 percent and 8 percent of the movements in mainland output, respectively.

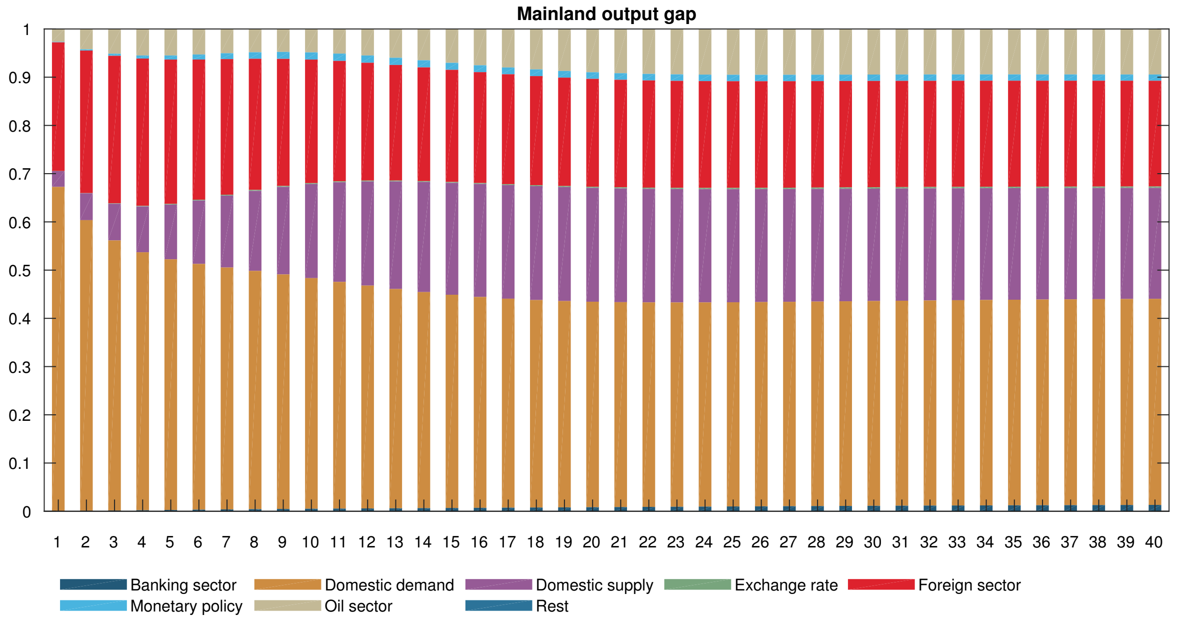

Figure 14: Forecast-error-variance decomposition of the mainland output gap

In the long run, the movements in output are still mainly accounted for by the domestic demand shocks (42 percent) followed by the foreign sector shocks (23 percent), the domestic supply shock group (22 percent) and the oil sector related shocks (10 percent). The shock to import demand is the primary contributor to the output variation with a share of 30 percent. The shock to output abroad and the shock to export demand preferences account for 11 percent and 10 percent of the fluctuations in output, respectively. The domestic supply shock group is mainly driven by the wage markup (10 percent of total variation) and the corporate investment adjustment cost shocks (9 percent of total variation). Moreover, the shock to oil prices contributes to explaining 6 percent of output gap while the shocks to oil investment adjustment costs and oil production account 3 percent and 2 percent of it, respectively. The financial shocks group and the monetary policy shock explain around 1 percent and 1.5 percent of the output fluctuations at all horizons, respectively.

Overall, the results seem to be broadly consistent with Aastveit *et al.* (2013) and Bergholt *et al.* (2017). Using a factor-augmented VAR approach, Aastveit *et al.* (2013) find that domestic shocks explain 80 percent of the variation in the mainland GDP up to eight quarters. Bergholt *et al.* (2017) show that around 85 percent of the fluctuations in mainland output is due to domestic shocks. In NEMO, we find that nearly 70 percent of the fluctuations in mainland GDP is due to domestic shocks. In the longer run, in Bergholt *et al.* (2017) foreign shocks account for about 40 percent of the variation in GDP while they explain around 20 percent of the fluctuations in output in NEMO. In addition, oil shocks account for more than 30 percent of the variation in output while they drive around 10 percent of the movements in GDP in NEMO.

4.4.3 Policy rate gap

Figure 15 indicates that in the short term, the foreign sector shock group is the main contributor to explaining the policy rate with a share of 34 percent, which is closely followed by the domestic supply shock group with a share of 31 percent. The shocks to foreign marginal costs, and to output abroad account for 19 percent and 12 percent of the observed variation in the policy rate, respectively. The domestic supply shock group is primarily driven by wage markup shocks (20 percent) followed by the temporary technology (4 percent), the price markup (4 percent) and the business investment adjustment cost (3 percent) shocks. The external risk premium shock and the domestic demand shocks each explain 8 percent of the variation in the policy rate while the shocks related to the oil sector account for 9 percent (with a 5 percent share of the shock to oil investment adjustment costs). The remaining 10 percent and 1 percent of the observed movements in the policy rate are driven by shocks to monetary policy preferences and the financial shock group, respectively.

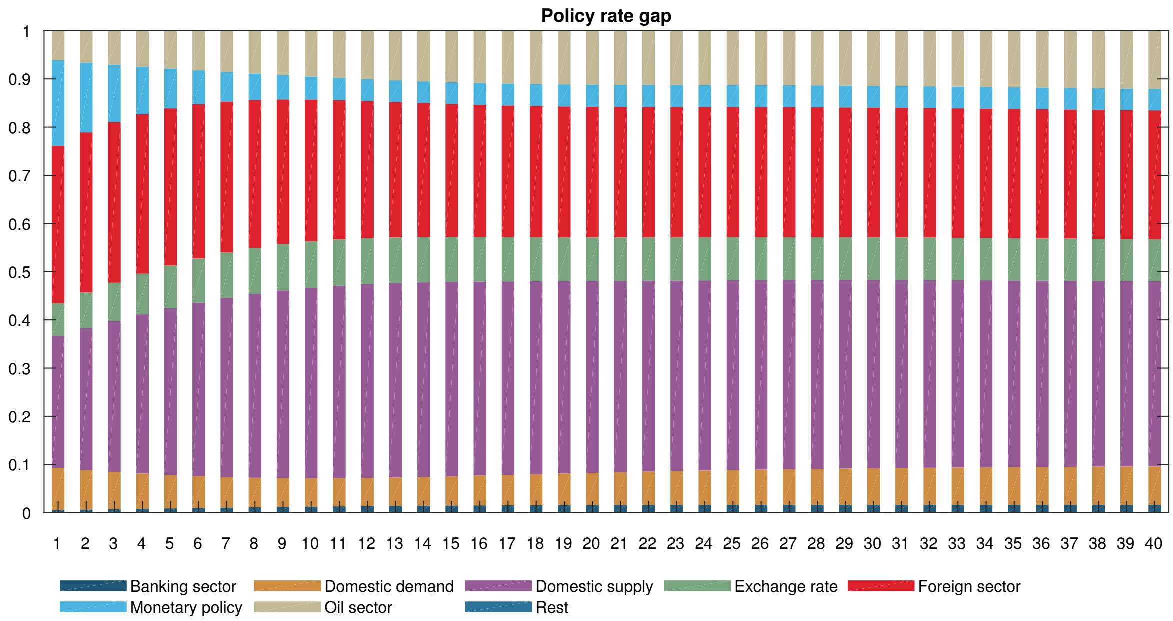

Figure 15: Forecast-error-variance decomposition of the policy rate gap

However, in the medium run, the domestic supply shocks start to dominate the foreign sector-related shocks in terms of their contributions to explaining the policy rate: 39 percent vs. 30 percent. The domestic supply shocks mainly consist of the wage markup shock (27 percent) followed by the temporary technology shock (5 percent), the price markup shock (3 percent), and the business investment adjustment cost shock (3 percent). The shock to foreign marginal costs is still the main contributor to the foreign shocks group (16 percent) followed by the shock to output abroad (10 percent) and to foreign inflation (3 percent). The oil sector shocks account for 11 percent of the observed fluctuations in the policy rate, of which 7 percent is due to the shock to oil investment adjustment costs and 3 percent is due to the oil price shock. While the shock to the exchange rate explains 9 percent of the policy rate changes, the shock to monetary policy preferences drive 5 percent of it. The financial shock group still drives only 1 percent of the variation in the policy rate.

Finally, in the long run, the domestic supply shocks still have more impact than the foreign sector related shocks in terms of their contributions to accounting for the policy rate: 36 percent vs. 29 percent. The wage markup shock is the primary driver of the policy rate with a share of 26 percent while the temporary technology shock, the price markup shock and firm investment adjustment cost shock only account for 5 percent, 3 percent and 2 percent, respectively. Furthermore, the shocks to marginal costs abroad, foreign output and foreign inflation contribute to explaining 14 percent, 9 percent and 3 percent of the movements in the policy rate, respectively. The shock to the exchange rate drives 8 percent of the variation in the policy rate while the domestic demand shock group explains 9 percent of it. The shocks to the oil investment adjustment costs and the oil price contribute to driving 8 percent and 3 percent of the policy rate changes, respectively. The financial shocks group and the monetary policy shock explain around 2 percent and 4 percent of the policy rate fluctuations in the long run, respectively.

Table 7: Root-mean square forecast errors (RMSEs): NEMO vs. VARs

Prediction horizon	**Inflation**		**Mainland output**		**Policy rate**	
Quarters	NEMO	VARs	NEMO	VARs	NEMO	VARs
1	0.23	0.23	0.80	0.91	0.28	0.37
2	0.37	0.39	1.26	1.39	0.58	0.68
3	0.55	0.57	1.71	1.89	0.83	0.94
4	0.79	0.82	2.29	2.49	1.04	1.17
5	0.83	0.88	2.48	2.55	1.21	1.36
6	0.93	0.91	2.57	2.59	1.38	1.52
7	1.00	0.97	2.58	2.61	1.55	1.66
8	1.02	0.94	2.54	2.61	1.71	1.78

Note: This table reports the RMSEs of unconditional one to eight quarters-ahead forecasts for core inflation, mainland GDP growth and the policy rate that come from both NEMO and VARs. The forecasts are computed out-of-sample over the period from 2005Q1 to 2017Q4. For NEMO, the forecasts are given by the means of the predictive densities conditional on the posterior mode estimates of the model's parameters.

4.5 Evaluation of real GDP, inflation and interest-rate forecasts

This section assesses the unconditional forecasting performance of NEMO compared to a pool of vector autoregressive (VAR) models where only subsets of the observed variables are considered.[58] We use the root-mean-square forecast error (RMSE) as our evaluation criterion. Out-of-sample forecasts are conducted by gradually extending the end of the data sample from 2005Q1 to 2017Q4.[59] For NEMO, the RMSEs are computed based on the mean forecasts at the posterior mode. We use the same parameter set for all the recursive forecasts from NEMO. Estimates of trends and unobserved variables are based on quasi-real-time data, meaning that we do not use vintage data that was available at

[58]The selection of VAR models is optimal in terms of explaining the data of gap variables. One can alternatively come up with B-VARs or VARs based on the data in levels or in growth rates.

[59]The estimation period for the VARs starts from 1993Q4.

the time.[60] We use quasi-real-time estimates of the parameters for the VAR models.[61]

Both VARs and NEMO provide forecasts only for gap variables in our exercise. In order to translate the gap forecasts into the inflation rate, the mainland GDP growth rate and the policy rate level, we also project the trends recursively. Annual inflation rate is assumed to have a constant trend of 2.5 percent. For the mainland GDP growth, the growth rate of the HP-filtered trend is used as a starting point of the recursively projected trend. We then assume that the trend gradually approaches to the average growth rate from 1993Q4 up until the date of the forecasting based on an AR(1) process with a persistence parameter of 0.9. Finally, we use the trend displayed in Figure 19 for the policy rate except that we first apply changes in the trends with a lag of one year.

Note that when NEMO is used in monetary policy assessments, it is conditioned on nowcasts and short-term forecasts from a wide set of additional data sources such as SAM (System for Averaging Models), sector expert judgement, market information, and Norges Bank's regional network. This additional input enhances the model's performance in terms of interpreting the state of the economy and improving the medium term forecasts. In this exercise, the model forecasts are unconditional on such information and therefore, the results presented here should not be interpreted as an assessment of Norges Bank's whole forecasting system.

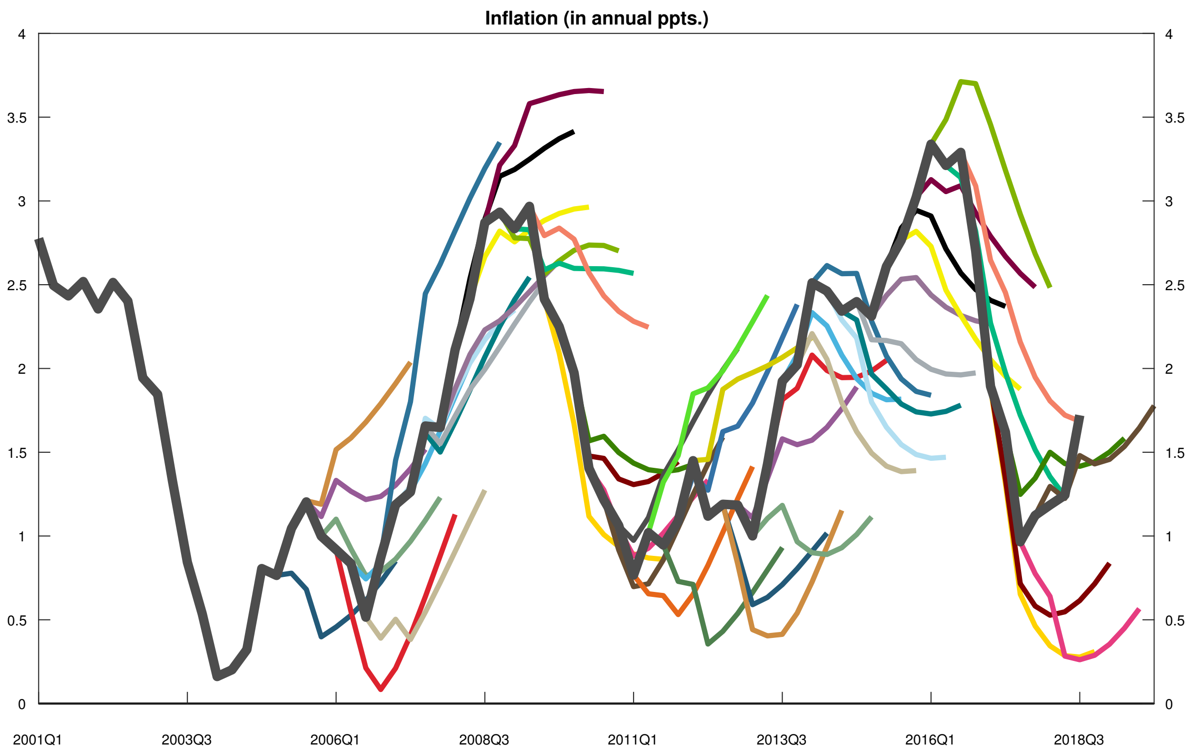

Figure 16: Unconditional out-of-sample forecast of the inflation gap in NEMO: Four-quarter change

Table 7 shows the RMSEs of unconditional one to eight quarters-ahead forecasts for core inflation, mainland GDP growth and the policy rate. Regarding the inflation rate forecasts, we see that in comparison to the VARs, NEMO has slightly lower RMSEs for the forecast horizons up to and including the fifth quarter followed by slightly higher RMSEs

[60] In this section, we filter the data based on HP-filter instead of DORY (see Section 3.1).

[61] See Gerdrup *et al.* (2017) for more details.

sixth to eighth quarters ahead. In terms of mainland GDP growth rate and the policy rate forecasts, NEMO dominates the VARs at all forecast horizons up to eight quarters in terms of RMSEs. Overall, the out-of-sample forecasting performance of NEMO is quite comparable to or even better than this group of VARs.

Figures 16, 17, and 18 show the recursive forecasts for the inflation rate, the growth rate of mainland GDP and the policy rate one to eight quarters ahead in NEMO. The recursive forecasts obtained from the VARs are presented in Appendix N. Overall, NEMO and the VAR models seem to show similar patterns for the inflation rate, the growth rate of mainland GDP and the policy rate (See Figures 122, 124, and 126).

Figure 16 indicates that NEMO underpredicts the fall in inflation starting in the first quarter of 2006 and then overpredicts the rise starting from the first quarter of 2008 during the global financial crisis when compared to the data. Around the Eurozone debt crisis in 2012, NEMO seems to overpredict the decline in the inflation rate after which it underestimates the rise during the episode of falling oil prices and a weaker real exchange rate starting from 2014. While the model overpredicts the rise in the inflation rate around the third quarter of 2015, it underestimates the decline in the following quarters as well as in the very recent episode.

The growth rate forecasts of mainland GDP in Figure 17 show that prior to the global financial crisis, NEMO underpredicts the increase in the growth rate while it underestimates the fall during the crisis by a small margin. However, it strongly overpredicts the rise in the growth rate in the recovery phase around 2010 and onwards. Around the Eurozone debt crisis in 2012, the model gives similar paths as the realized data until 2017, in which it underestimates the growth rate a little bit.

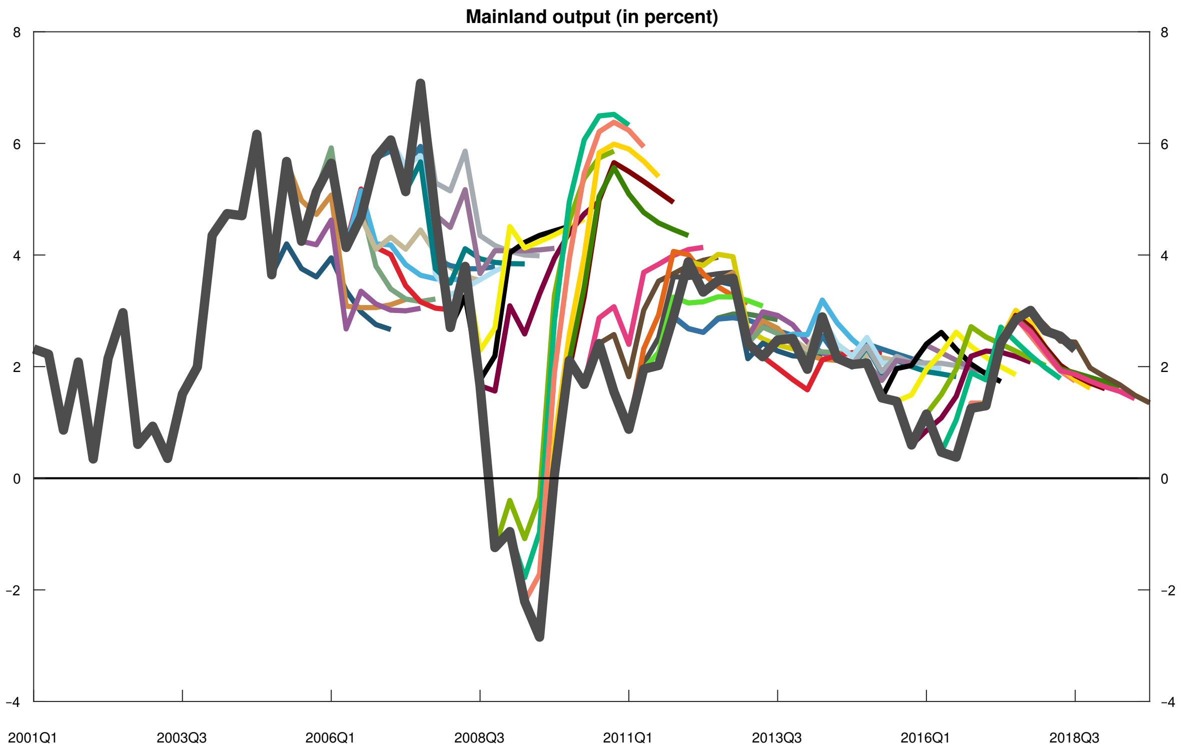

Figure 17: Unconditional out-of-sample forecast of the mainland output gap in NEMO: Four-quarter growth

Finally, Figure 18 shows the forecast paths for the policy rate. During the Lehman

Brothers collapse around 2008Q3, Norges Bank sharply lowered its policy rate from 5.75 percent to 1.25 percent in June 2009. The forecast path at the time starting from the first quarter of 2008 underpredicts the reduction in the policy rate, after which it overestimates the fall in the policy rate in 2009 to 2010. As most of the other central banks' models, NEMO overpredicts how fast the policy rate would return to more normal levels after the global financial crisis.

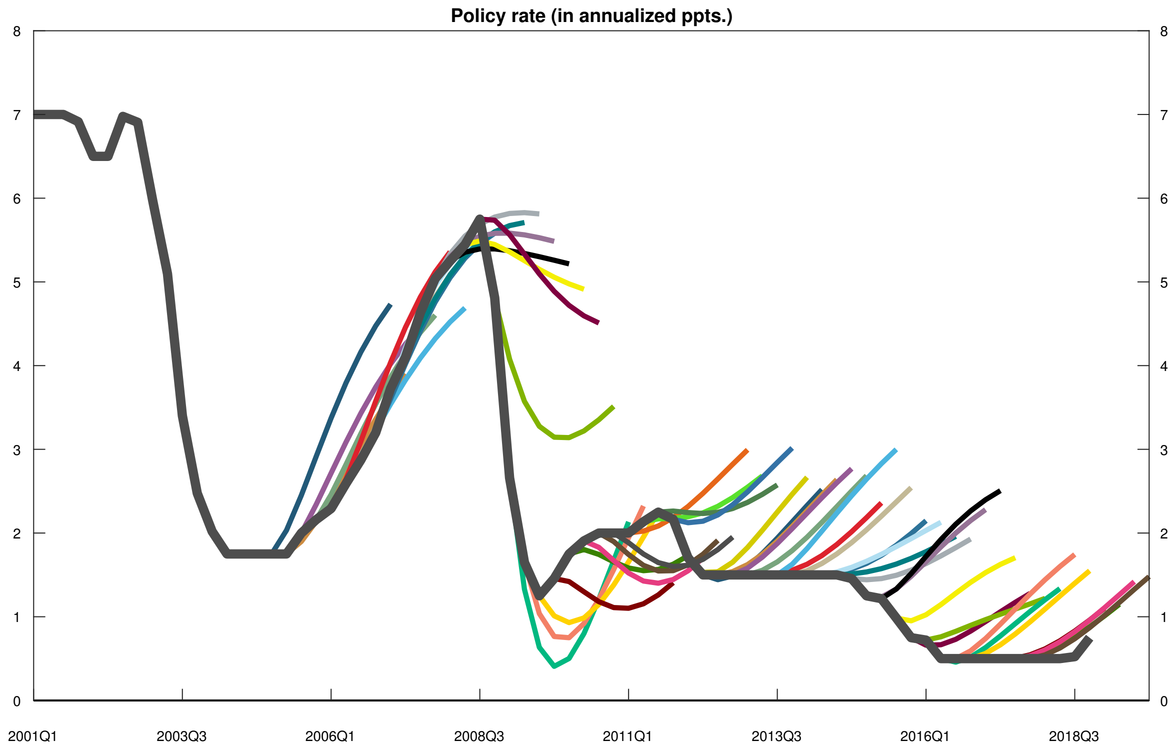

Figure 18: Unconditional out-of-sample forecast of the policy rate in NEMO (in levels)

5 Conclusion

This paper presents a newly estimated version of NEMO, Norges Bank's main macroeconomic model for monetary policy analysis, which is regularly employed for staff projections at the Bank. Since 2006, the model is enriched by the addition of a banking sector and an explicit role for housing services and house prices as in Gerali *et al.* (2010), long-term debt contracts and simple moving average forecast rules as in Gelain *et al.* (2018), and a detailed oil sector following Bergholt *et al.* (2017). These developments over time allow the staff to conduct more comprehensive policy analysis using the model. Moreover, the model has also been used for macro-prudential stress testing for the banking sector starting from 2018.

We describe the details of the estimation results for NEMO obtained using Bayesian techniques and system priors. We employ the latter to reflect our beliefs about the model's behavior as a system. We also use the identification package by Ratto and Iskrev (2011) in order to check for identification issues typically present in DSGE models. We analyze the quantitative properties of NEMO through examining business cycle moments, conducting impulse response analysis as well as historical and forecast-error-variance decompositions, and finally investigating the forecasting performance of the model.

We have reached a couple of important milestones by re-calibrating and re-estimating the model. First, due to sufficiently long time series data, we have been able to estimate the model using data for the period of inflation targeting alone, i.e. since 2001. Second, we have re-calibrated the steady state of the model, which is more in line with the data for a relevant time period. For example, the levels of household debt and housing wealth relative to mainland GDP have risen sharply over time. Exports and imports shares of traditional goods and services are also higher now than was the case in the 1990s. Third, we have obtained empirically-relevant fluctuations in the model's endogenous variables as observed in the data. Finally, we have been able to match the effects of monetary policy and oil price shocks to the results found in empirical models.

In the re-estimated version of NEMO, the values of parameters related to the costs involved in changing prices have increased. As a consequence, the Phillips curves are flatter, i.e. that a given increase in capacity utilization has a somewhat smaller effect on wages and prices. This brings estimated relationships in NEMO closer to other models Norges Bank uses in its forecasting.

In isolation, the higher steady-state levels of household debt and housing wealth suggest that an interest rate change in the model would have a somewhat stronger impact. However, since the estimated degree of real rigidities such as habit persistence in consumption and investment adjustment costs is higher relative to the previous version of the model, overall effects of a shock to the policy rate are somewhat smaller. Due to higher export and import shares, external shocks have a somewhat greater impact on the domestic economy in the re-estimated version of the model.

Further development of NEMO is important for the model to continue to be a useful tool for monetary policy analysis. For instance, in this regard, we currently investigate the so-called forward guidance puzzle in NEMO, which will be documented in a forthcoming Norges Bank Staff Memo.[62]

[62]See Carlstrom *et al.* (2015), Negro *et al.* (2015), McKay *et al.* (2016) for a discussion of the forward guidance puzzle typically present in New-Keynesian DSGE models.

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Appendices

A Data

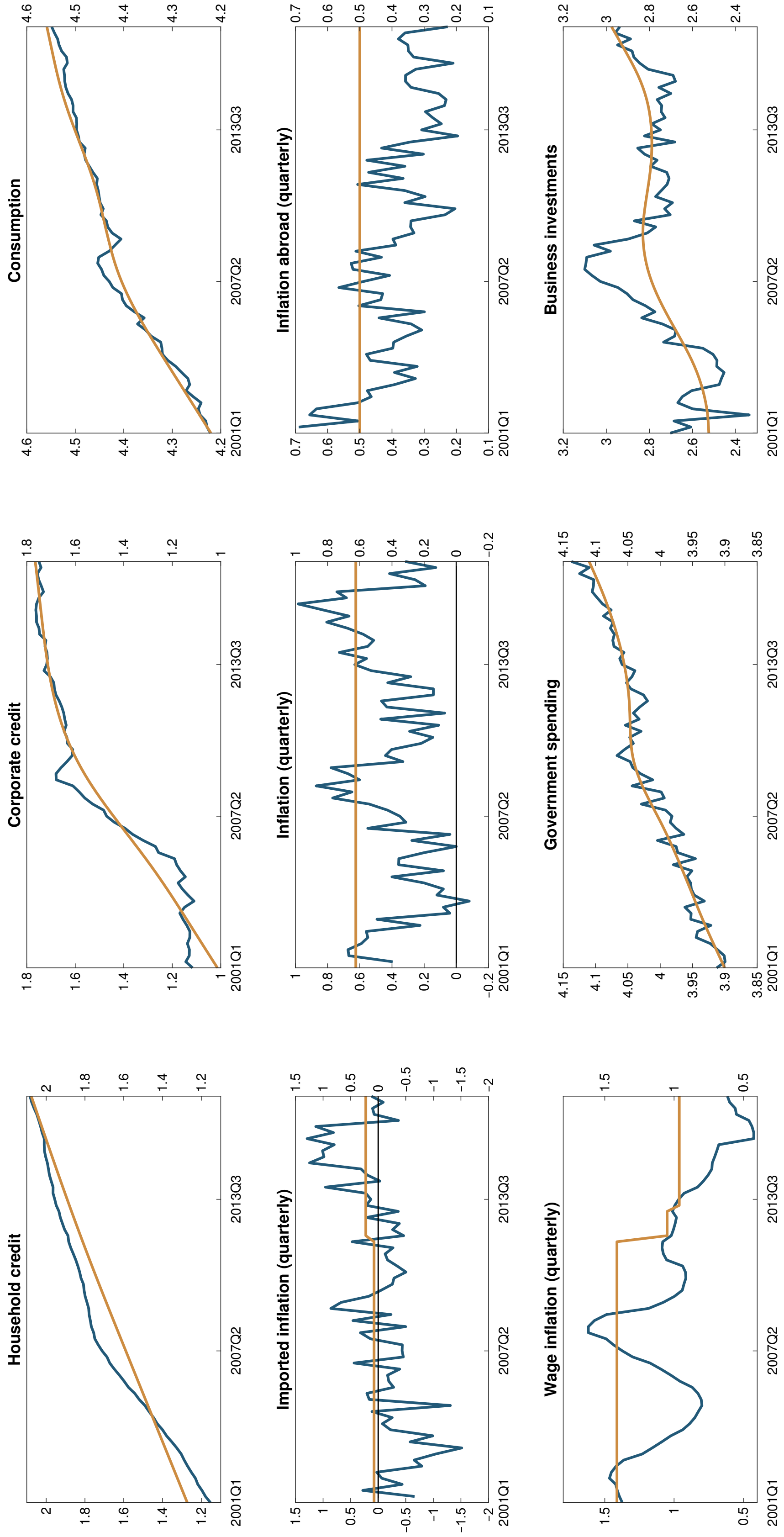

Figure 19: Observable variables, levels (blue) and trends (yellow). Volumes are in log per capita.

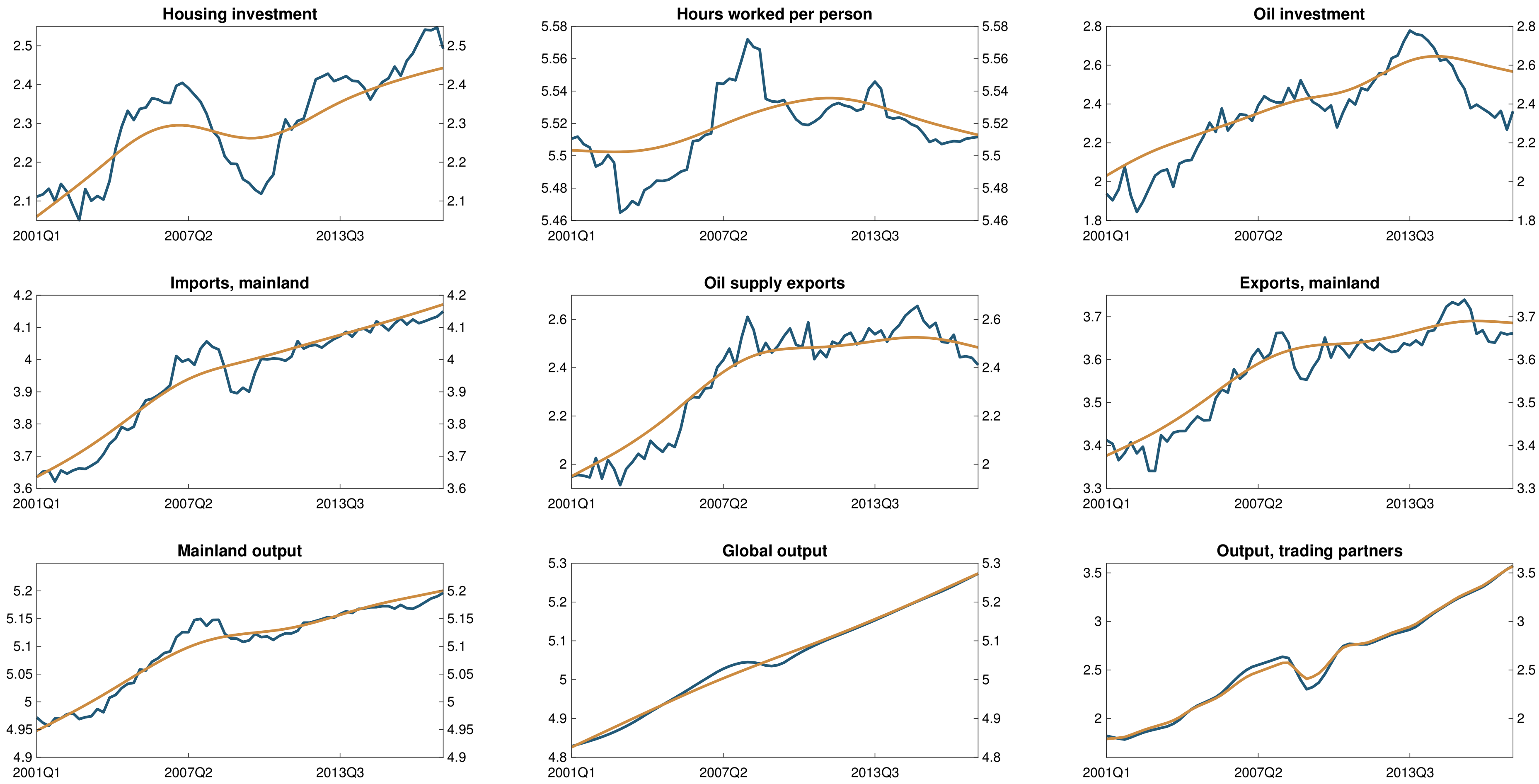

Figure 19: Observable variables, levels (blue) and trends (yellow). Volumes are in log per capita. *Cont.*

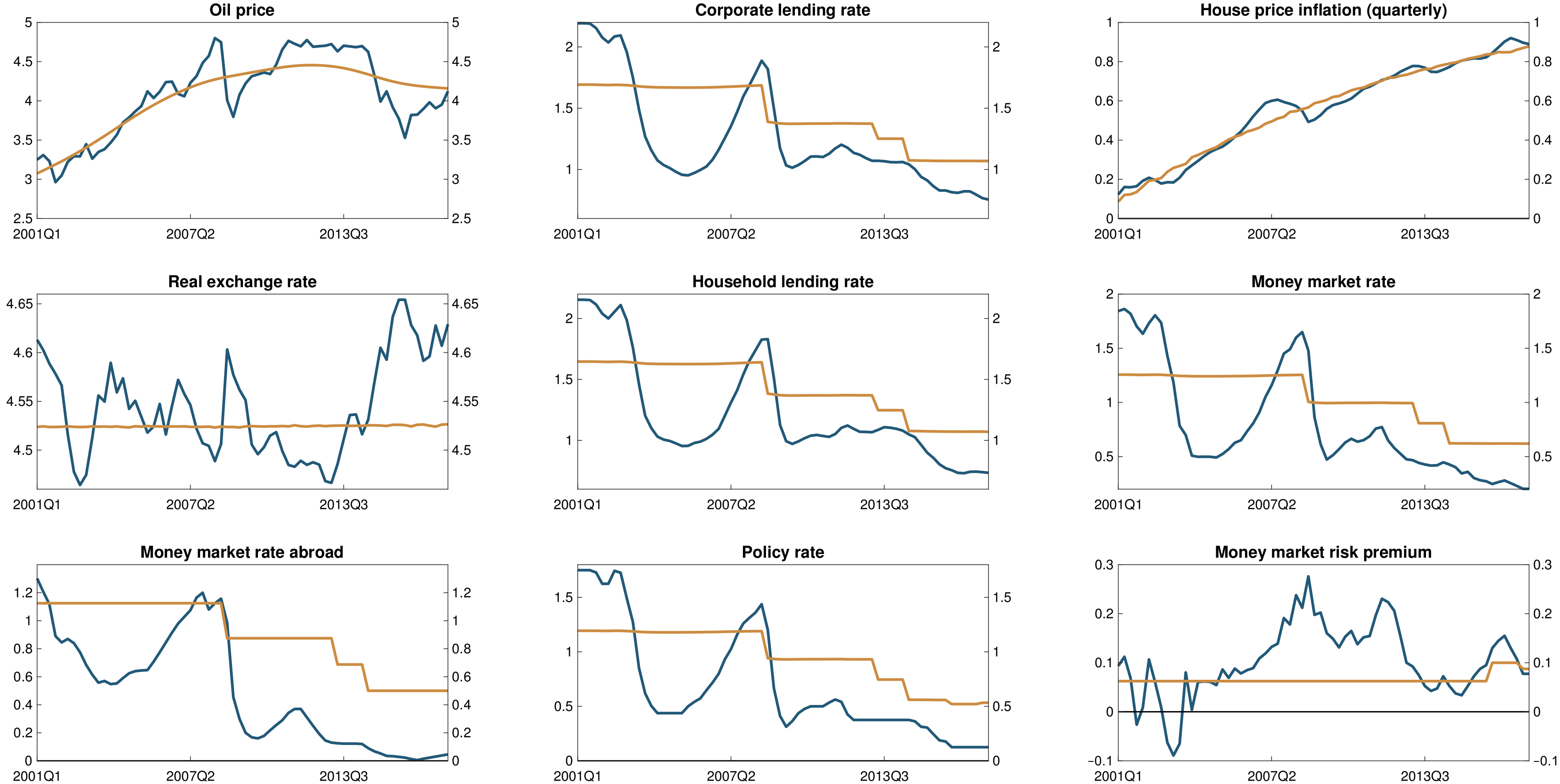

Figure 19: Observable variables, levels (blue) and trends (yellow). Volumes are in log per capita. *Cont.*

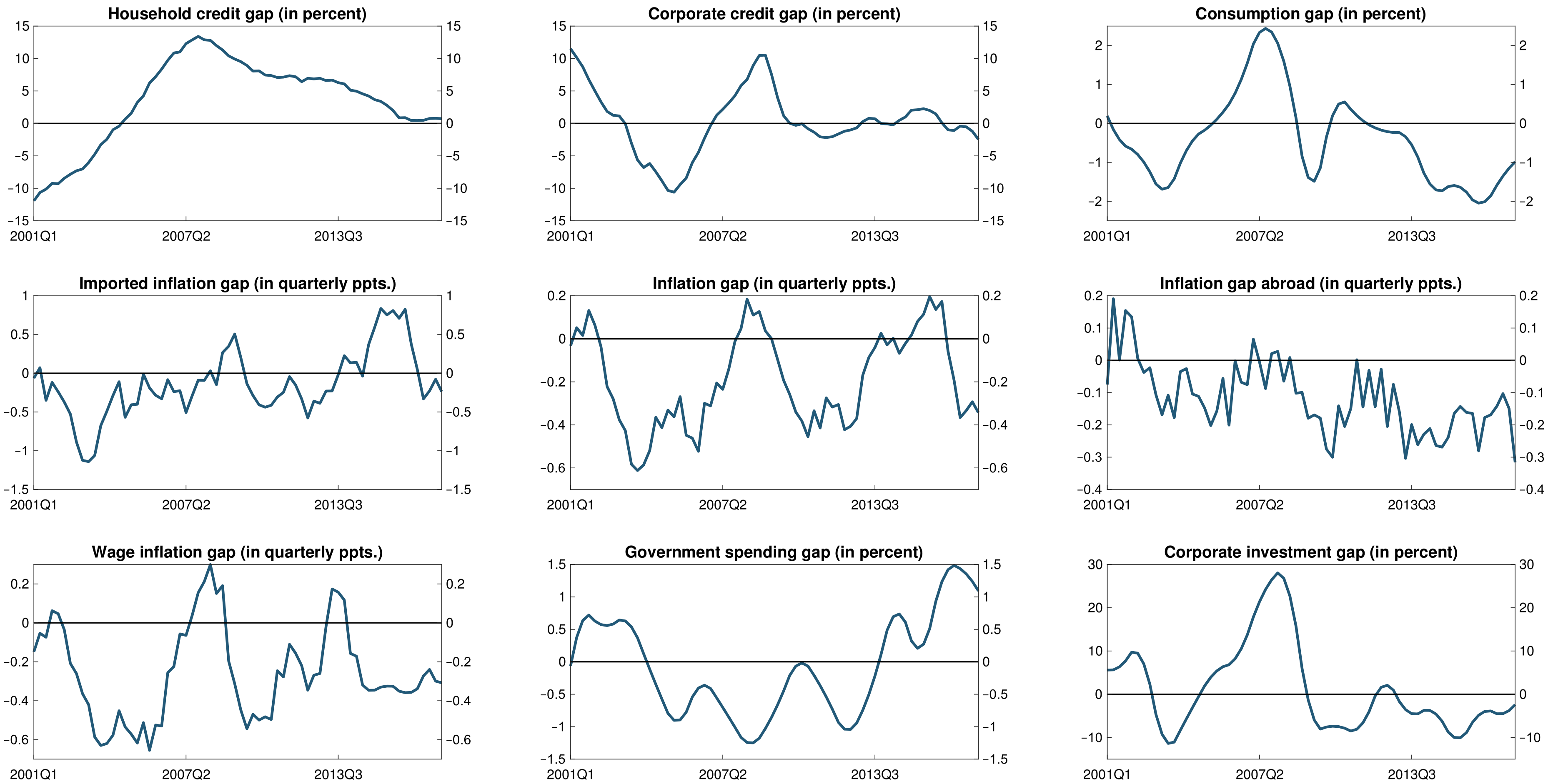

Figure 20: Observable variables, gaps.

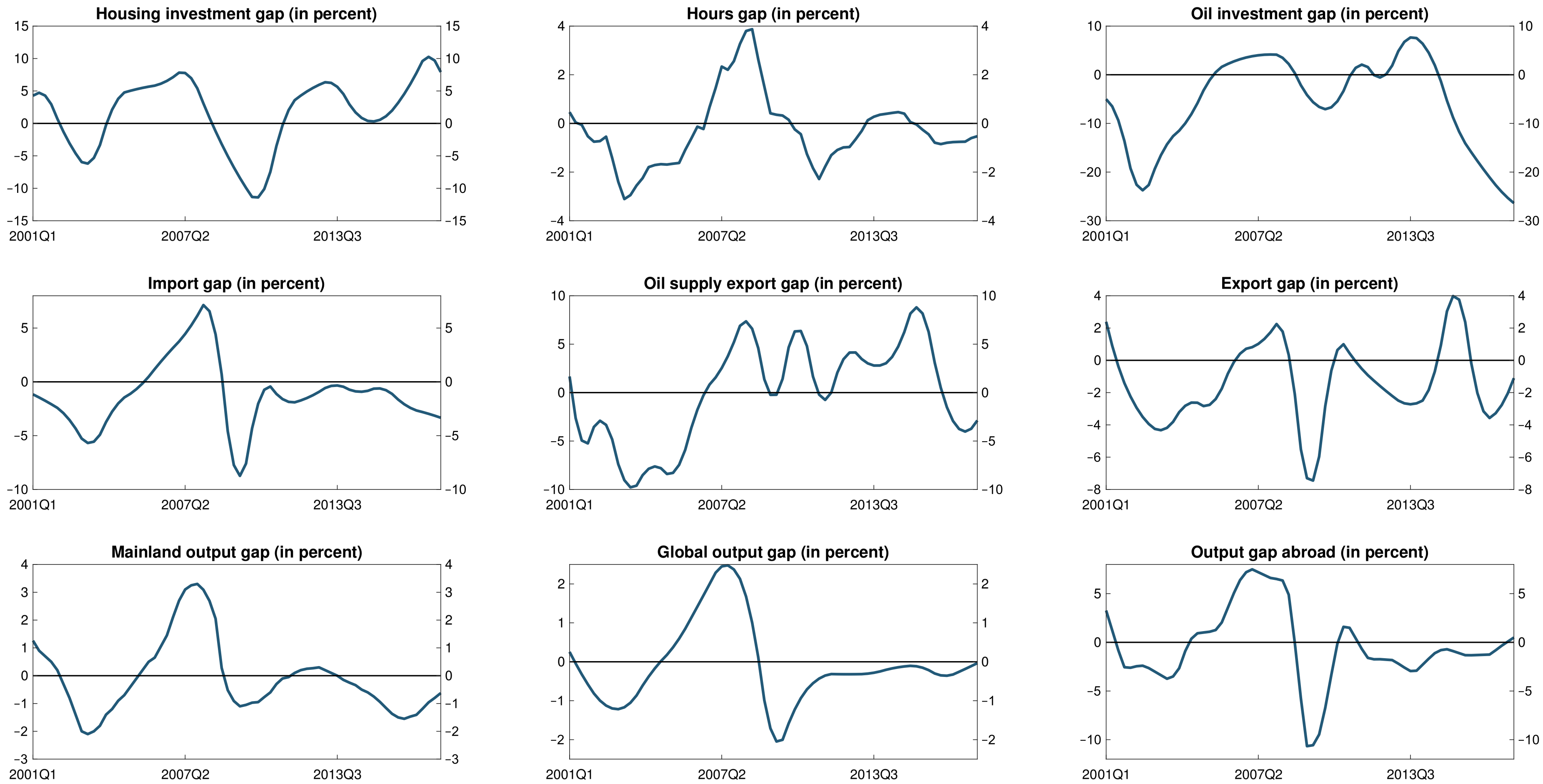

Figure 20: Observable variables, gaps. *Cont. cont.*

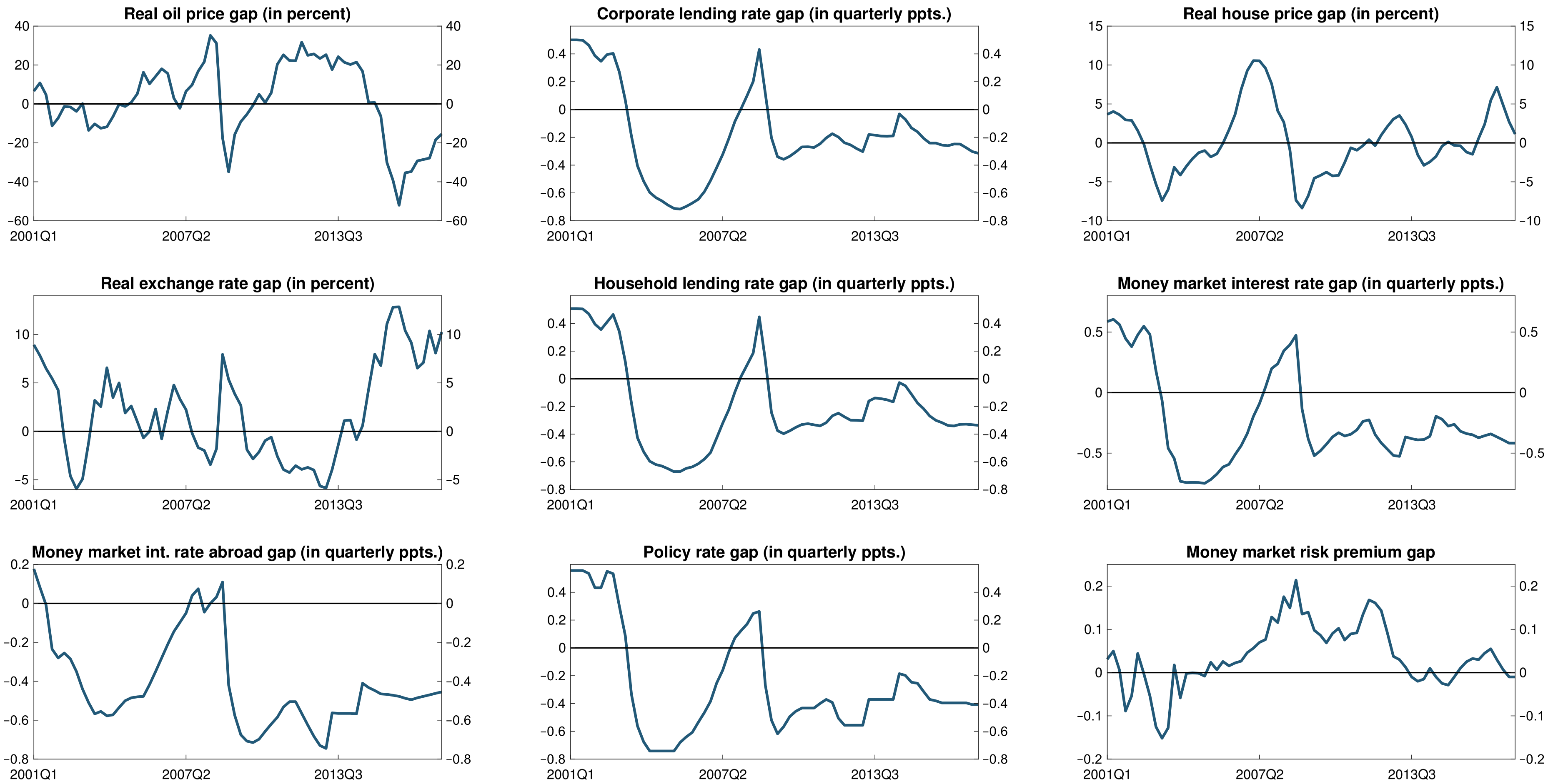

Figure 20: Observable variables, gaps. *Cont. cont.*

B Macroeconomic aggregates

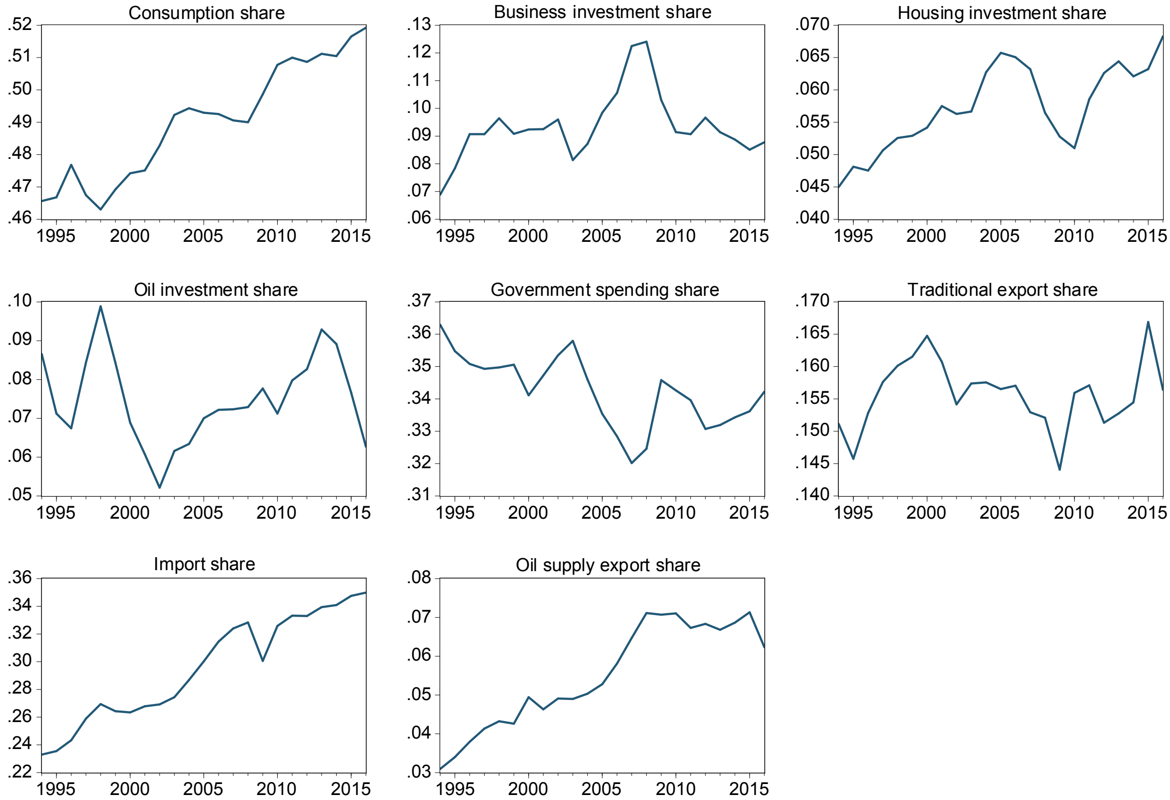

Figure 21: Macroeconomic aggregates, 1994-2016. Share of mainland GDP.

C List of parameters

Table 8: Dynamic parameters

Parameter	Value	Description
Households		
α^h	0.9959	Parameter governing the dynamics of the amortization rate for households
κ^h	1.0487	Parameter governing the dynamics of the amortization rate for households
b^{sa}	0.6393	Share of households with backward-looking expectations regarding house prices
b^c	0.9384	Habit persistence in consumption
b^d	0.4813	Habit persistence in deposits
β	0.99	Discount factor
b^h	0.9867	Habit persistence in housing services
b^l	0.5862	Habit persistence in leisure
δ^H	0.0228	Depreciation rate for housing capital
λ^{sa}	0.9495	Degree of how backward-looking agents are while forming house price expectations
ϕ^W	666.92	Cost of changing wages
z^d	0.1889	Deposit preferences
ζ	3	The inverse of the Frisch elasticity of labor supply
Intermediate goods sector		
α	0.256	Share of capital used in intermediate-goods production
ϕ^{PM^*}	285.60	Cost of changing export prices in foreign currency
ϕ^{PQ}	669	Costs of changing domestic prices
θ^{F*}	6	Elasticity of substitution between exported goods
ξ	0.929	Elasticity of substitution between capital and labor
Final goods		
μ	0.5	Elasticity of substitution between domestic and imported goods
Entrepreneurs		
α^e	0	Parameter governing the dynamics of the amortization rate for entrepreneurs
κ^e	0.9977	Parameter governing the dynamics of the amortization rate for entrepreneurs
ϕ_u	0.2192	Cost of changing the utilization rate for entrepreneurs
Capital producers		
δ	0.0108	Depreciation rate of capital
ϕ_{I1}	12.5432	Cost of changing business investment from its steady-state value
ϕ_{I2}	165.6624	Cost of changing business investment from the previous period's value
Housing sector		
ϕ_{H1}	60.7278	Cost of changing housing investment from its steady-state value
ϕ_{H2}	199.6549	Cost of changing housing investment from the previous period's value
Banking sector		
χ_c	10	Cost of deviating from the target capital-to-assets ratio
χ_o	0.0046	Fixed operational cost of banks (spread btw wholesale lending rate and money market rate)
δ^b	0.0161	Fraction of bank capital that is paid as dividends to shareholders
ϕ^B	0.0016	Elasticity of interest rate risk premium w.r.t. net foreign assets
ϕ^D	0.0732	Adjustment costs for changing deposit rate
ϕ^e	18.5013	Adjustment costs for changing business loan rate
ϕ^F	18.3597	Adjustment costs for changing household loan rate
ϕ^S	0	Elasticity of interest rate risk premium w.r.t. real exchange rate
θ^D	7.007	Elasticity of substitution between household deposits
ς^h	0.4	Risk weight on loans to households
ς^e	0.8	Risk weights on loans to households
Oil sector		
α_l	0.28	Share of labor used in oil supply goods production
α_{o*}	0.15	Foreign oil extractor's share of oil supply goods from home country in production

α_o	0.55	Share of rigs used in oil production
α_q	0.69	Share of final goods used in oil supply goods production
δ_O	0.021	Depreciation rate of oil rigs
γ^O	0.0336	Cost of changing utilization rate for oil extractors (first)
ϕ^{uf}	17.7955	Cost of changing utilization rate for oil extractors (second)
ϕ^{PR}	1245.6	Cost of adjusting oil supply goods prices in the domestic market
ϕ^{PR^*}	1723.1	Cost of adjusting oil supply goods prices in the foreign market
ϕ^{RI}	8.2151	Cost of changing oil investment
ρ_{G_F}	0.0501	The fraction of transfer from GPFG to banking sector
θ^R	400	Elasticity of substitution between oil supply goods domestically
θ^{R^*}	5	Elasticity of substitution between oil supply goods for export
Z_O	1	Oil extraction productivity
Z_R	1	Oil supply productivity
Foreign sector		
α^{P*}	0.1497	Parameter governing how expected inflation affects current inflation of trading partners
α^{GLOB}	0.1	Weight of trading partner's output gap in global output gap
α^{Y*}	0.0462	Parameter governing how trading partners' output affects current inflation of trading partners
β^O	0.2026	Parameter governing how expected real oil price affects current real oil price
β^*	0.999	Discount factor abroad
κ^O	4.0027	Parameter governing how global output gap affects real oil price
λ^{YNTP}	0.9258	Persistence of non-trading partners output gap
μ^*	0.5	Foreigners' elasticity of substitution between foreign and exported goods
ω^{P*}	1.4606	Response coefficient to inflation in the Taylor rule for trading partners
ω^{R*}	0.8414	Interest rate smoothing in the Taylor rule for trading partners
ω^{Y*}	0.04	Response coefficient to output in the Taylor rule for trading partners
ϕ^{P*}	0.8862	Persistence of trading partners' inflation process
ϕ^{OP*}	0.0006	Parameter governing how real oil price affects trading partners' inflation
ϕ^{PM}	830.10	Cost of changing prices of imported goods
ϕ^{ONTP}	0.0012	Parameter governing how real oil price affects non-trading partners' output gap
ϕ^{YNTP}	0.0114	Parameter governing how trading partners' output gap affects non-trading partners' output gap
ϕ^{Y*}	0.6146	Persistence of trading partners' output gap
ϕ^{O*}	0.0048	Parameter governing how real oil price affects trading partners' output gap
ϕ^{YNTP*}	1.0994	Parameter governing how non-trading partners' output gap affects trading partners' output gap
ψ^{R*}	0.7569	Parameter governing how foreign real interest rate affects trading partners' output gap
θ^F	6	Elasticity of substitution between imported goods
Monetary policy		
β_p	0.99	Discount factor of the central bank
λ_{dr}	0.4	Weight on the annualized policy rate change in the loss function
λ_{lr}	0.02	Weight on the annualized interest rate gap in the loss function
λ_y	0.3	Weight on the output gap in the loss function
ω_P	0	Response coefficient to inflation in the mimicking rule
ω_{P1}	0.2921	Response coefficient to future expected inflation in the mimicking rule
ω_{PREM}	0	Response coefficient to money market premium in the mimicking rule
ω_R	0.6663	Interest rate smoothing in the mimicking rule
ω_{RF}	0	Response coefficient to foreign interest rate in the mimicking rule
ω_S	0.0159	Response coefficient to real exchange rate in the mimicking rule
ω_W	0.8705	Response coefficient to wage inflation in the mimicking rule
ω_Y	0.2417	Response coefficient to output in the mimicking rule

Table 9: Shock-related parameters

Parameter	Value	Description
Persistence parameters		
λ_B	0.737	Exchange rate risk premium shock
λ_G	0.9145	Government spending shock
λ_h	0.6938	Housing preferences shock
λ_I	0.6457	Shock to business investment adjustment costs
λ_{IH}	0.8608	Shock to housing investment adjustment costs
λ_{inf}	0.75	Monetary policy shock (Optimal policy)
λ_{IOIL}	0.834	Shock to oil investment technology
λ_{z^L}	0.804	Temporary productivity shock in the intermediate goods sector
λ_{MC*}	0.0965	Shock to marginal costs abroad
λ_{ν}	0.9336	Import demand shock
λ_{ν_*}	0.9238	Export demand shock
λ_{PO*}	0.8736	Real oil price (supply) shock
$\lambda_{\phi^{ent}}$	0.9102	Shock to LTV ratio of entrepreneurs
λ_{ϕ}	0.783	Shock to LTV ratio of households
λ_{prem}	0.8168	Shock to money market premium
λ_{ψ}	0.2797	Wage markup shock
λ_{RN3M}	0.7919	Monetary policy shock (Taylor rule)
λ_{R*}	0.3222	Monetary policy shock (trading partners)
λ_{θ^e}	0.9641	Markup shock to lending rate for loans to entrepreneurs
λ_{θ^H}	0.4347	Price markup shock
$\lambda_{\theta^{H*}}$	0.0523	Trading partners' price markup shock
$\lambda_{\theta^{IH}}$	0.8895	Markup shock to lending rate for loans to households
λ_u	0.7248	Consumption preference shock
λ_{U*}	0.7825	Trading partners' demand shock
λ_{wedge}	0.838	Inventory shock
λ_{YO*}	0.7458	Shock to the oil production abroad
St.dev. (multiplied by 100)		
σ_B	0.6178	Exchange rate risk premium shock
σ_G	0.3806	Government spending shock
σ_h	28.6767	Housing preferences shock
σ_I	23.0179	Shock to business investment adjustment costs
σ_{IH}	2.575	Shock to housing investment adjustment costs
σ_{inf}	1	Monetary policy shock (Optimal policy)
σ_{IOIL}	2.6119	Shock to oil investment technology
σ_{z^L}	0.598	Temporary productivity shock in the intermediate goods sector
σ_{MC*}	34.629	Shock to marginal costs abroad
σ_{ν}	0.4277	Import demand shock
σ_{ν_*}	4.2376	Export demand shock
σ_{PO*}	7.9181	Real oil price (supply) shock
$\sigma_{\phi^{ent}}$	2.5902	Shock to LTV ratio of entrepreneurs
σ_{ϕ}	25.4232	Shock to LTV ratio of households
σ_{prem}	0.0372	Shock to money market premium
σ_{ψ}	63.3097	Wage markup shock
σ_{RN3M}	0.0302	Monetary policy shock (Taylor rule)
σ_{R*}	0.0841	Monetary policy shock (Trading partners)
σ_{θ^e}	84.8579	Markup shock to lending rate for loans to entrepreneurs
σ_{θ^H}	20.1448	Price markup shock
$\sigma_{\theta^{H*}}$	0.8327	Trading partners' price markup shock
$\sigma_{\theta^{IH}}$	167.9416	Markup shock to lending rate for loans to households
σ_u	3.0209	Consumption preference shock
σ_{U*}	1.1147	Trading partners' demand shock
σ_{wedge}	0.1844	Inventory shock
σ_{YNTP}	0.1828	Global demand shock
σ_{YO*}	3.4093	Shock to oil production abroad
Other		
ρ_{ffm}	0.5269	Oil price-induced effects on wage bargaining

Table 10: Steady-state parameters

Parameter	Value	Description
π_{ss}	1.0062	Gross inflation (quarterly)
π^*_{ss}	1.005	Gross foreign inflation (quarterly)
π^h_{ss}	1.0113	Relative house price trend inflation (quarterly)
π^z_{ss}	1.0025	Trend productivity growth (quarterly)
G_{ss}	1.5484	Government spending as a share of output
$z_{inf,ss}$	1	Inflation target shock
$M_{O*,ss}$	0.11	Oil supply goods export volume
MC^*_{ss}	1	Foreign marginal cost
γ^b_{ss}	0.136	Bank capital-to-risk-weighted assets ratio target
CCB^b_{ss}	0.02	Countercyclical capital buffer
$Y_{NAT*,ss}$	1	Foreign output
ν_{ss}	0.65	Share of domestic goods in final goods production
ν^*_{ss}	0.212	Share of domestic goods abroad (export demand)
O_{ss}	0.1011	Oil in the ground
P^{O*}_{ss}	1	Real oil price
ϕ^{ent}_{ss}	0.9917	Collateral coefficient governing LTV ratio for entrepreneurs
ϕ_{ss}	0.1095	Collateral coefficient governing LTV ratio for households
ψ_{ss}	2.5	Elasticity of substitution between differentiated labor
R^*_{ss}	1.005	Money market interest rate abroad (quarterly)
θ^e_{ss}	13.95	Elasticity of substitution between loans to entrepreneurs
θ^H_{ss}	6	Elasticity of substitution between intermediate goods
θ^{IH}_{ss}	29.2846	Elasticity of substitution between loans to households
$Z_{B,ss}$	0	Risk premium shock
z^h_{ss}	0.523	Housing preference shock
$z_{I,ss}$	1	Shock to business investment adjustment costs
$z_{IH,ss}$	1	Shock to housing investment adjustment costs
$Z_{IOIL,ss}$	1	Shock to oil investment specific technology
z^L_{ss}	1	Temporary productivity shock in the intermediate goods sector
$Z_{prem,ss}$	1.0012	Shock to money market risk premium
z^u_{ss}	2.6315	Consumption preference shock
$z_{x,ss}$	1.0772	Inventory shock

D List of shock equations

There are 26 shocks in the model.[63] All (except the global demand shock) are assumed to be AR(1) processes, where the λ's govern the persistence of the processes (i.e. autocorrelation), the ϵ's are standard normally distributed white noise innovations and the σ's are parameters governing the standard deviations of the respective shocks. Most shock processes are modeled as log-deviations from their steady state.

Exogenous exchange rate risk premium shock:

$$z_t^B = (1-\lambda_B)z_{ss}^B + \lambda_B z_{t-1}^B + \epsilon_{B,t}\sigma_B. \tag{119}$$

Government expenditure shock:

$$\log(G_t) = (1-\lambda_G)\log(G_{ss}) + \lambda_G \log(G_{t-1}) + \epsilon_{G,t}\sigma_G. \tag{120}$$

Shock to households' preferences for housing:

$$\log(z_t^h) = (1-\lambda_h)\log(z_{ss}^h) + \lambda_h \log(z_{t-1}^h) + \epsilon_{h,t}\sigma_h. \tag{121}$$

Business investment adjustment cost shock:

$$\log(z_{I,t}) = (1-\lambda_I)\log(z_{I,ss}) + \lambda_I \log(z_{I,t-1}) + \epsilon_{I,t}\sigma_I. \tag{122}$$

Housing investment adjustment cost shock:

$$\log(z_{IH,t}) = (1-\lambda_{IH})\log(z_{IH,ss}) + \lambda_{IH} \log(z_{IH,t-1}) + \epsilon_{IH,t}\sigma_{IH}. \tag{123}$$

Oil investment adjustment cost shock:

$$\log(Z_{IOIL,t}) = (1-\lambda_{IOIL})\log(Z_{IOIL,ss}) + \lambda_{IOIL} \log(Z_{IOIL,t-1}) + \epsilon_{IOIL,t}\sigma_{IOIL}. \tag{124}$$

Temporary productivity shock in the intermediate goods sector:

$$\log(z_t^L) = (1-\lambda_{z^L})\log(z_{ss}^L) + \lambda_{z^L} \log(z_{t-1}^L) + \epsilon_{z^L,t}\sigma_{z^L}. \tag{125}$$

Shock to marginal costs abroad:

$$\log(\widetilde{MC}_t^*) = (1-\lambda_{MC*})\log(MC_{ss}^*) + \lambda_{MC*} \log(MC_{t-1}^*) + \epsilon_{MC*,t}\sigma_{MC*}. \tag{126}$$

Import shock:

[63] 27 shocks are listed since monetary policy can be solved either using optimal policy or a policy rule, hence only one monetary policy shock is active at any point in time.

$$\log(\nu_t) = (1-\lambda_\nu)\log(\nu_{ss}) + \lambda_\nu \log(\nu_{t-1}) + \epsilon_{\nu,t}\sigma_\nu. \tag{127}$$

Export demand shock:

$$\log(\nu_t^*) = (1-\lambda_{\nu^*})\log(\nu_{ss}^*) + \lambda_{\nu^*} \log(\nu_{t-1}^*) + \epsilon_{\nu^*,t}\sigma_{\nu^*}. \tag{128}$$

Shock to a parameter that can be mapped to the corporate loan-to-value ratio:

$$\log(\phi_t^{ent}) = (1-\lambda_{\phi^{ent}})\log(\phi_{ss}^{ent}) + \lambda_{\phi^{ent}} \log(\phi_{t-1}^{ent}) + \epsilon_{\phi^{ent},t}\sigma_{\phi^{ent}}. \tag{129}$$

Shock to a parameter that can be mapped to the household loan-to-value ratio:

$$\log(\phi_t) = (1-\lambda_\phi)\log(\phi_{ss}) + \lambda_\phi \log(\phi_{t-1}) + \epsilon_{\phi,t}\sigma_\phi. \tag{130}$$

Shock to money market risk premium:

$$\log(z_{prem,t}) = (1-\lambda_{prem})\log(z_{prem,ss}) + \lambda_{prem} \log(z_{prem,t-1}) + \epsilon_{prem,t}\sigma_{prem}. \tag{131}$$

Shock to the competition in the labor market (wage markup shock):

$$\log(\psi_t) = (1-\lambda_\psi)\log(\psi_{ss}) + \lambda_\psi \log(\psi_{t-1}) + \epsilon_{\psi,t}\sigma_\psi - \rho_{ffm}FFM_t, \tag{132}$$

where FFM_t is defined as $FFM_t = 0.75\widehat{L_{O,t}} + 0.25\widehat{P_t^{O*}}$.

Monetary policy shock (optimal policy):

$$\log(z_{inf,t}) = (1-\lambda_{rnfolio})\log(z_{inf,ss}) + \lambda_{rnfolio} \log(z_{inf,t-1}) + \epsilon_{inf,t}\sigma_{inf}. \tag{133}$$

Monetary policy shock (Taylor rule):

$$Z_{RN3M,t} = \lambda_{RN3M} Z_{RN3M,t-1} + \epsilon_{RN3M,t}\sigma_{RN3M}. \tag{134}$$

Shock to the competition in the market for the domestic good (price markup shock):

$$\log(\theta_t^H) = (1-\lambda_{\theta^H})\log(\theta_{ss}^H) + \lambda_{\theta^H} \log(\theta_{t-1}^H) + \epsilon_{\theta^H,t}\sigma_{\theta^H}. \tag{135}$$

Shock to inflation abroad (in gap-form) (trading partners' price markup shock):

$$\widehat{z_{\theta^{H*},t}} = \lambda_{\theta^{H*}} \widehat{z_{\theta^{H*},t-1}} + \epsilon_{\theta^{H*},t}\sigma_{\theta^{H*}}. \tag{136}$$

Markup shock to lending rate for loans to households:

$$\log(\theta_t^{IH}) = (1-\lambda_{\theta^{IH}})\log(\theta_{ss}^{IH}) + \lambda_{\theta^{IH}} \log(\theta_{t-1}^{IH}) + \epsilon_{\theta^{IH},t}\sigma_{\theta^{IH}}. \tag{137}$$

Markup shock to lending rate for loans to entrepreneurs:

$$\log(\theta^e_t) = (1-\lambda_{\theta^e})\log(\theta^e_{ss}) + \lambda_{\theta^e}\log(\theta^e_{t-1}) + \epsilon_{\theta^e,t}\sigma_{\theta^e}. \tag{138}$$

Shock to household preferences for consumption:

$$\log(z^u_t) = (1-\lambda_u)\log(z^u_{ss}) + \lambda_u\log(z^u_{t-1}) + \epsilon_{u,t}\sigma_u. \tag{139}$$

Inventory shock:

$$\log(z_{x,t}) = (1-\lambda_{wedge})\log(z_{x,ss}) + \lambda_{wedge}\log(z_{x,t-1}) + \epsilon_{wedge,t}\sigma_{wedge}. \tag{140}$$

Shock to output abroad, trading partners (in gap-form):

$$\widehat{z_{U*,t}} = \lambda_{U*}\widehat{z_{U*,t-1}} + \epsilon_{U*,t}\sigma_{U*}. \tag{141}$$

Shock to output abroad, non-trading partners (global demand shock) (in gap-form):

$$\widehat{z_{YNTP,t}} = \epsilon_{YNTP,t}\sigma_{YNTP}. \tag{142}$$

Oil production shock abroad:

$$\log(Y_{O*,t}) = (1-\lambda_{YO*,t})\log(Y_{O*,ss}) + \lambda_{YO*,t}\log(Y_{O*,t-1}) + \epsilon_{YO*,t}\sigma_{YO*}. \tag{143}$$

Real oil price (supply) shock (in gap-form):

$$\widehat{z_{PO*,t}} = \lambda_{PO*}\widehat{z_{PO*,t-1}} + \epsilon_{PO*,t}\sigma_{PO*}. \tag{144}$$

Monetary policy shock (trading partners) (in gap-form):

$$\widehat{z_{R*,t}} = \lambda_{R*}\widehat{z_{R*,t-1}} + \epsilon_{R*,t}\sigma_{R*}. \tag{145}$$

E Mimicking monetary policy rule

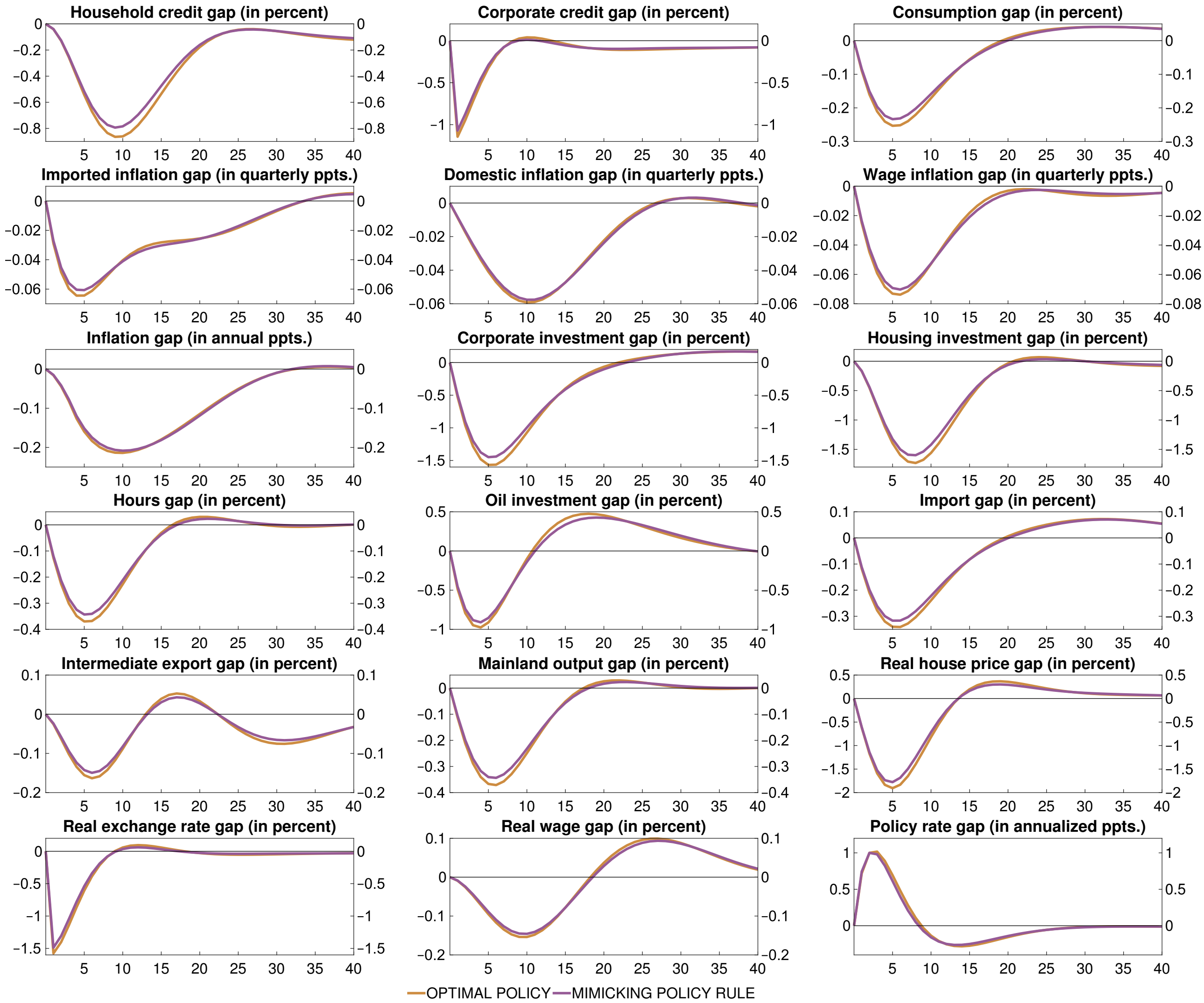

Figure 22: Impulse responses to a monetary policy shock: Optimal policy vs. mimicking policy rule (used in estimation).

F Identification plots

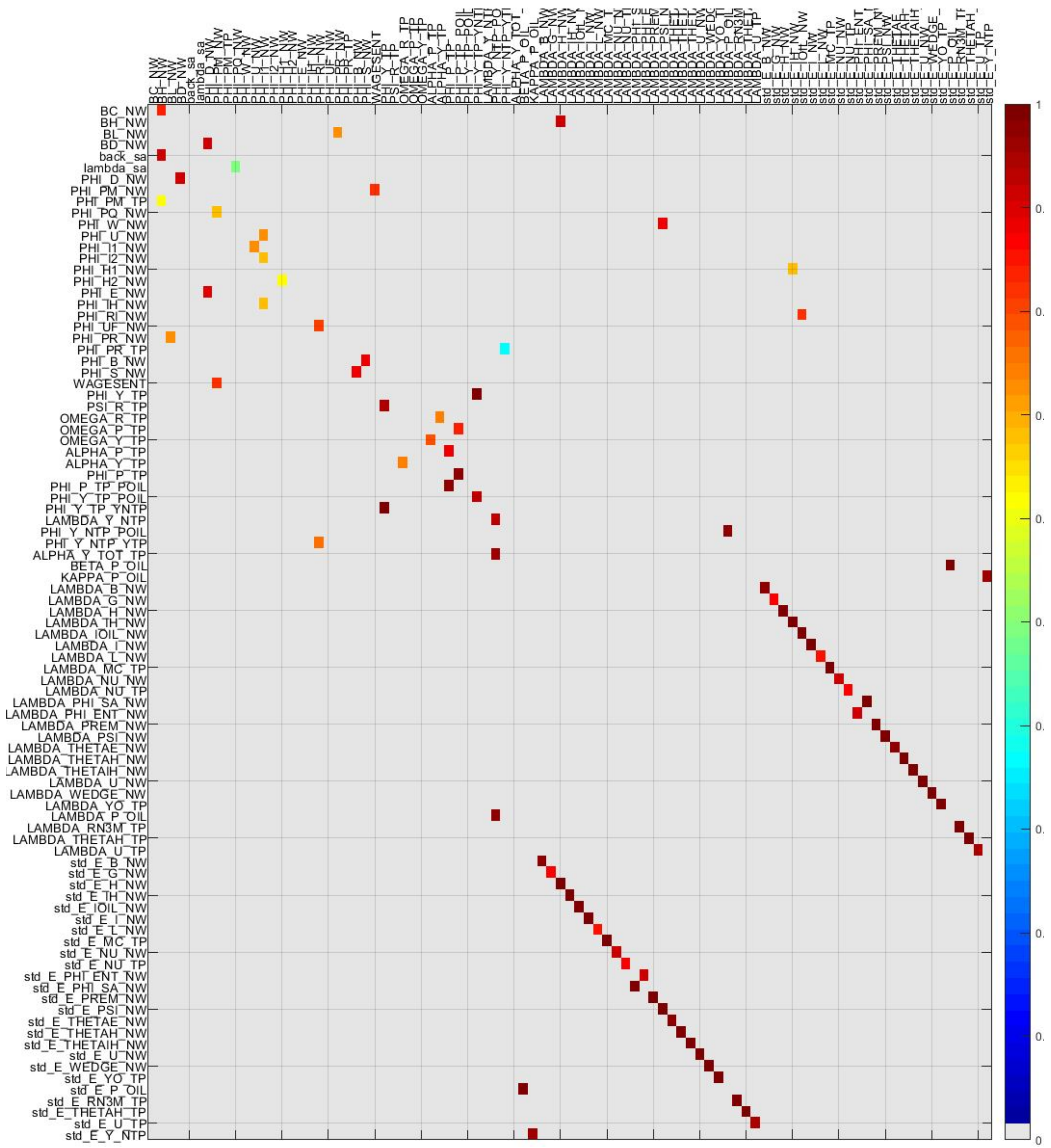

Figure 23: Collinearity pattern with 1 parameter. See main text for explanation.

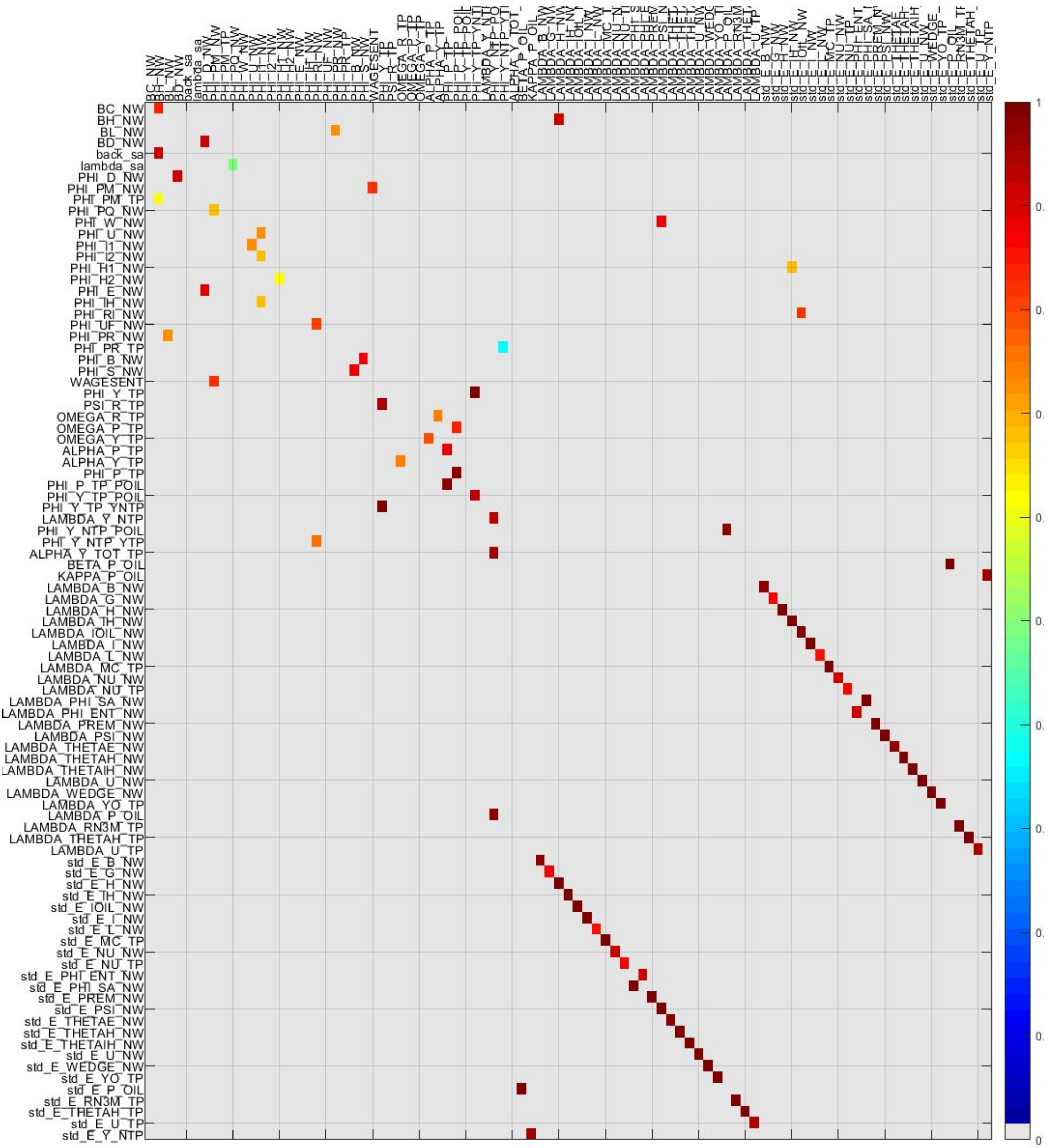

Figure 24: Collinearity pattern with 2 parameters. See main text for explanation.

G Convergence statistics: PSRF, MPSRF and auto-correlations

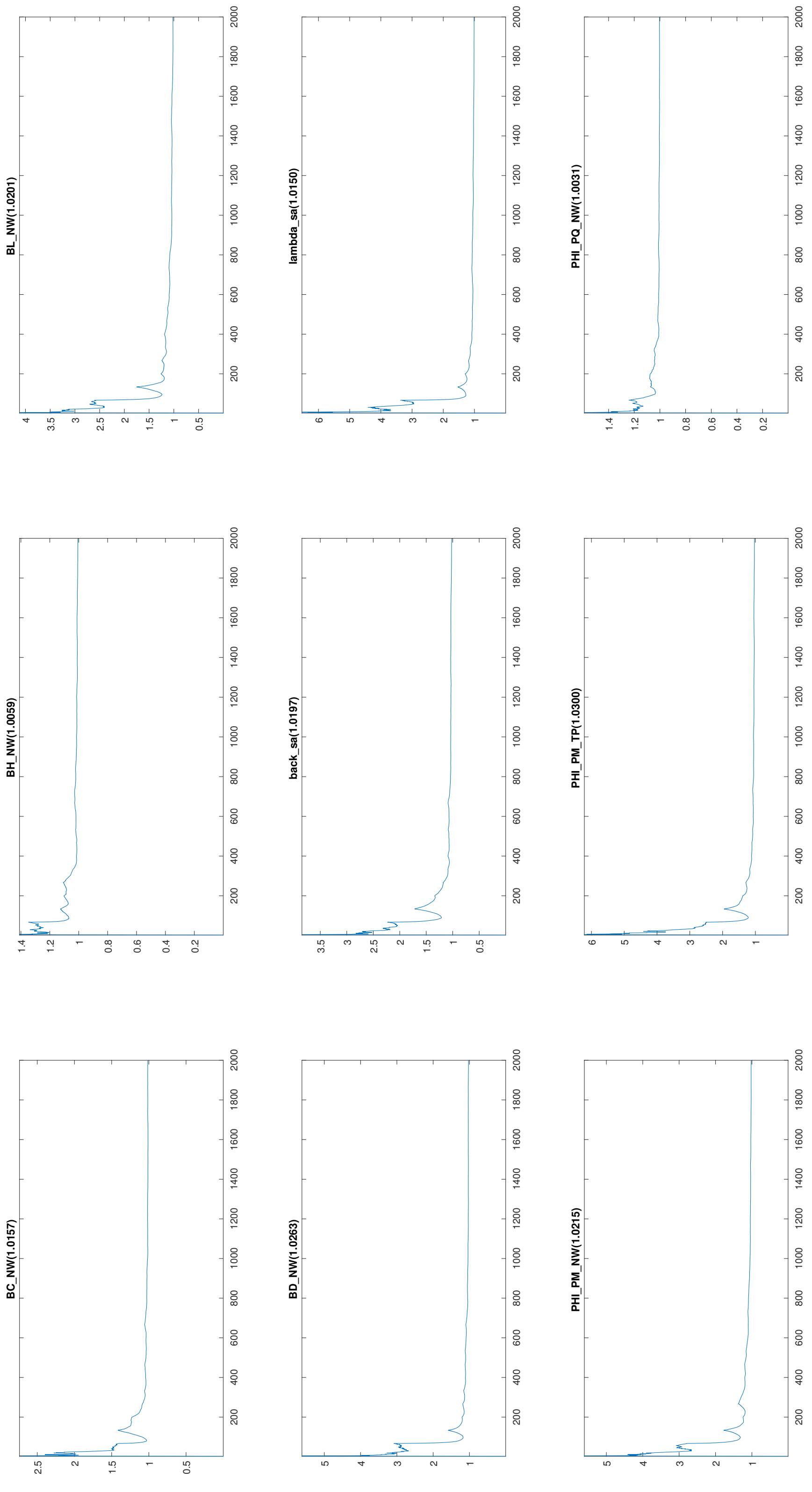

Figure 25: Potential scale reduction factor (PSRF) of estimated parameters

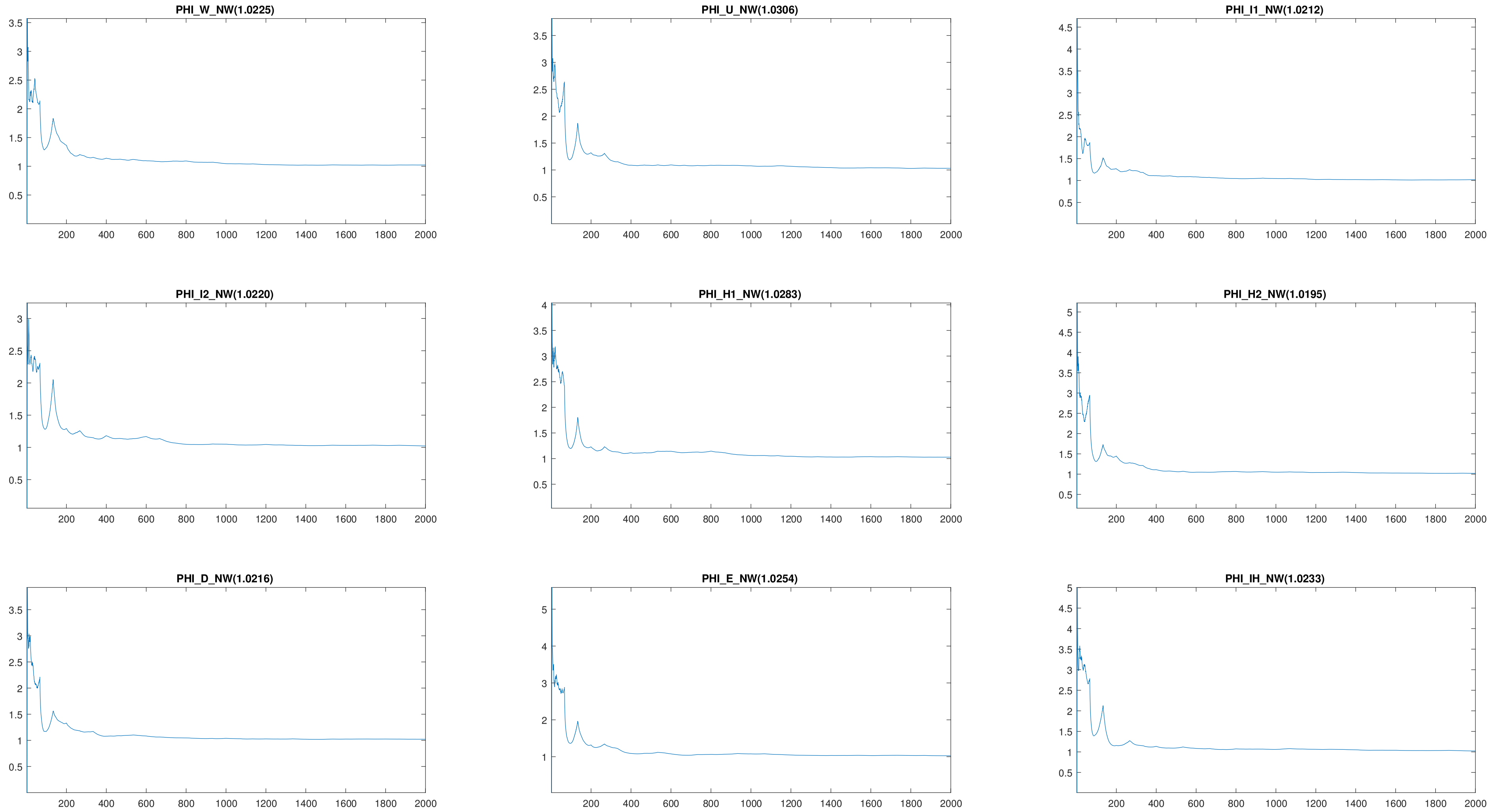

Figure 26: Potential scale reduction factor (PSRF) of estimated parameters

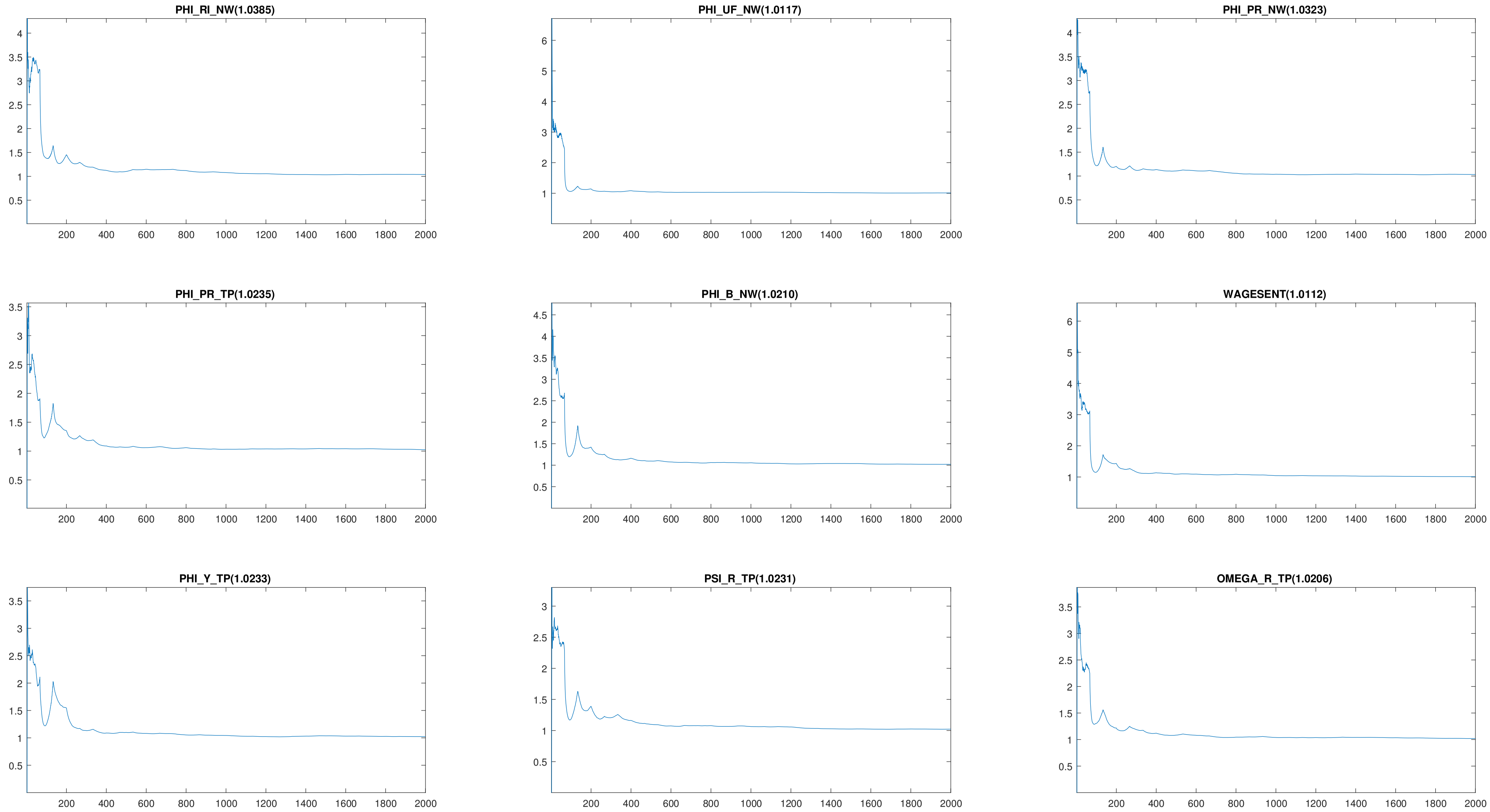

Figure 27: Potential scale reduction factor (PSRF) of estimated parameters

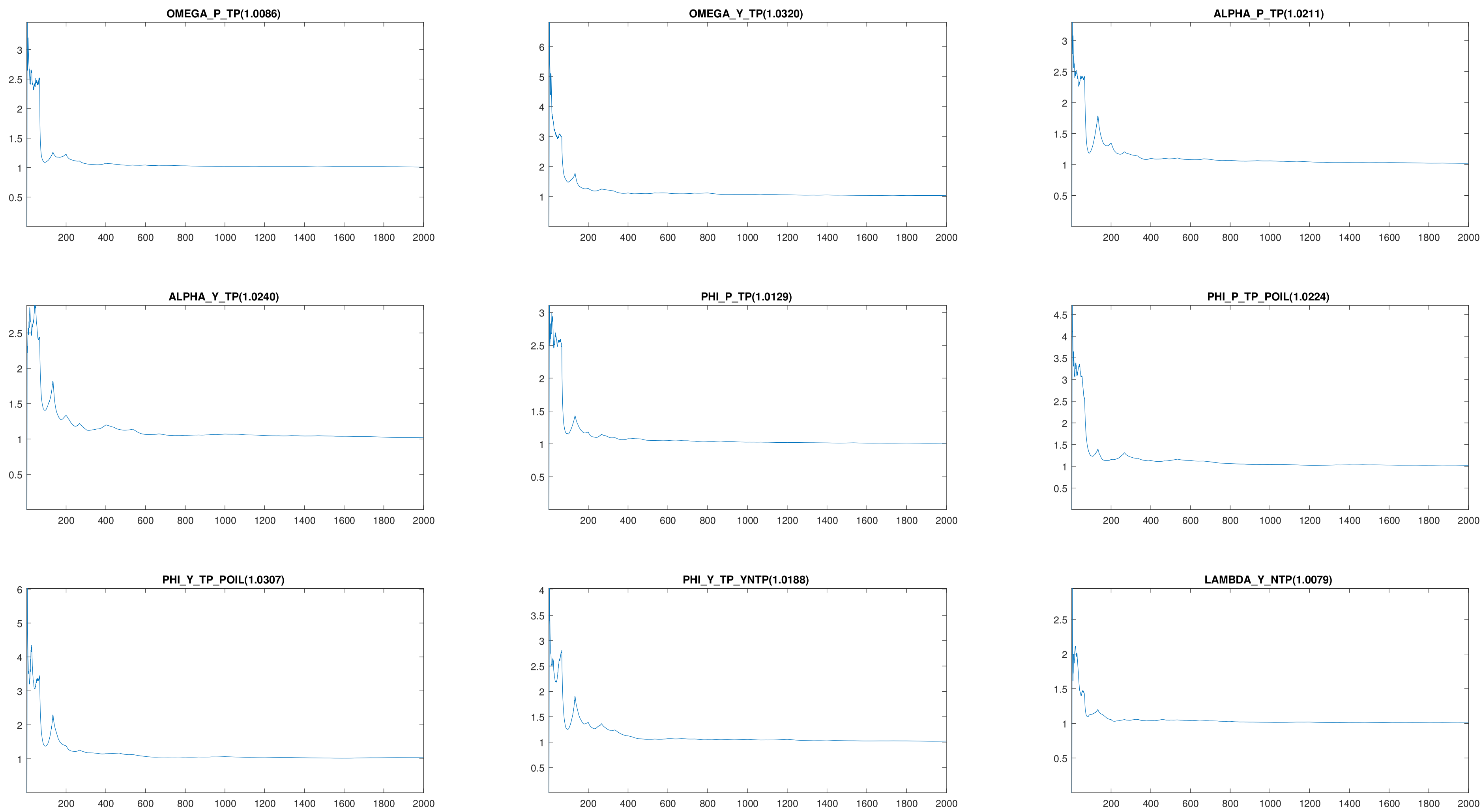

Figure 28: Potential scale reduction factor (PSRF) of estimated parameters

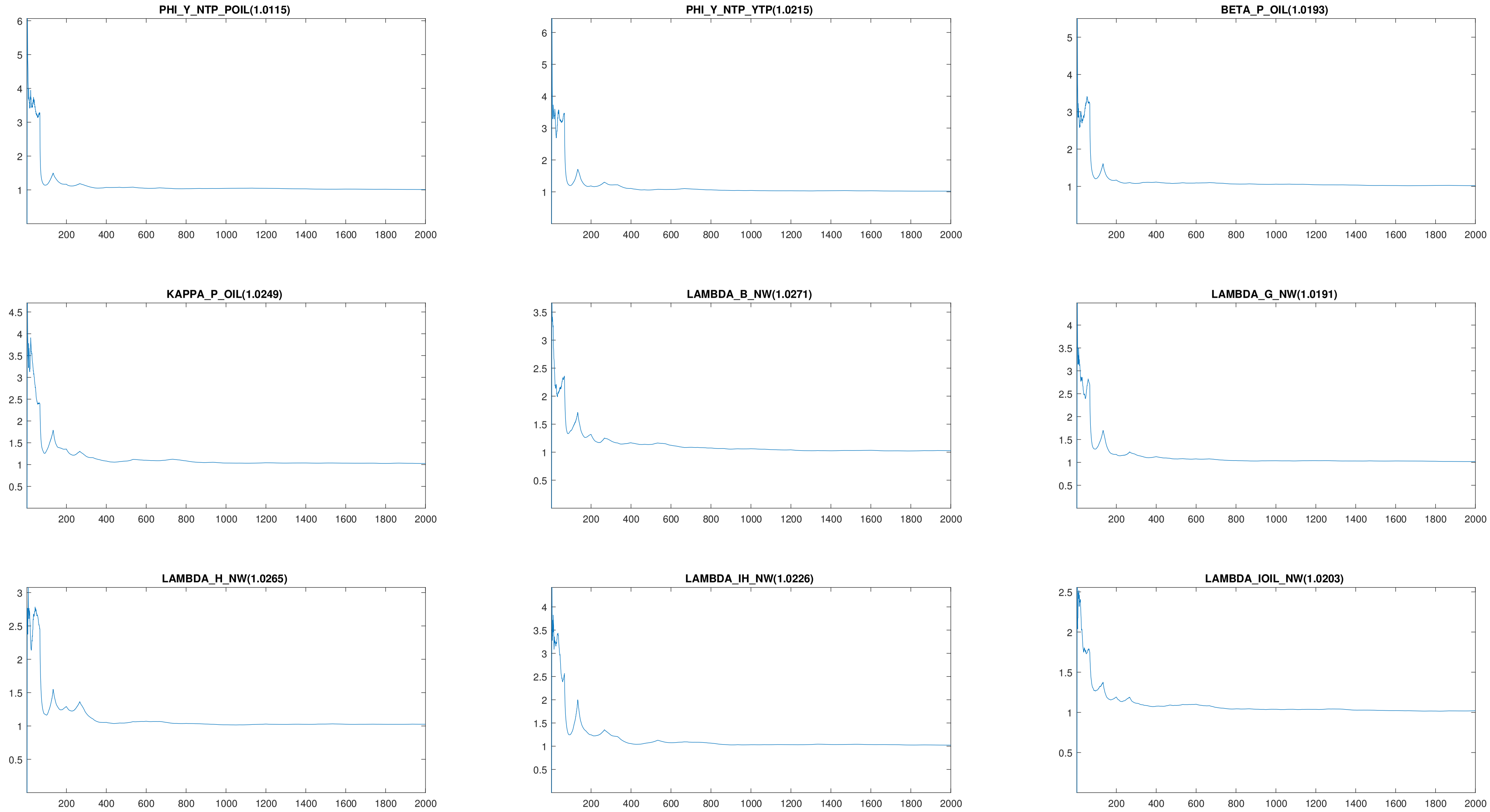

Figure 29: Potential scale reduction factor (PSRF) of estimated parameters

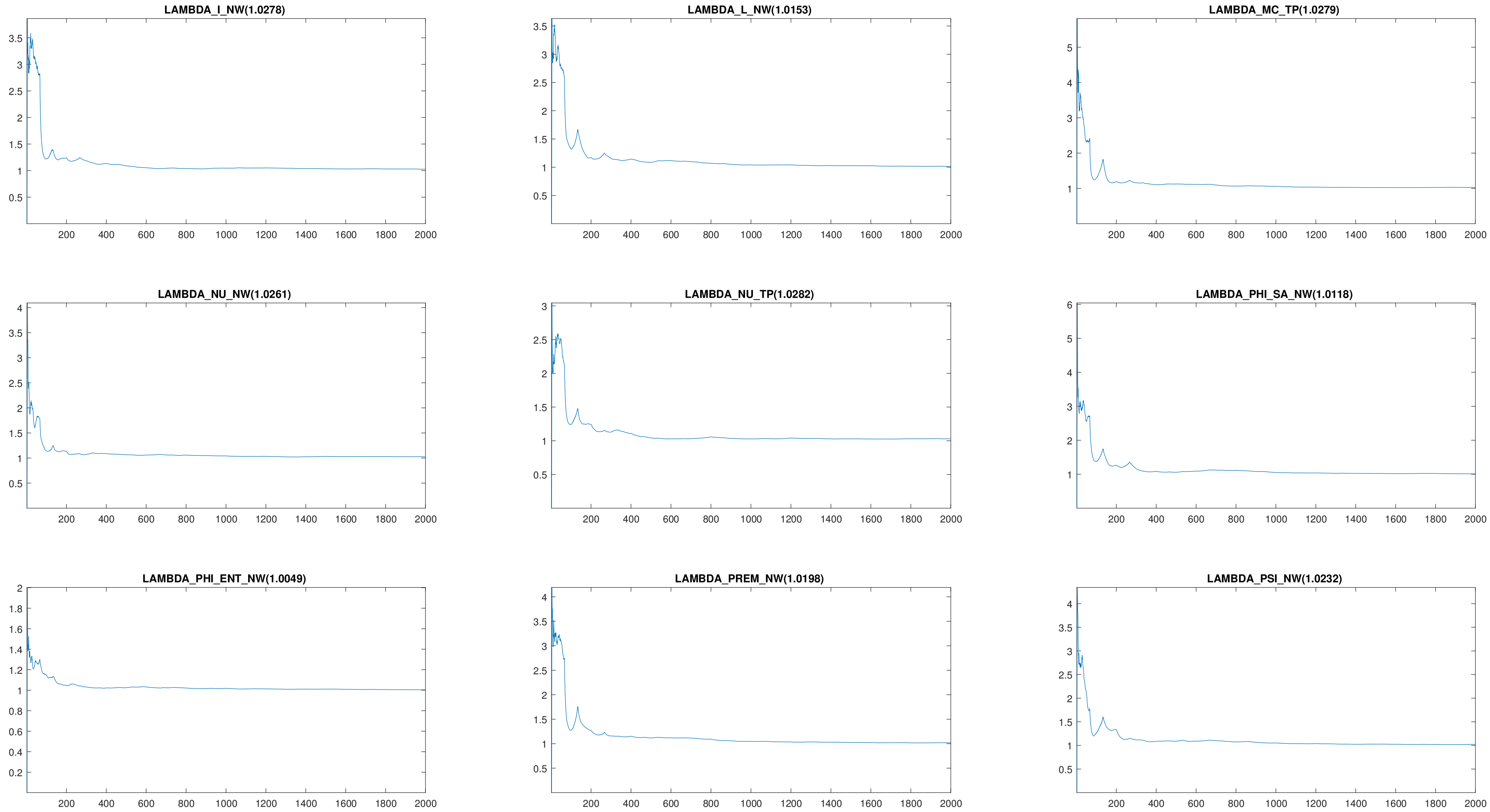

Figure 30: Potential scale reduction factor (PSRF) of estimated parameters

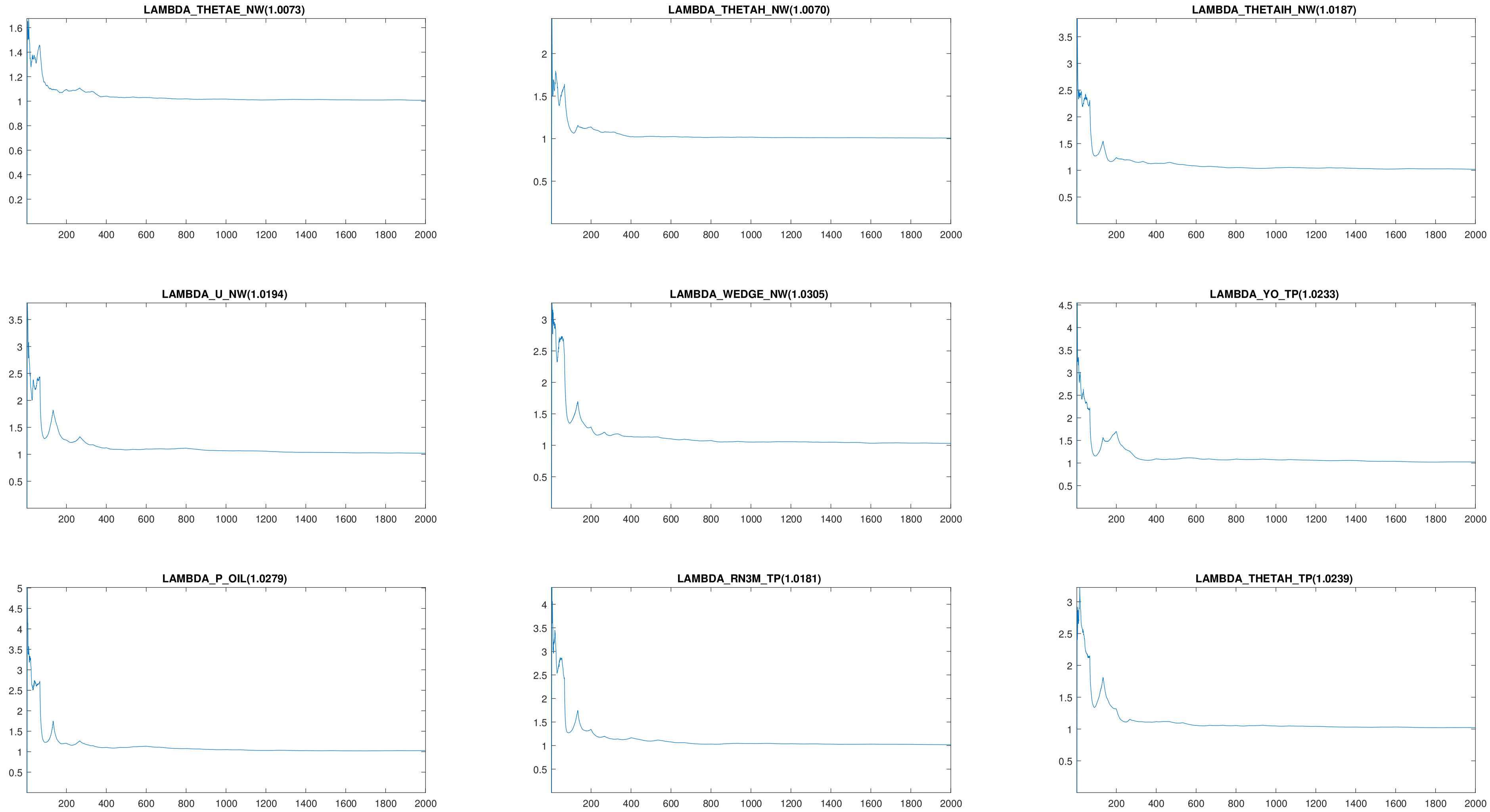

Figure 31: Potential scale reduction factor (PSRF) of estimated parameters

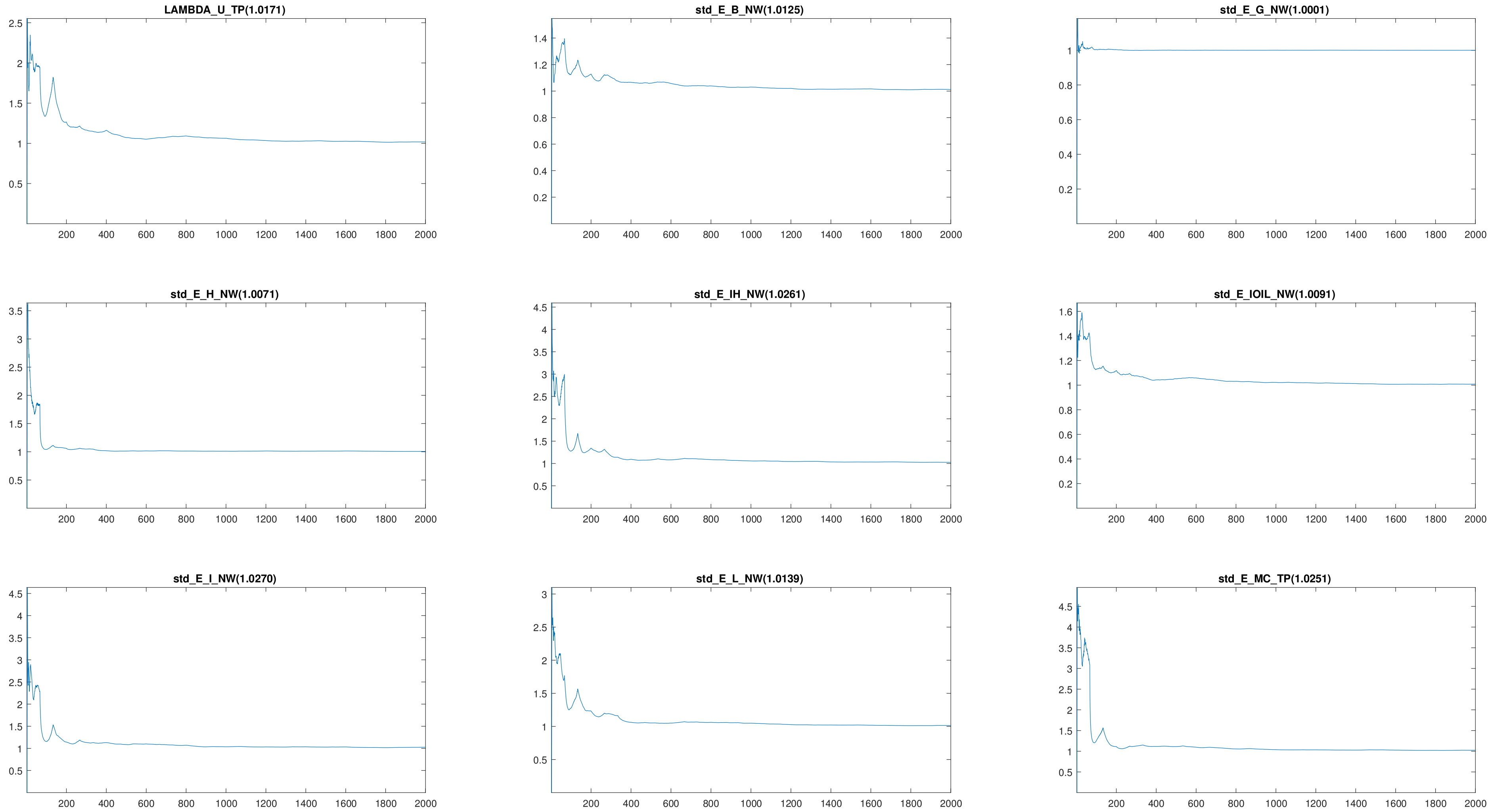

Figure 32: Potential scale reduction factor (PSRF) of estimated parameters

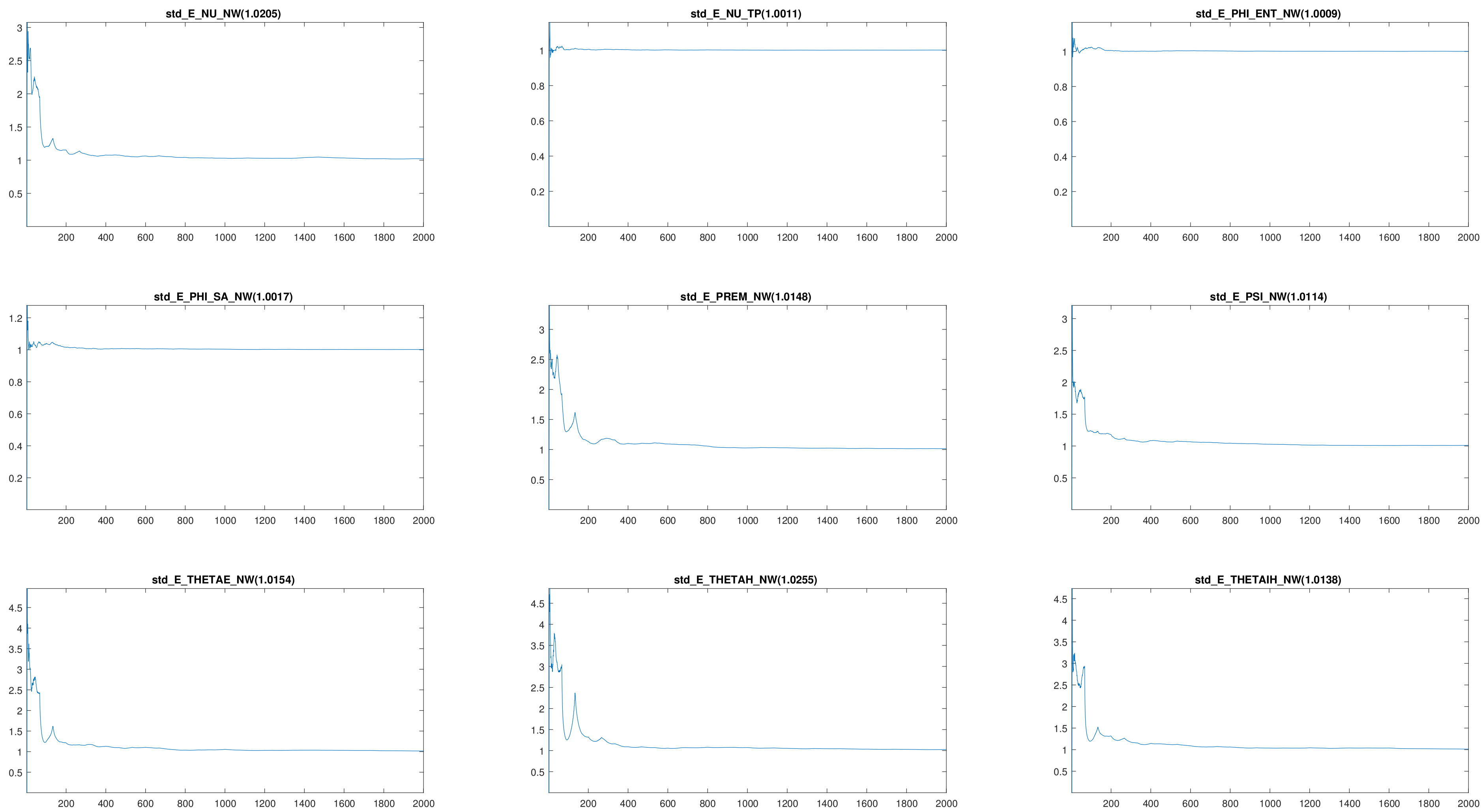

Figure 33: Potential scale reduction factor (PSRF) of estimated parameters

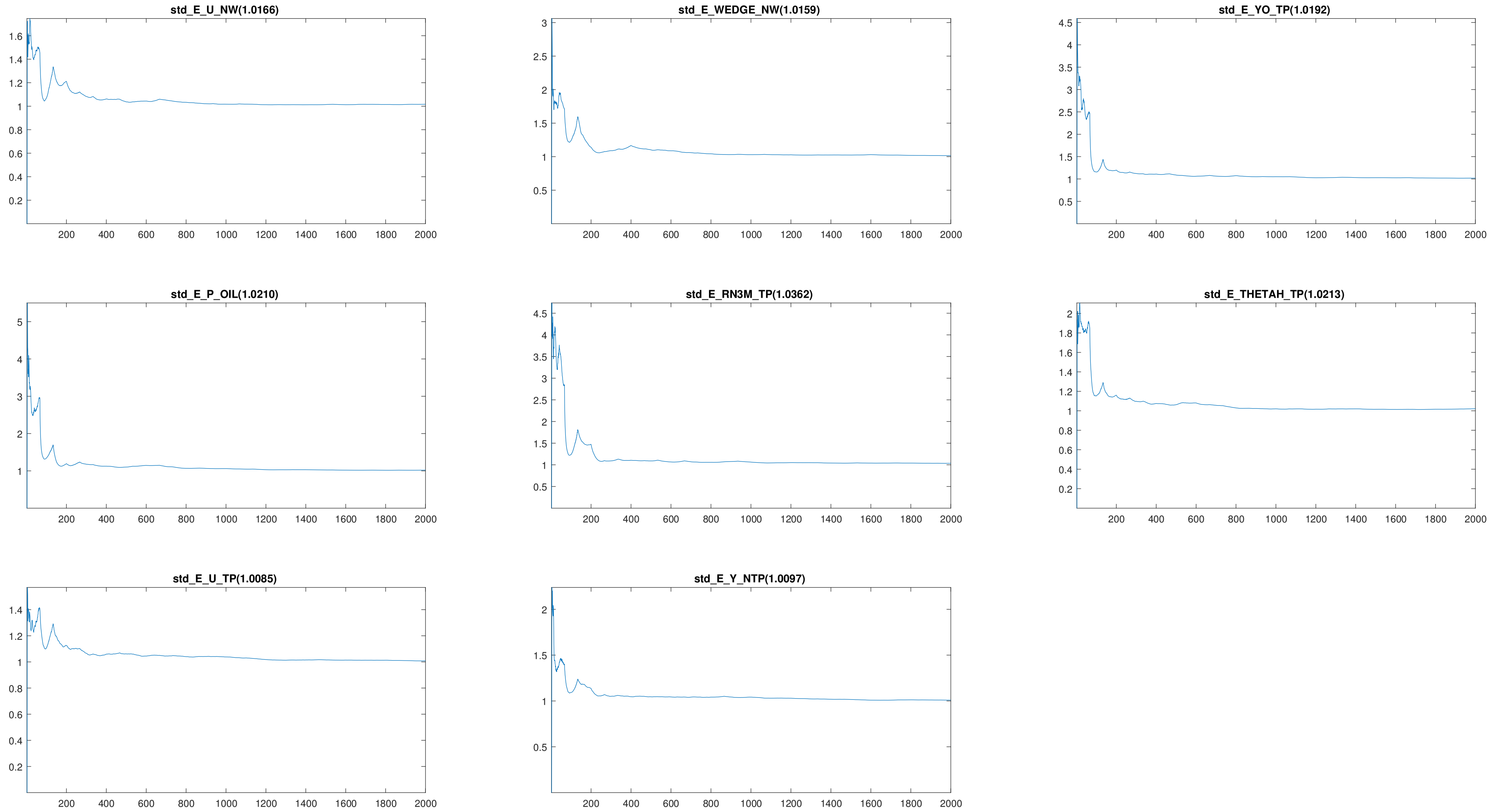

Figure 34: Potential scale reduction factor (PSRF) of estimated parameters

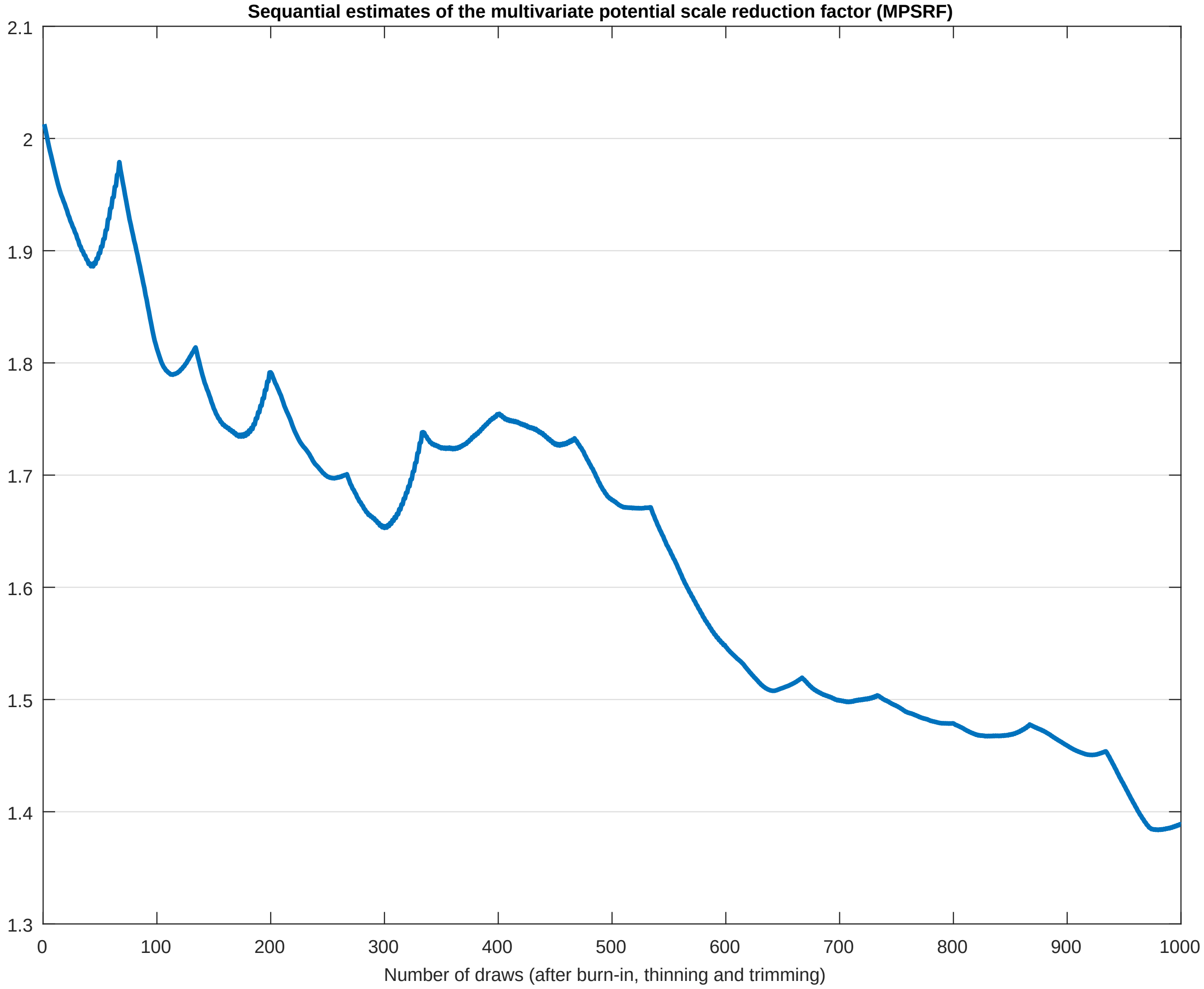

Figure 35: Multivariate potential scale reduction factor (MPSRF)

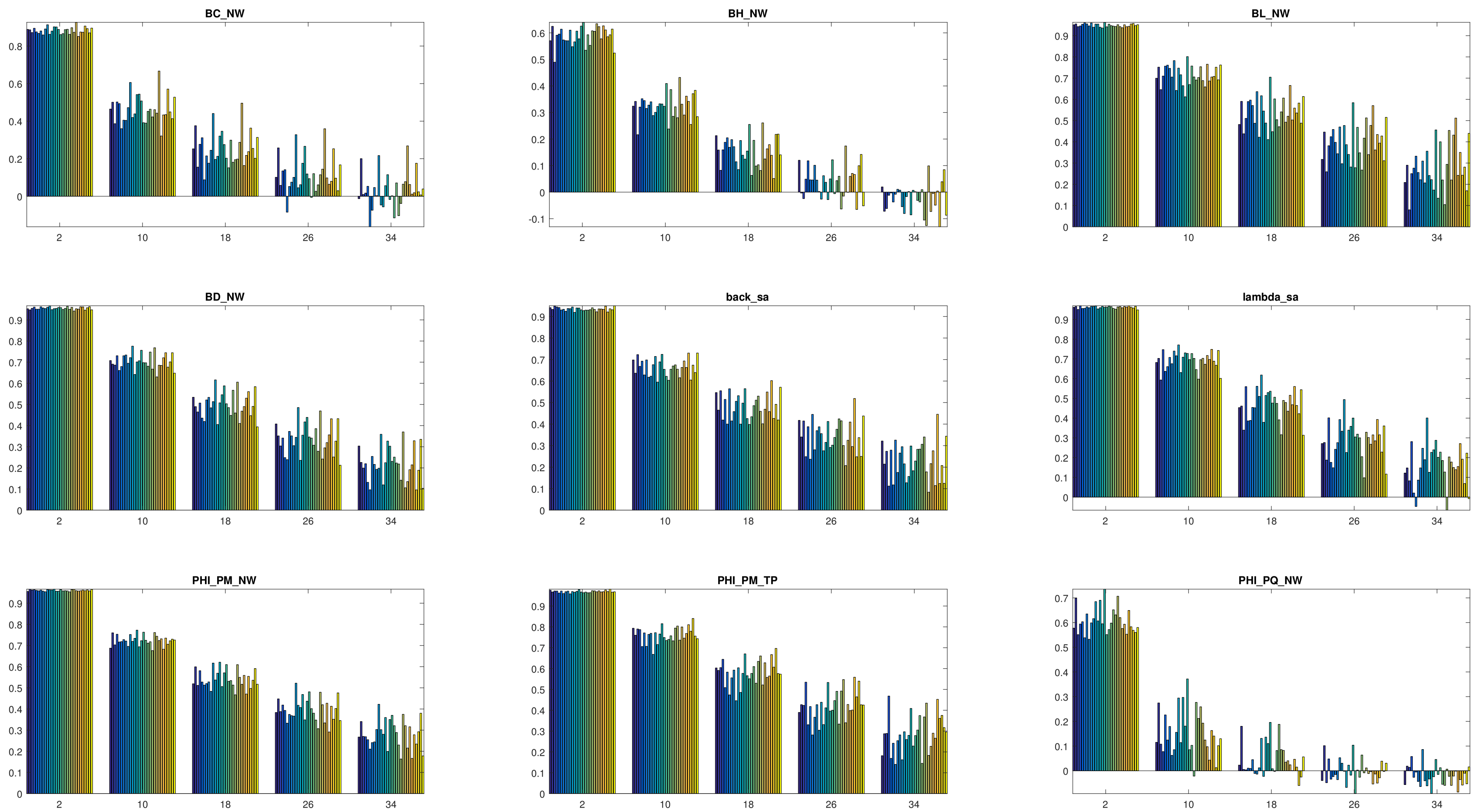

Figure 36: Autocorrelations of estimated parameters

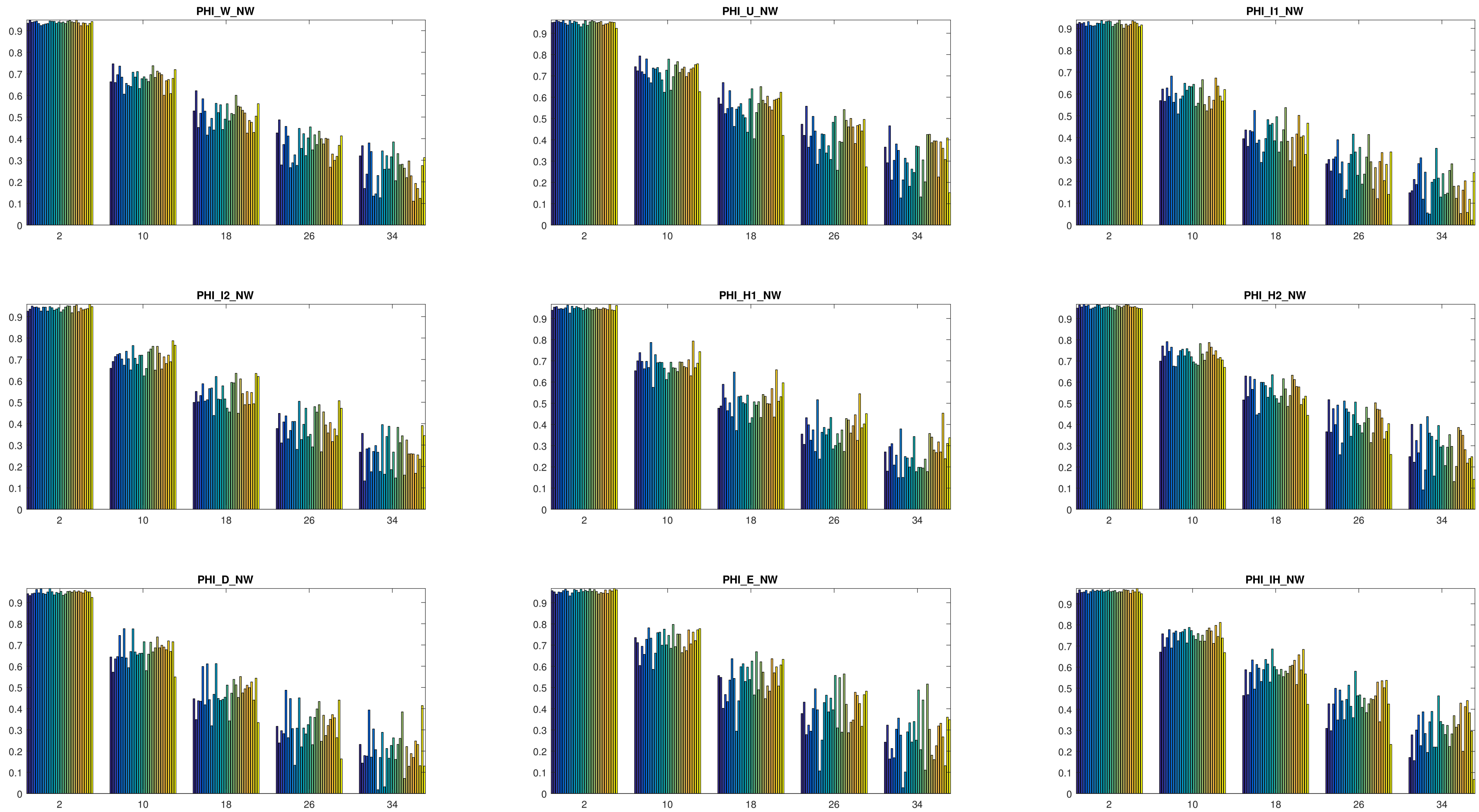

Figure 37: Autocorrelations of estimated parameters

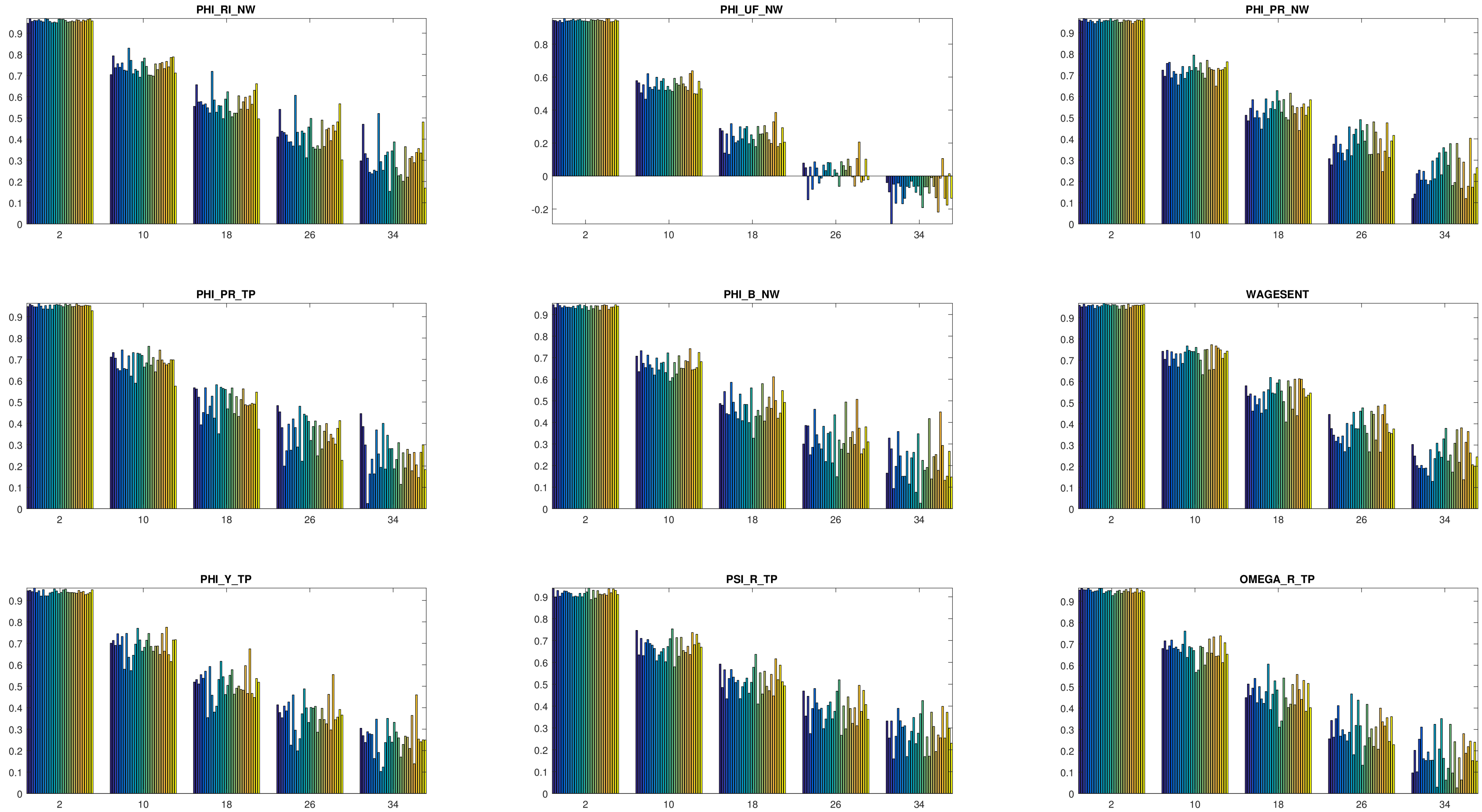

Figure 38: Autocorrelations of estimated parameters

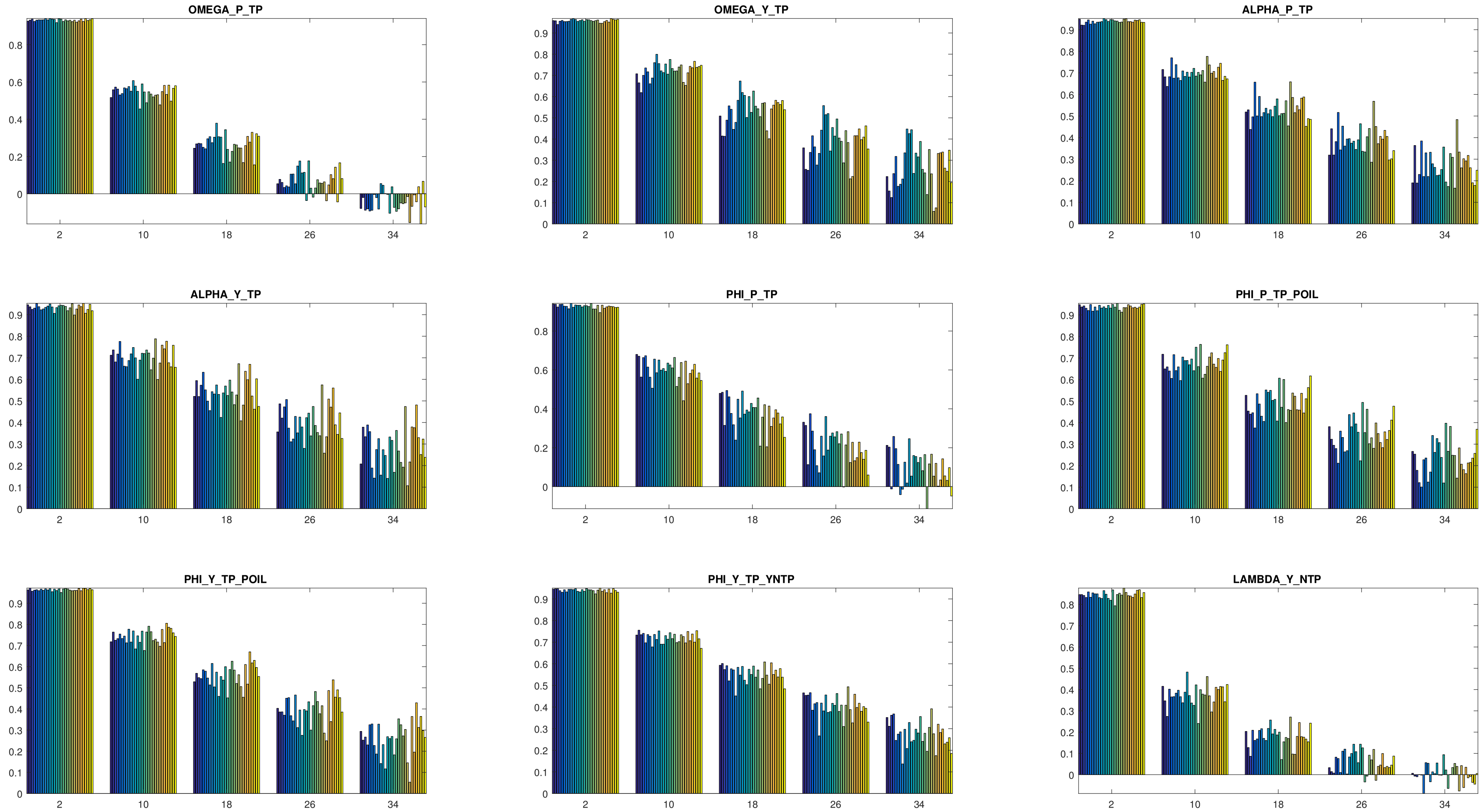

Figure 39: Autocorrelations of estimated parameters

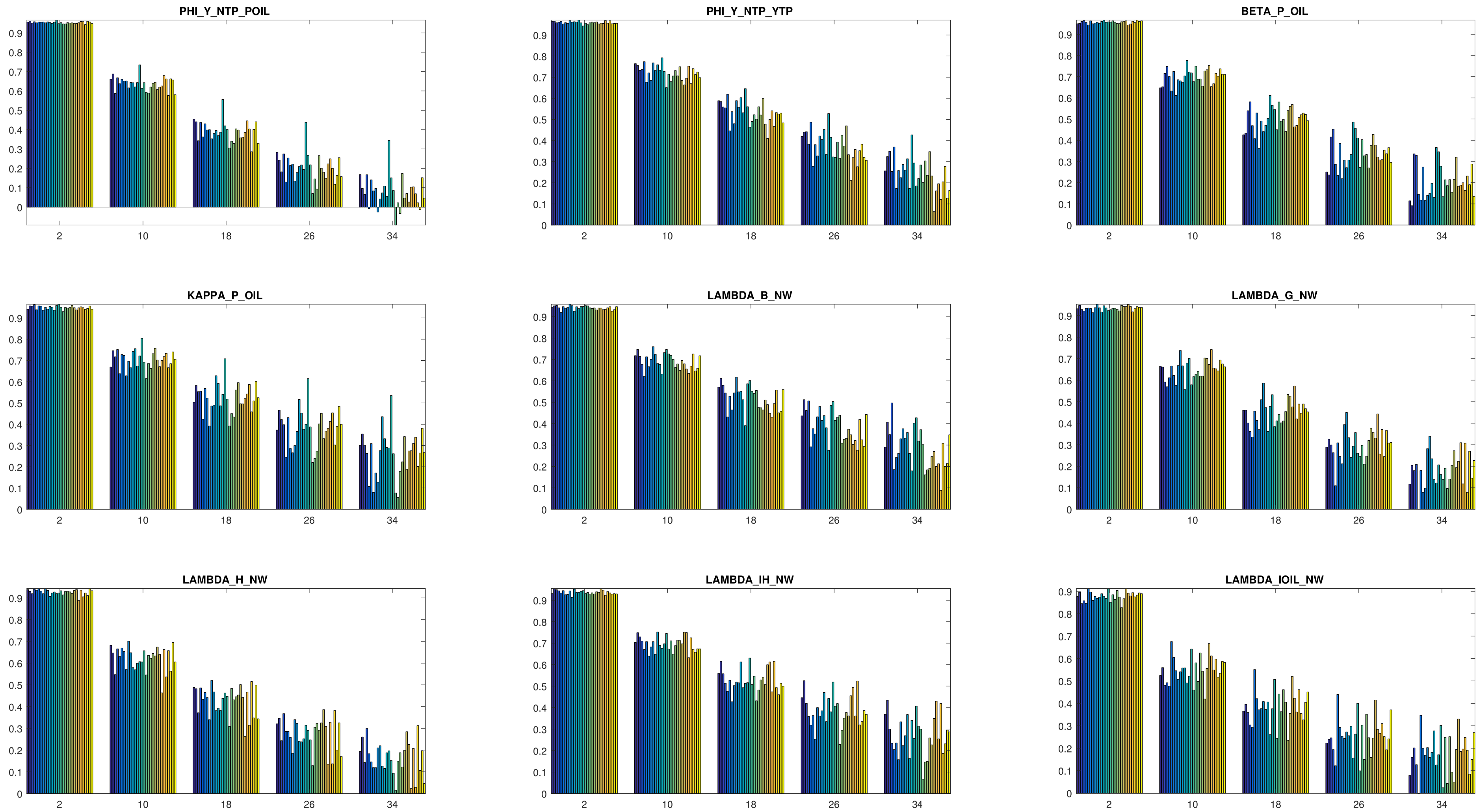

Figure 40: Autocorrelations of estimated parameters

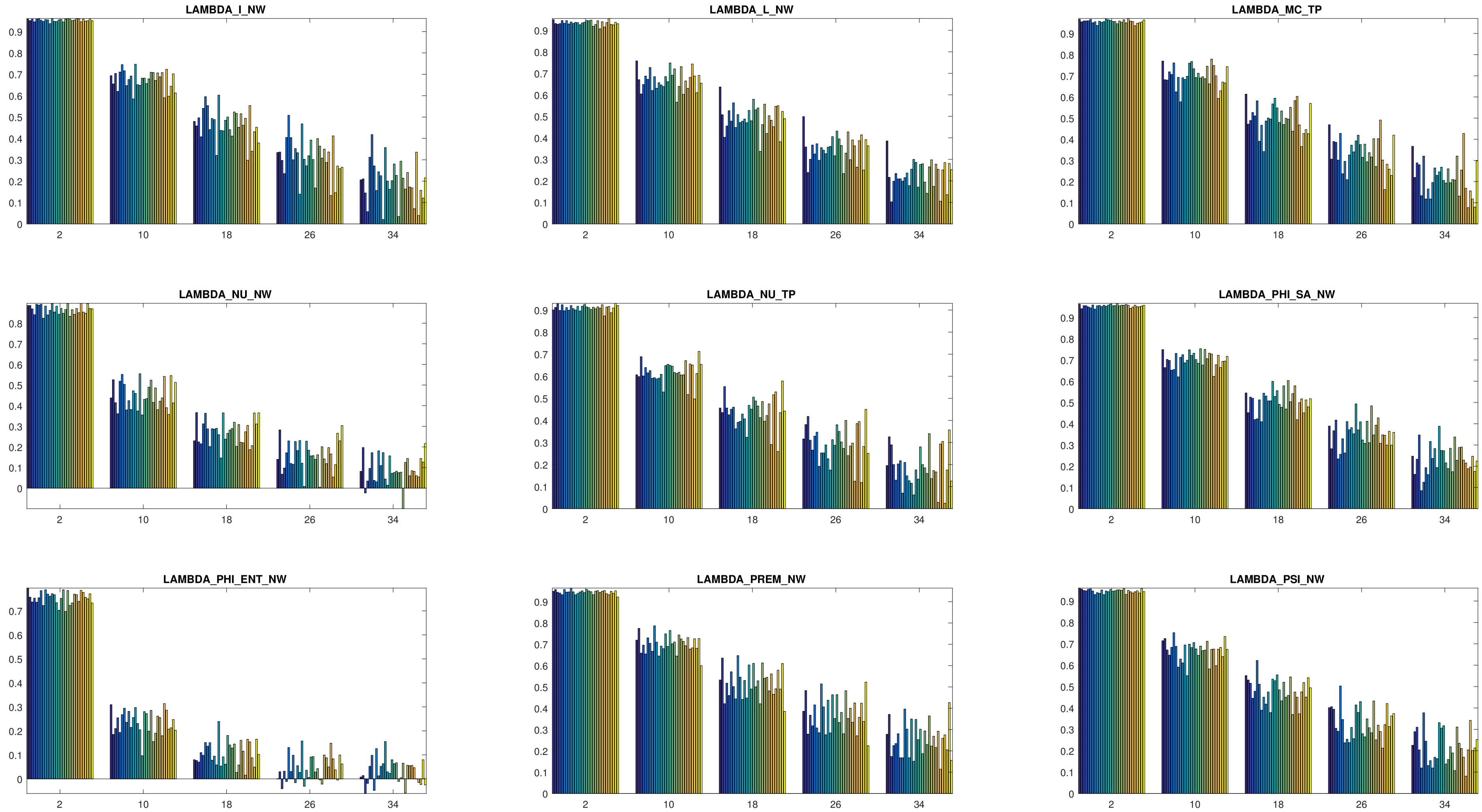

Figure 41: Autocorrelations of estimated parameters

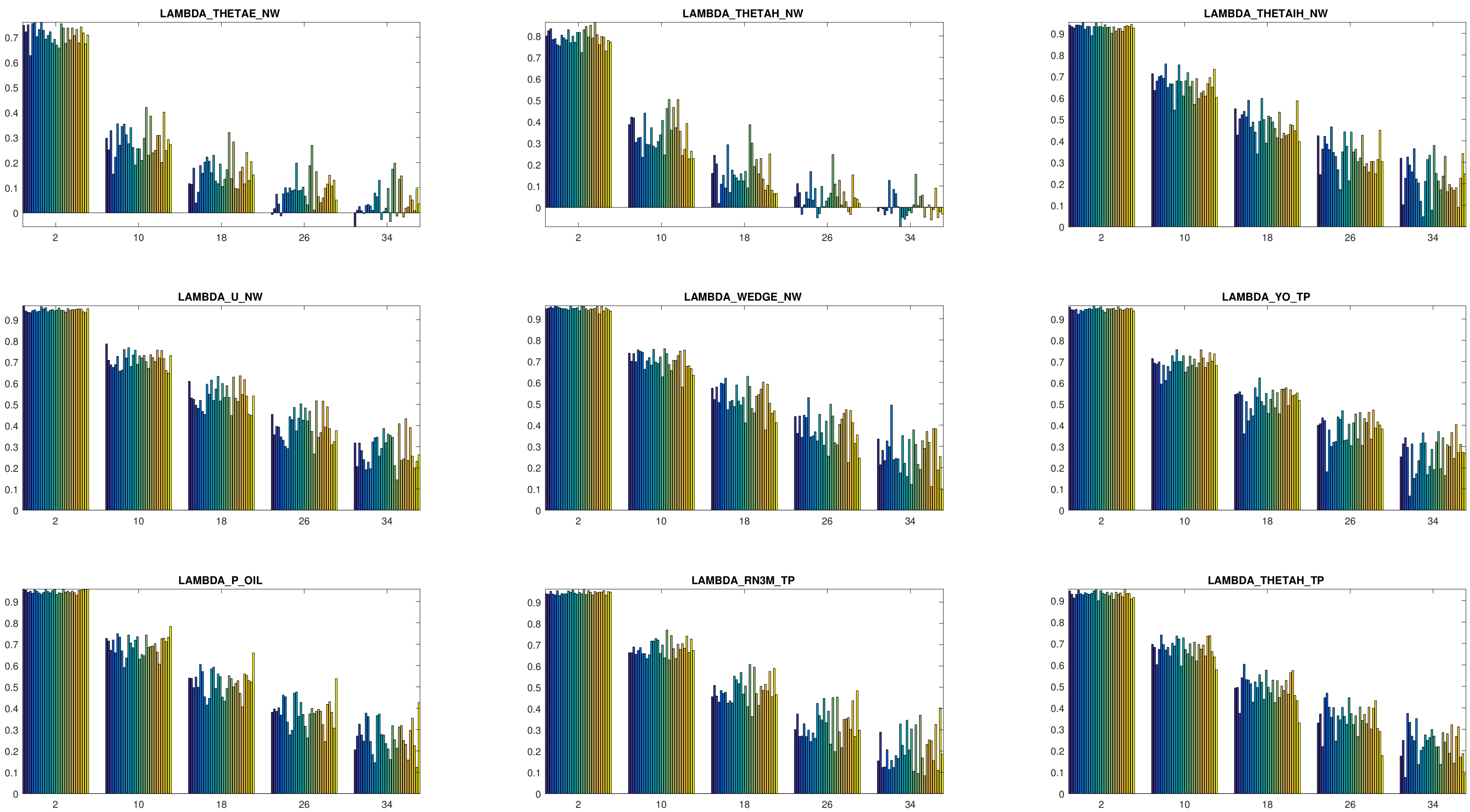

Figure 42: Autocorrelations of estimated parameters

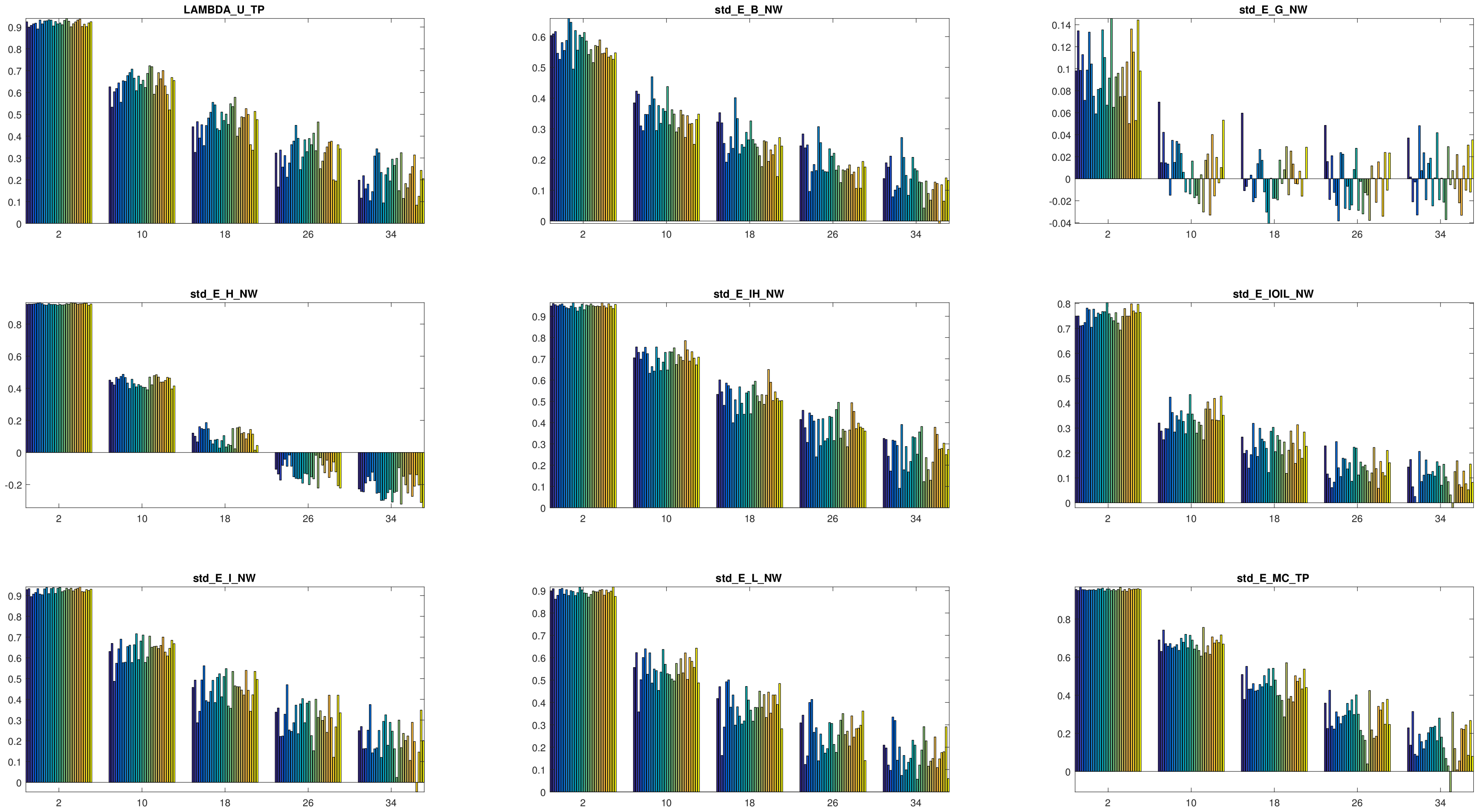

Figure 43: Autocorrelations of estimated parameters

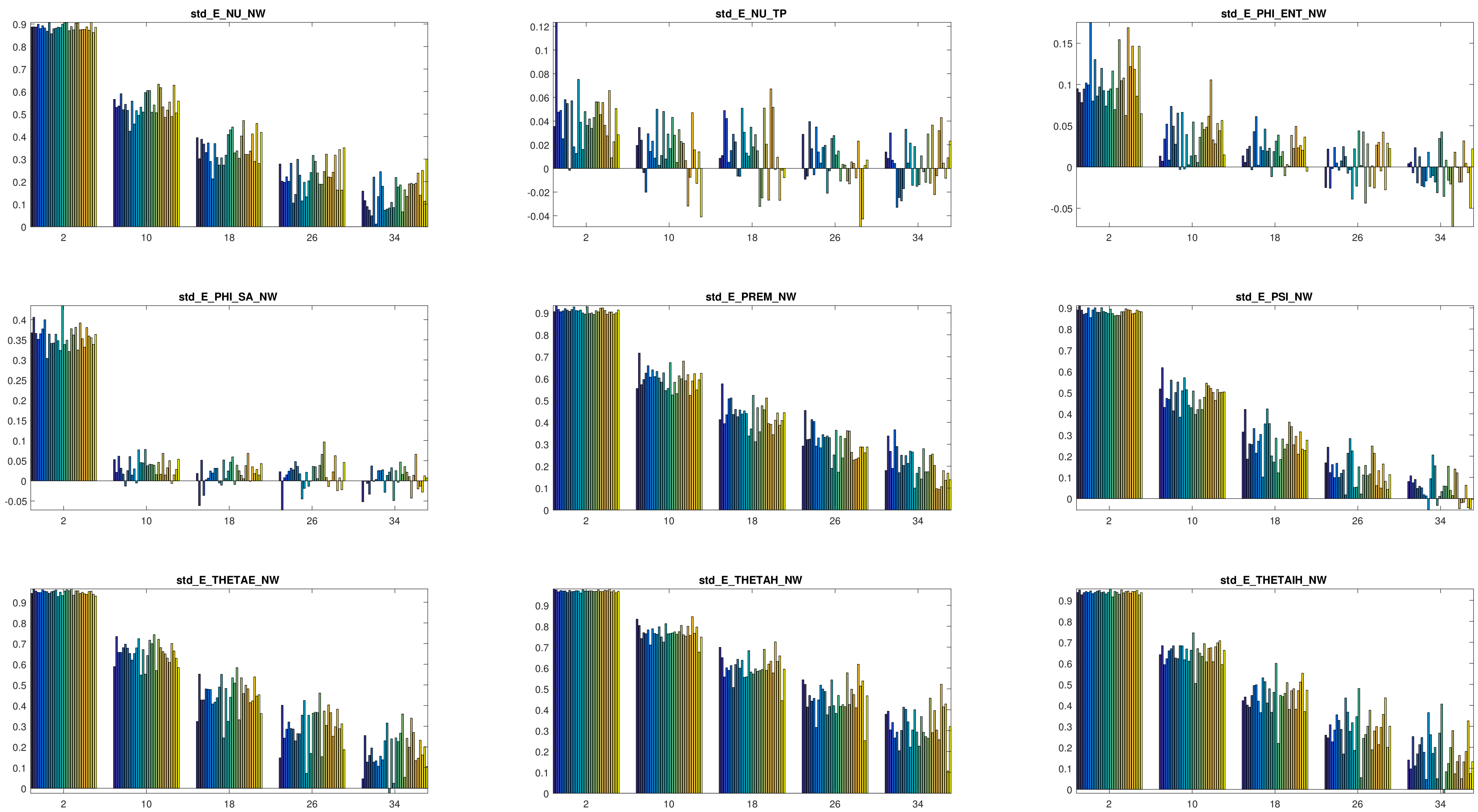

Figure 44: Autocorrelations of estimated parameters

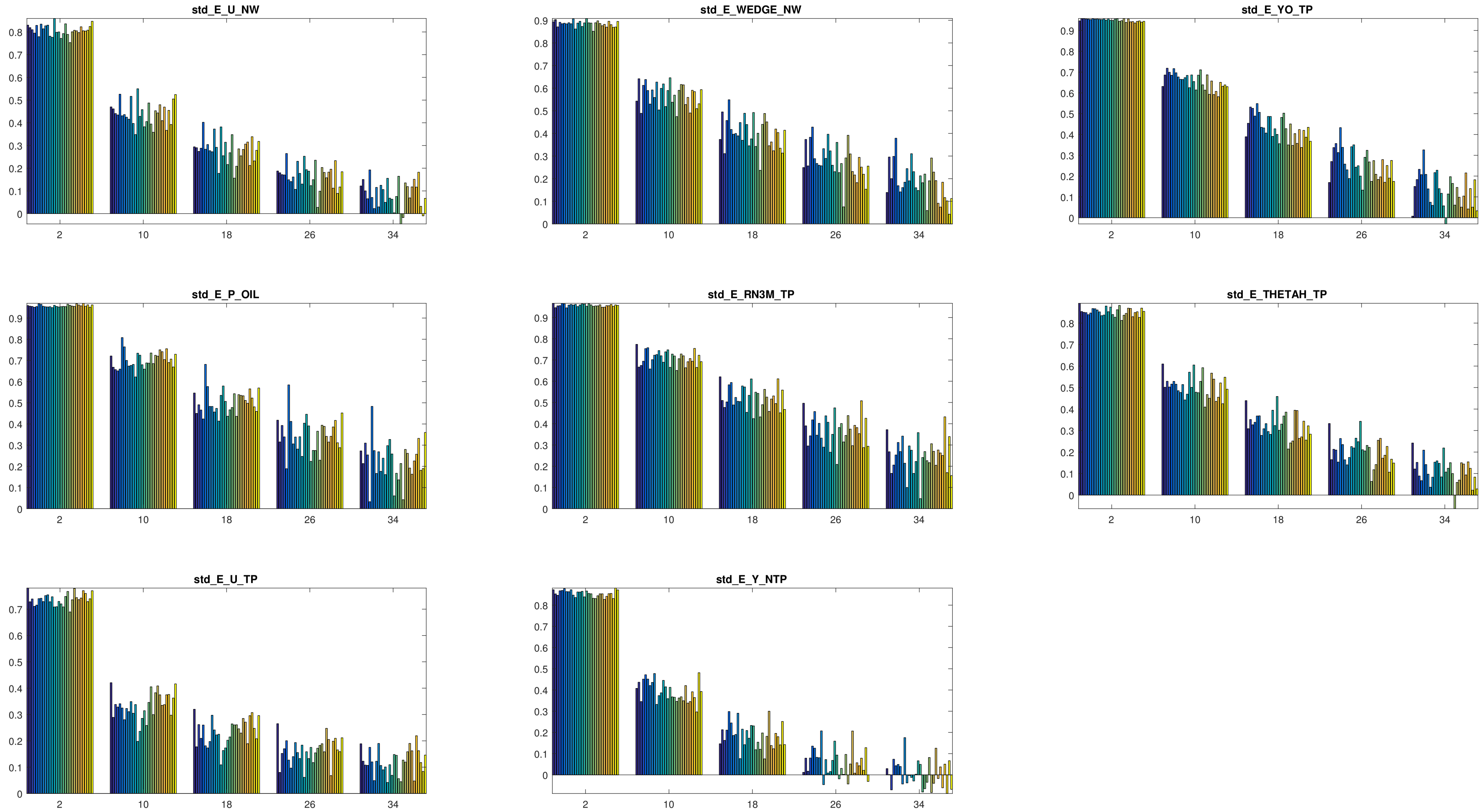

Figure 45: Autocorrelations of estimated parameters

H Prior and posterior distributions

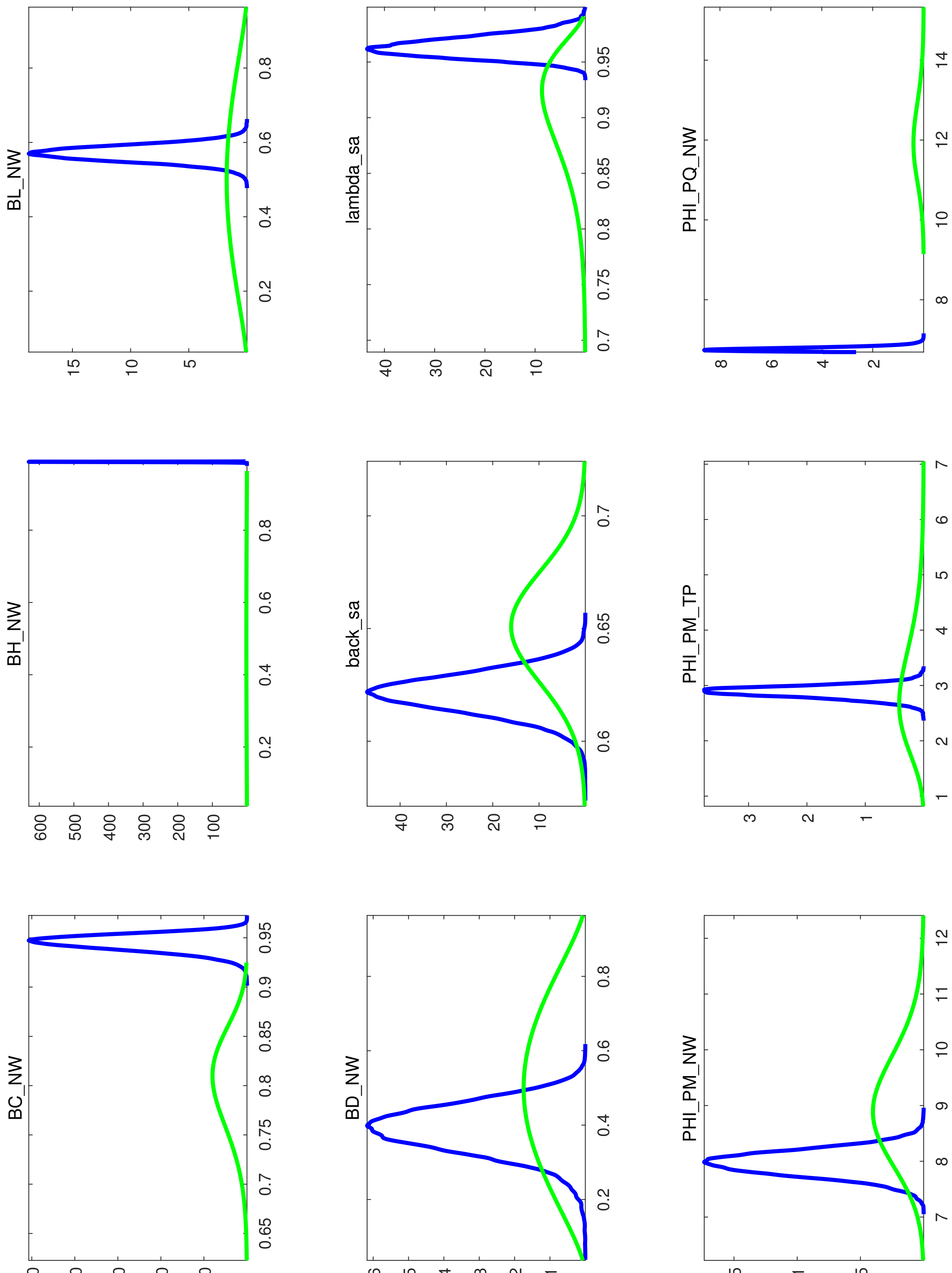

Figure 46: Marginal prior (green) and posterior distributions (blue).

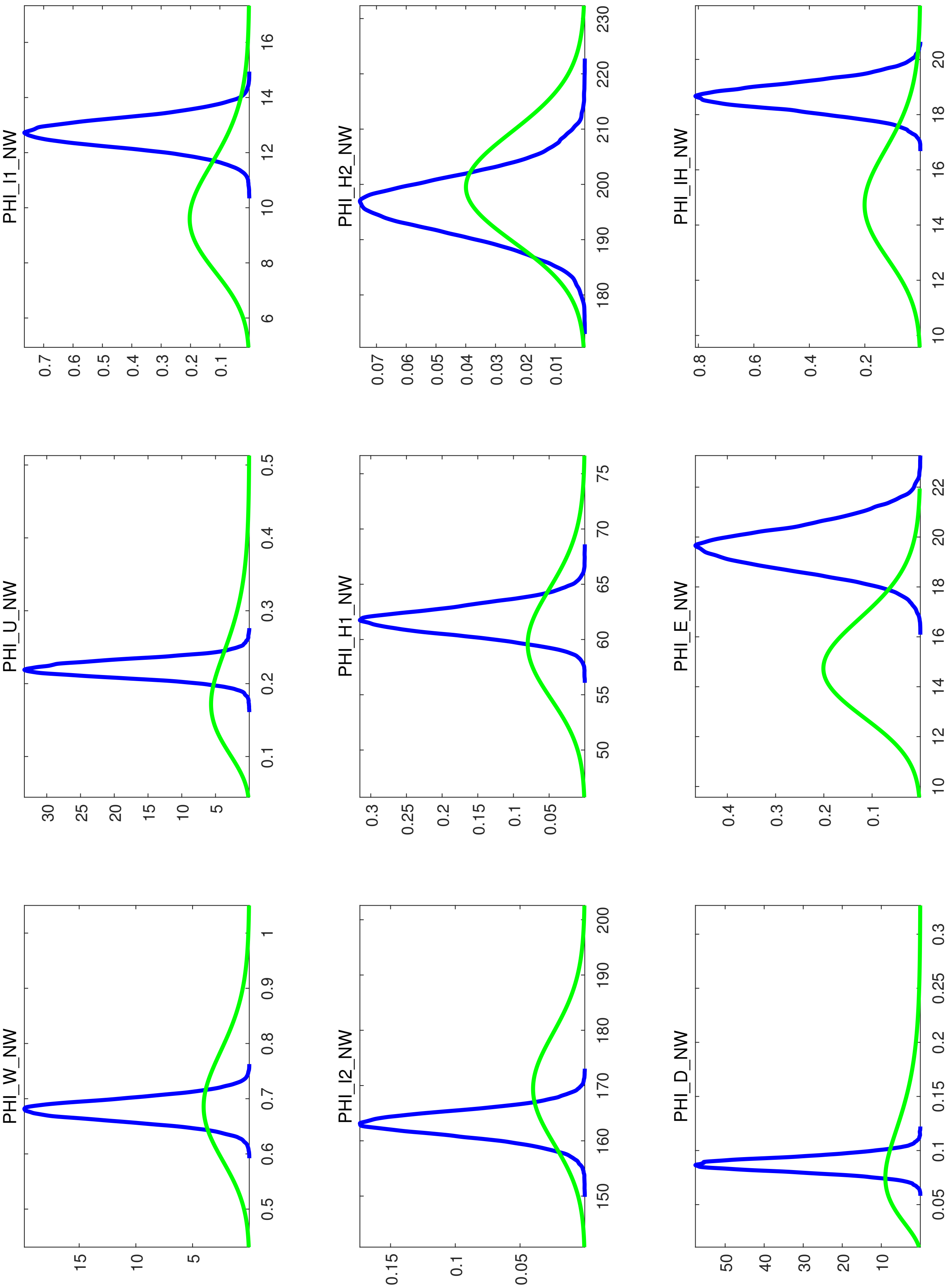

Figure 46: Marginal prior (green) and posterior distributions (blue) *cont.*

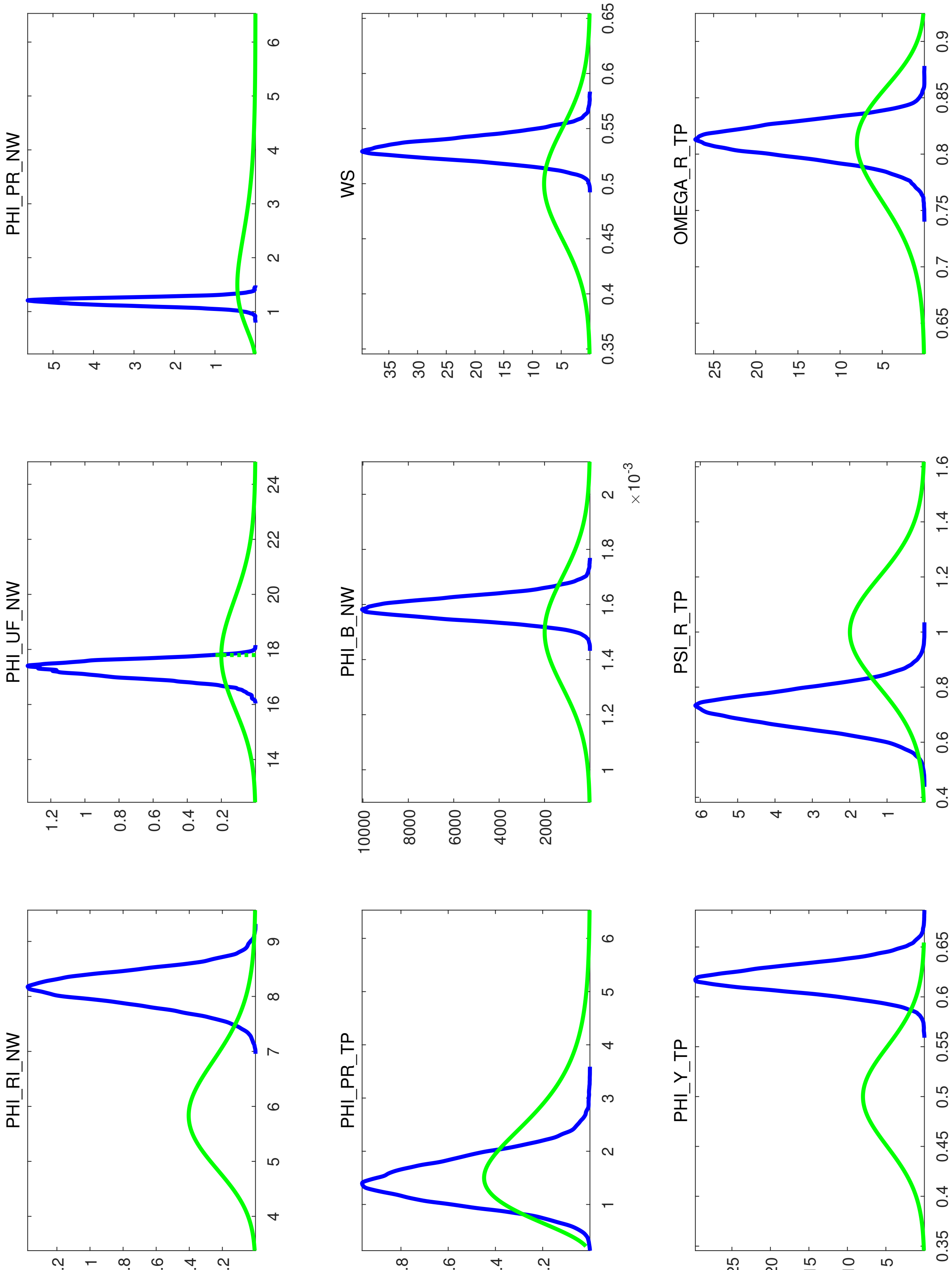

Figure 46: Marginal prior (green) and posterior distributions (blue) *cont.*

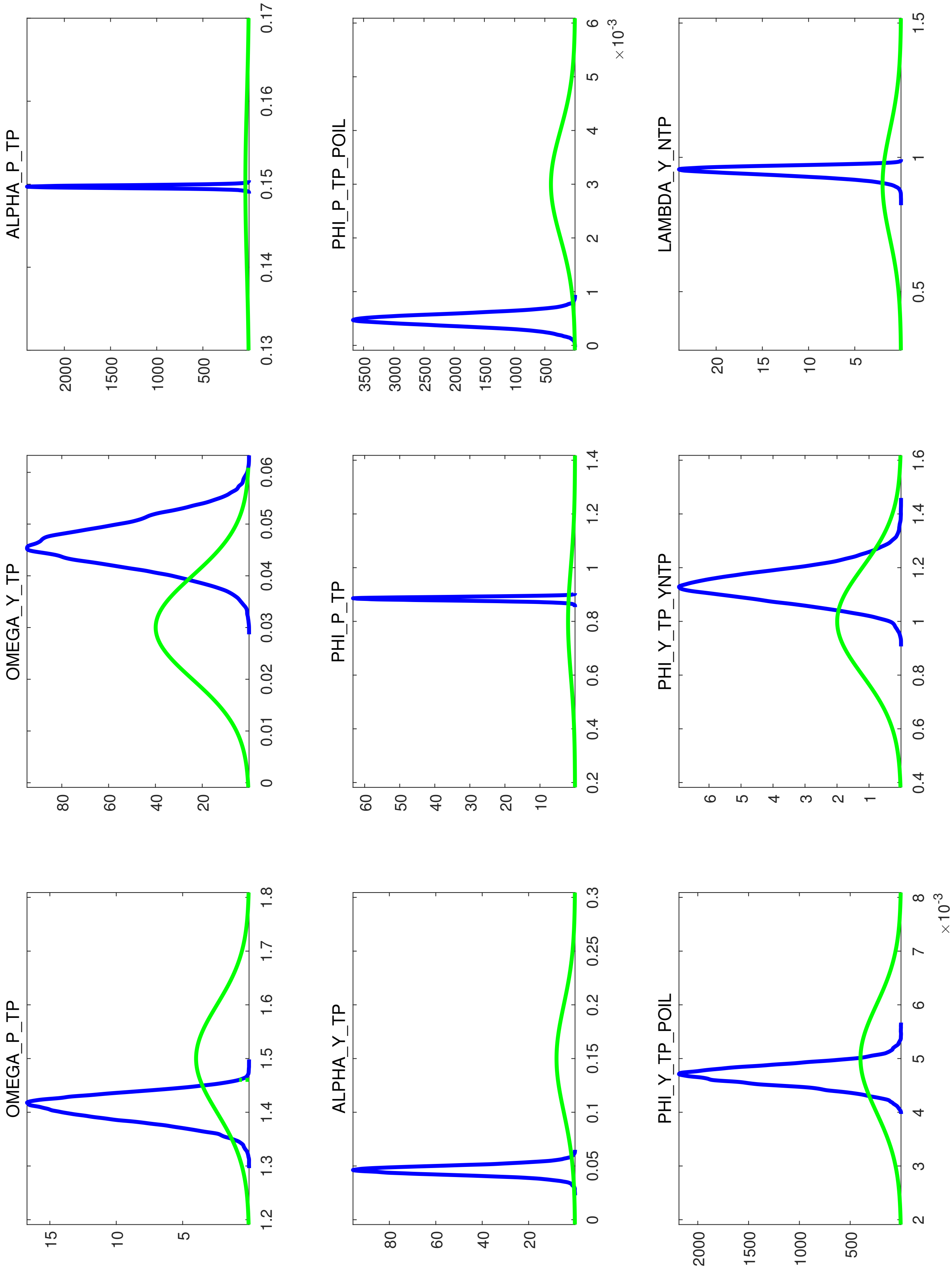

Figure 46: Marginal prior (green) and posterior distributions (blue) *cont.*

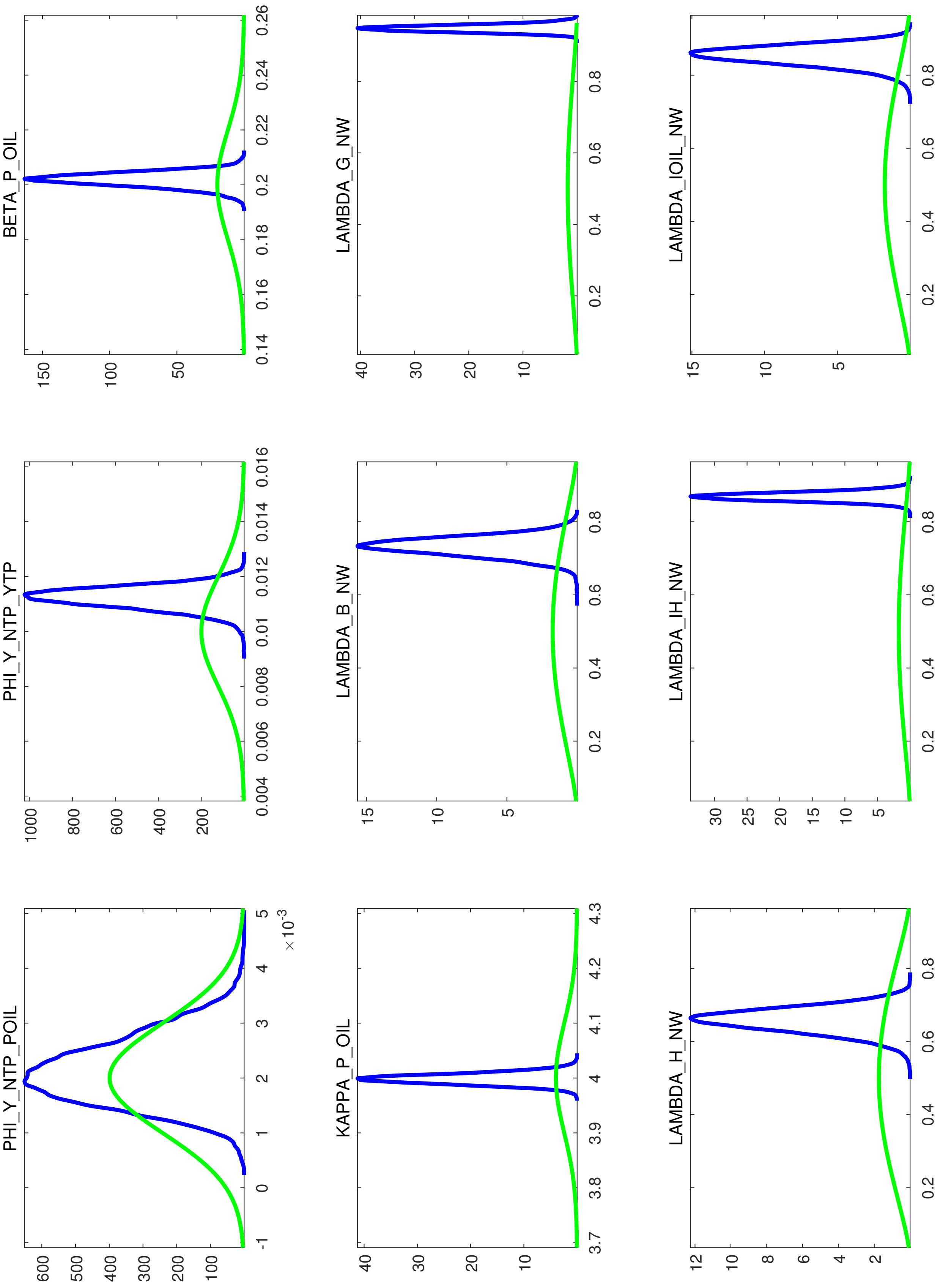

Figure 46: Marginal prior (green) and posterior distributions (blue) *cont.*

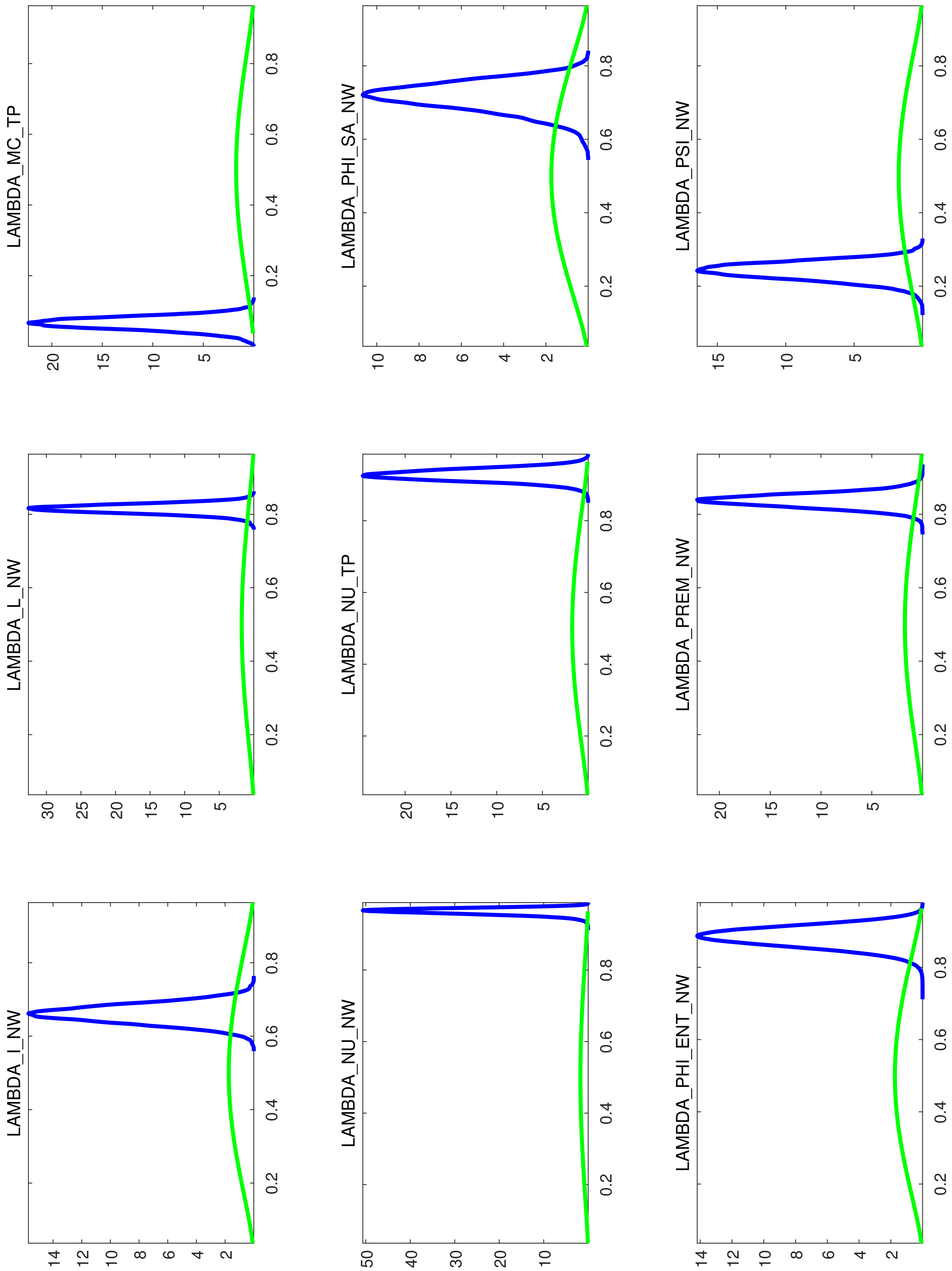

Figure 46: Marginal prior (green) and posterior distributions (blue) *cont.*

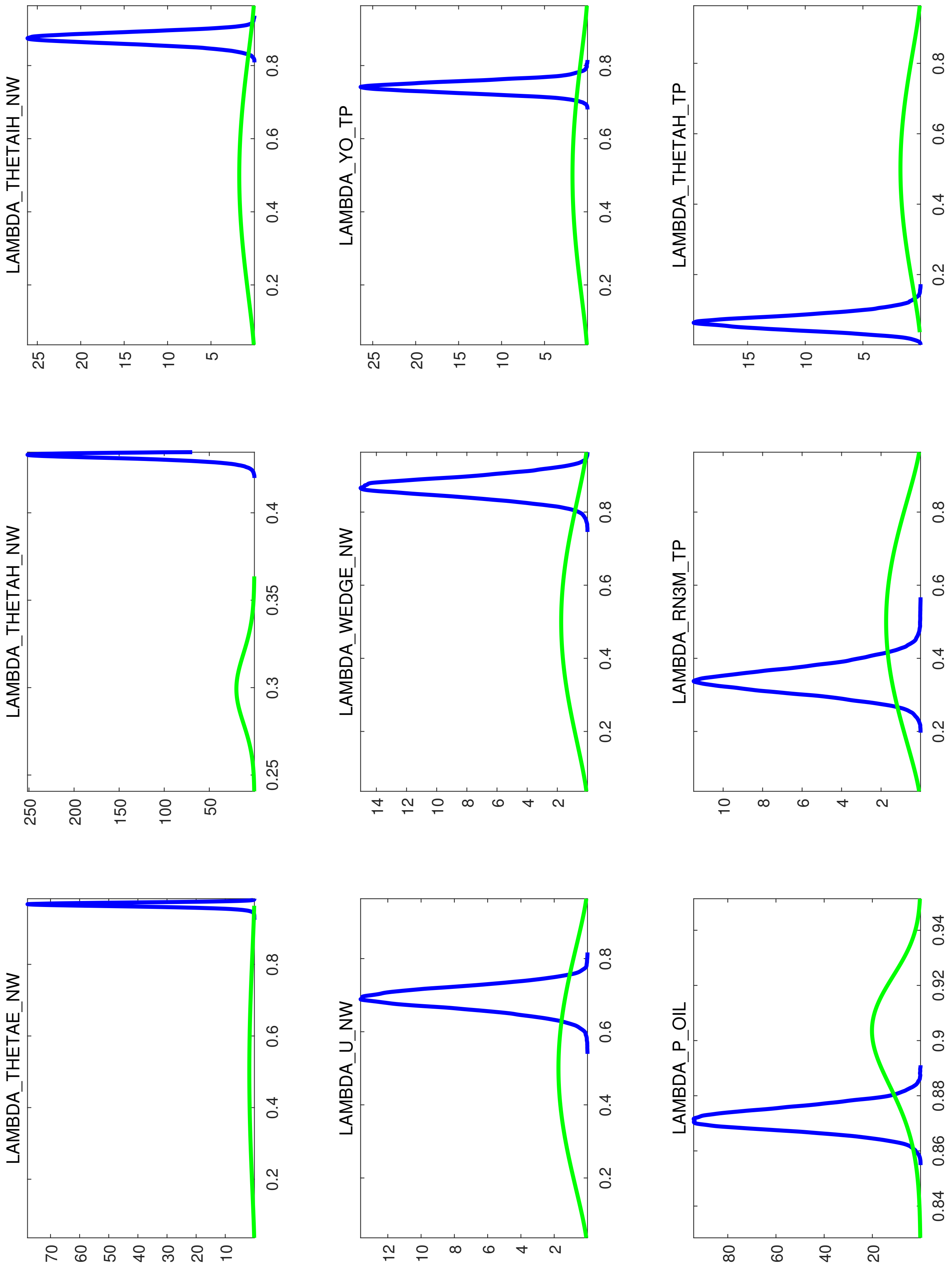

Figure 46: Marginal prior (green) and posterior distributions (blue) *cont.*

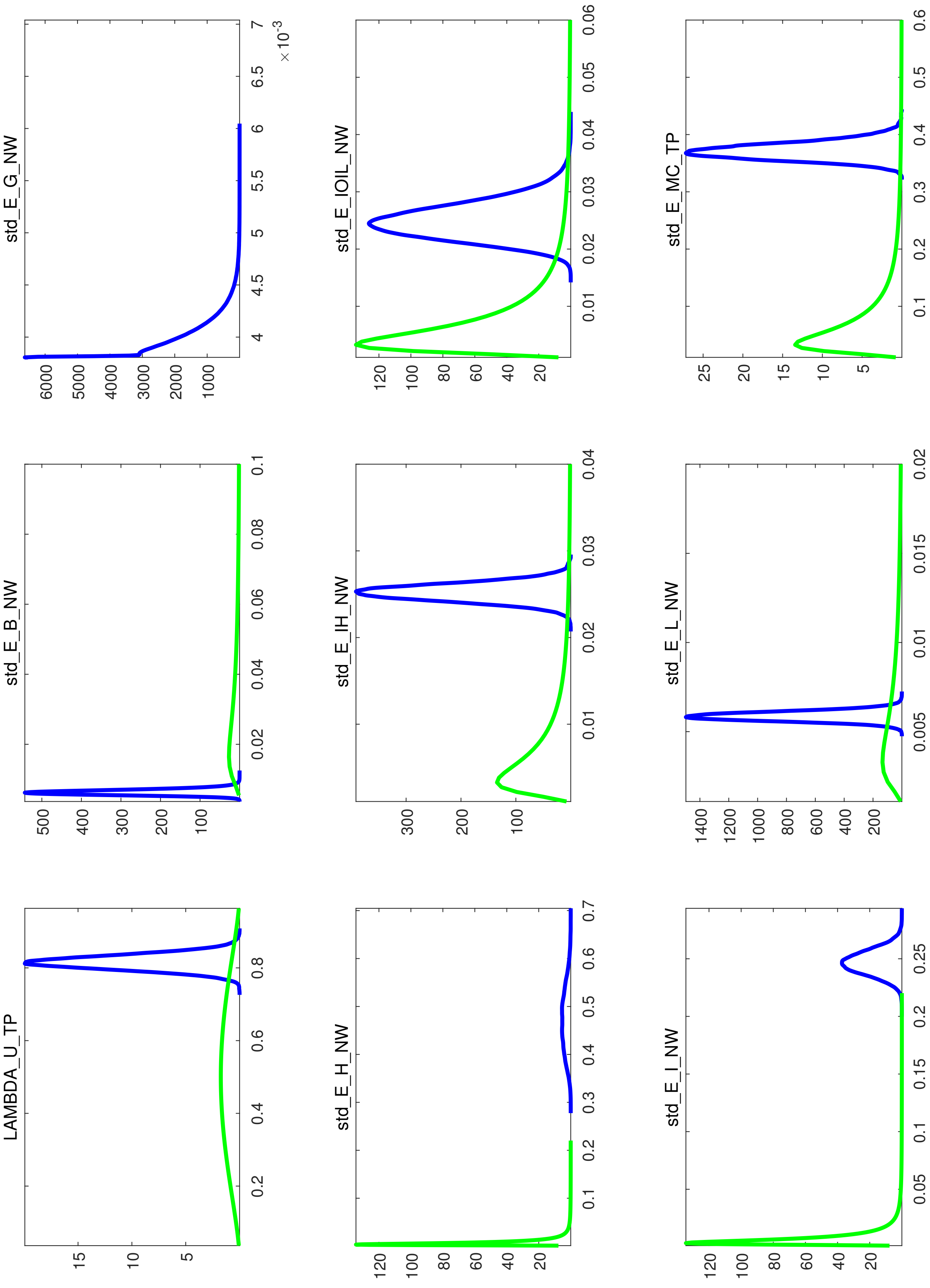

Figure 46: Marginal prior (green) and posterior distributions (blue) *cont.*

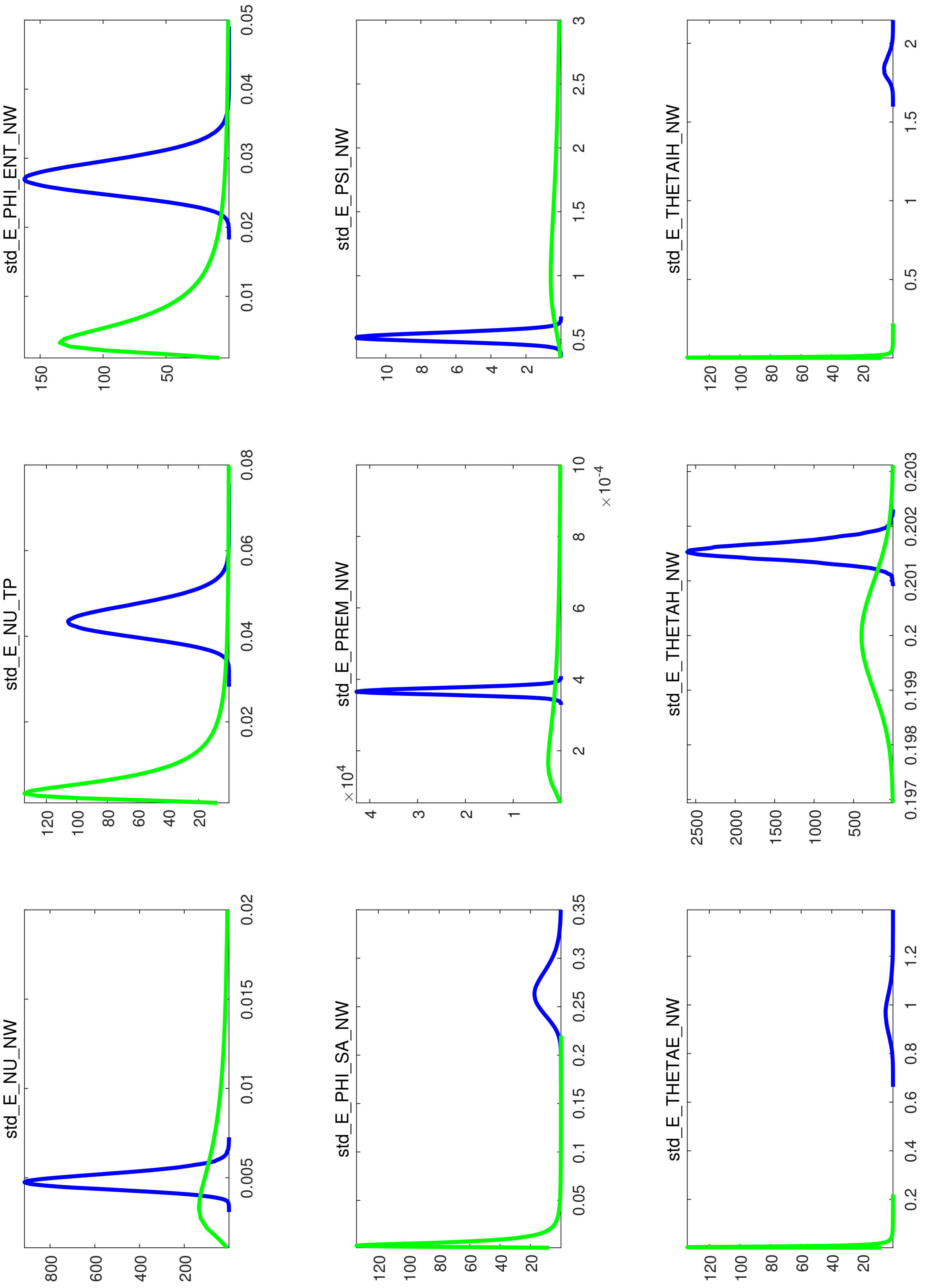

Figure 46: Marginal prior (green) and posterior distributions (blue) *cont.*

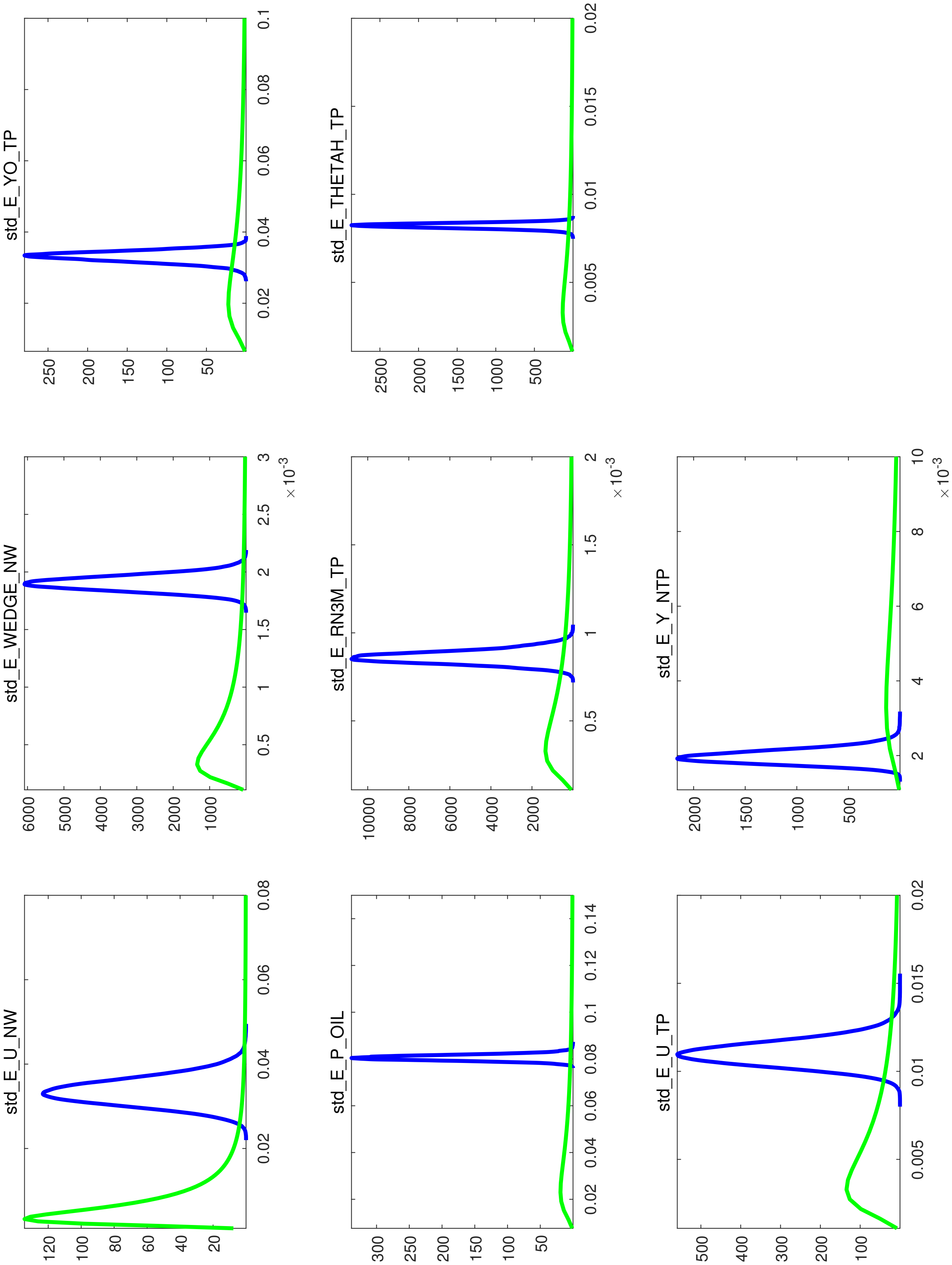

Figure 46: Marginal prior (green) and posterior distributions (blue) *cont.*

I Impulse responses with confidence intervals

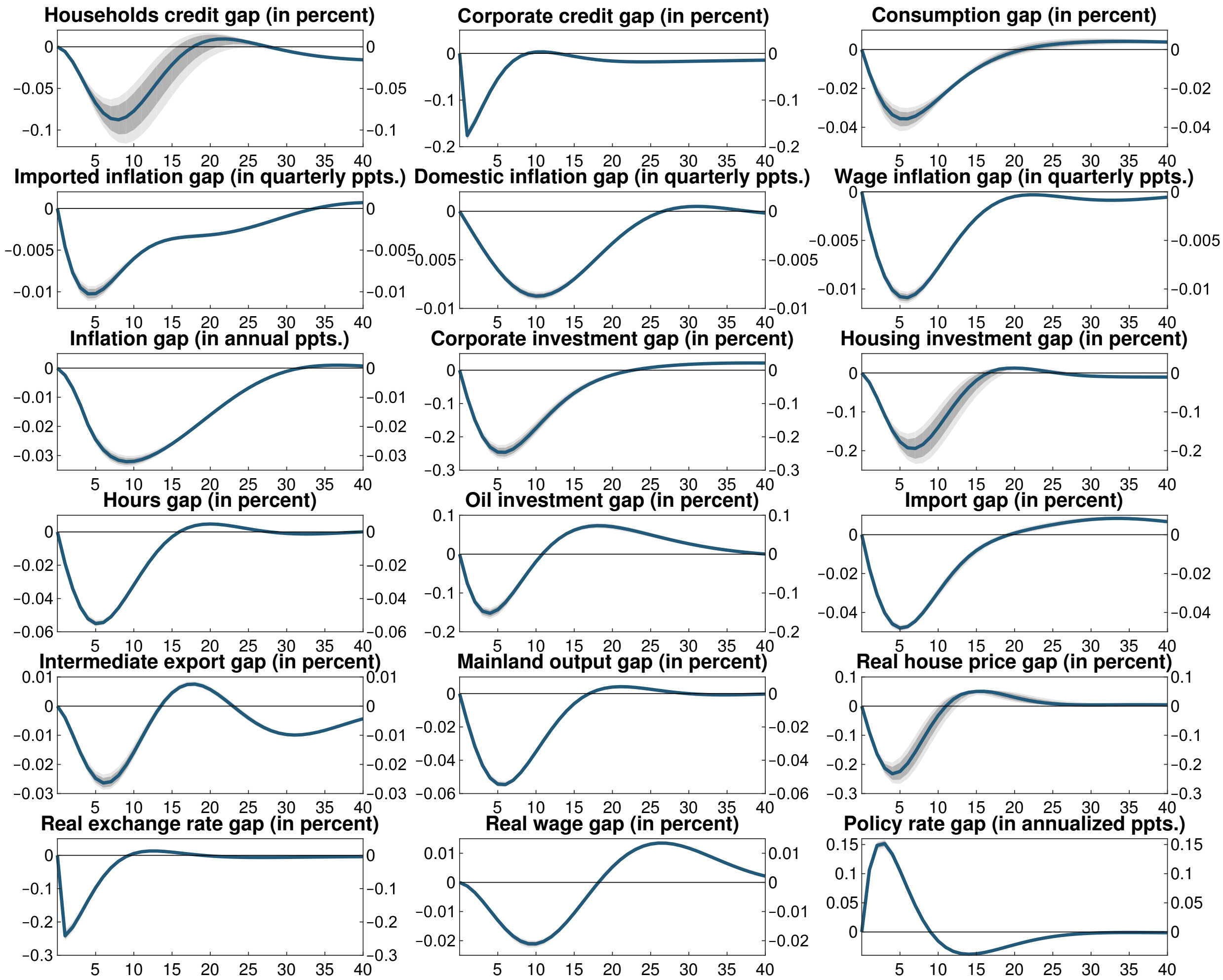

Figure 47: Impulse responses to a monetary policy shock (not normalized)

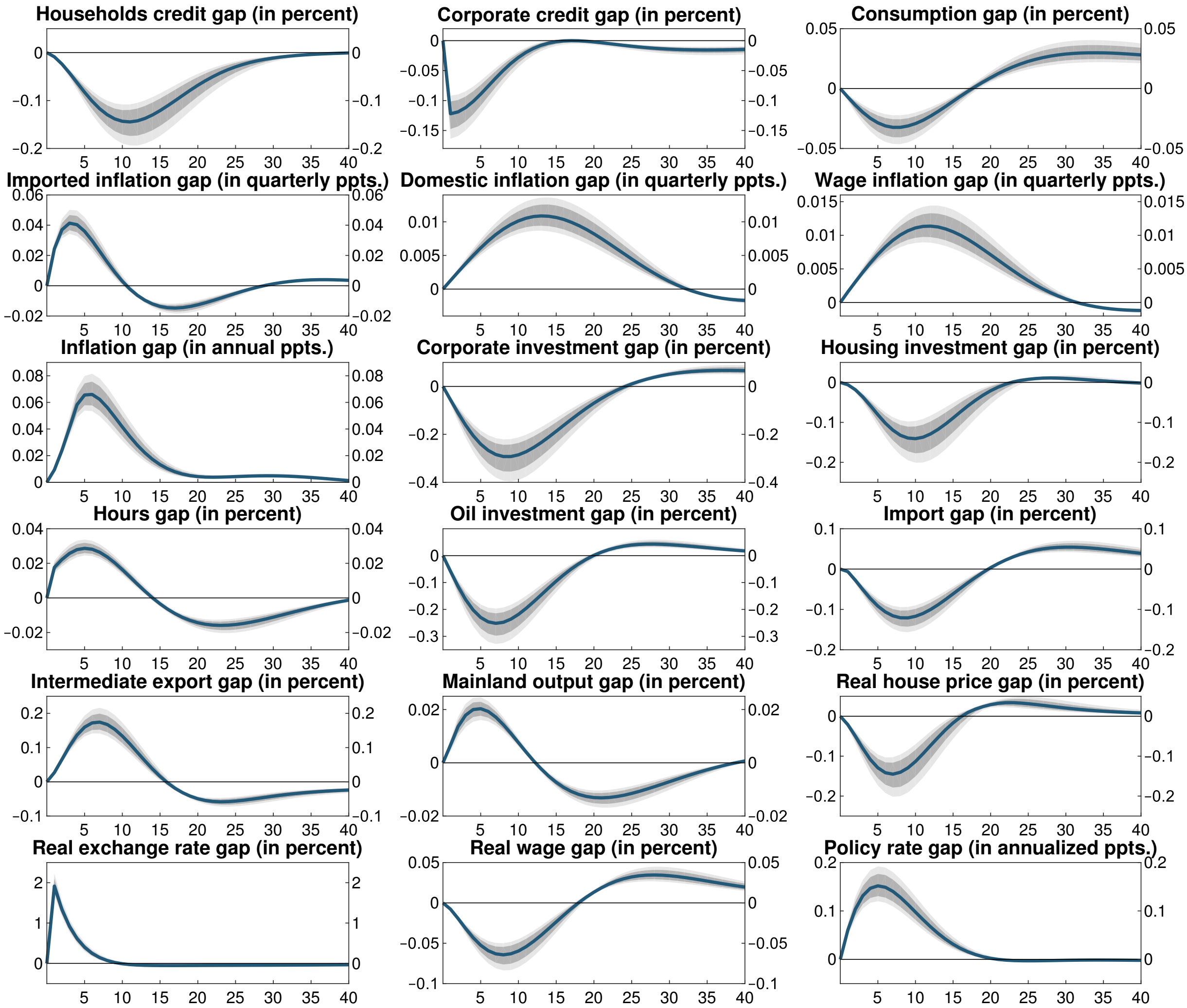

Figure 48: Impulse responses to an external risk premium shock (not normalized)

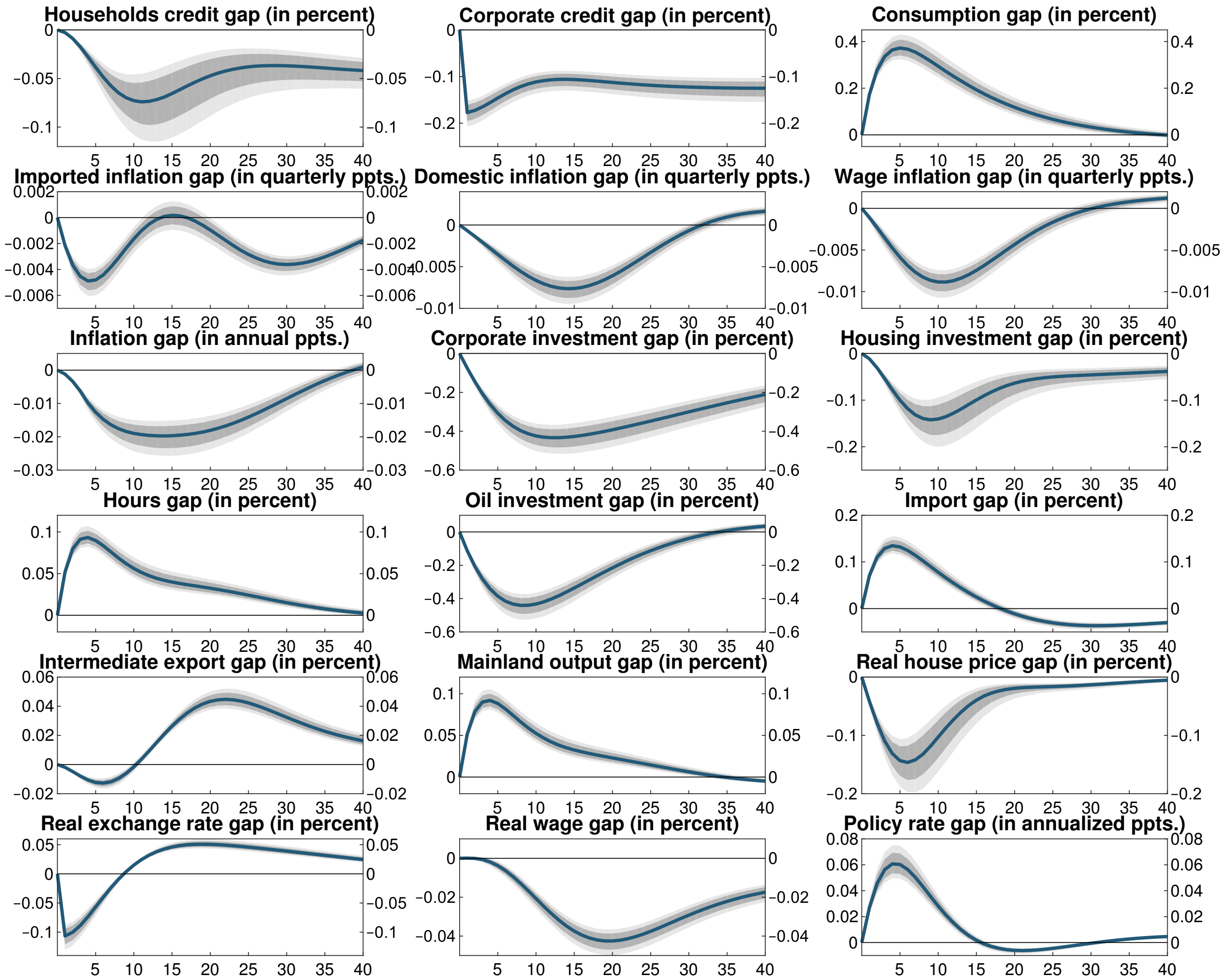

Figure 49: Impulse responses to a consumption preference shock (not normalized)

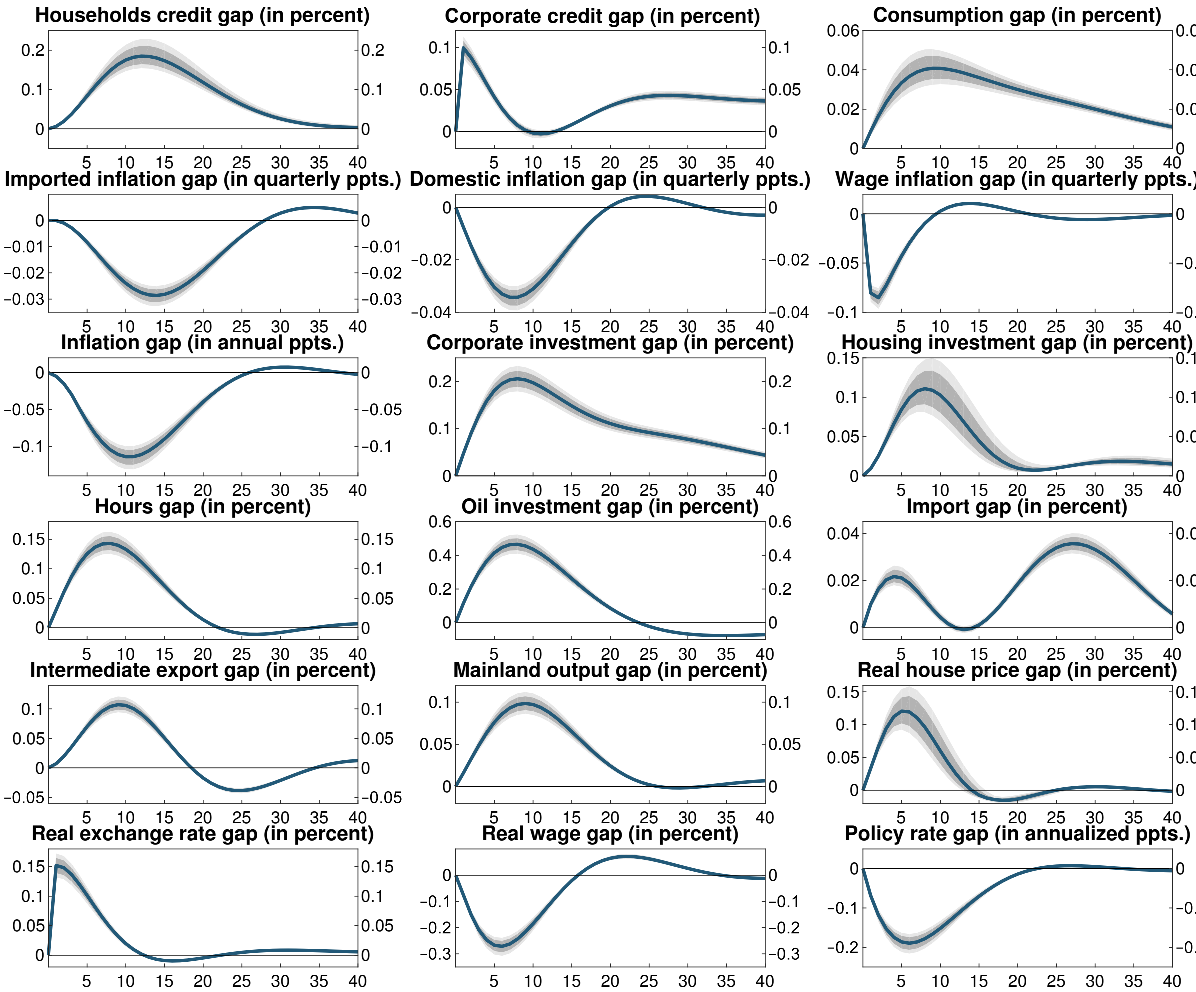

Figure 50: Impulse responses to a wage markup shock (not normalized)

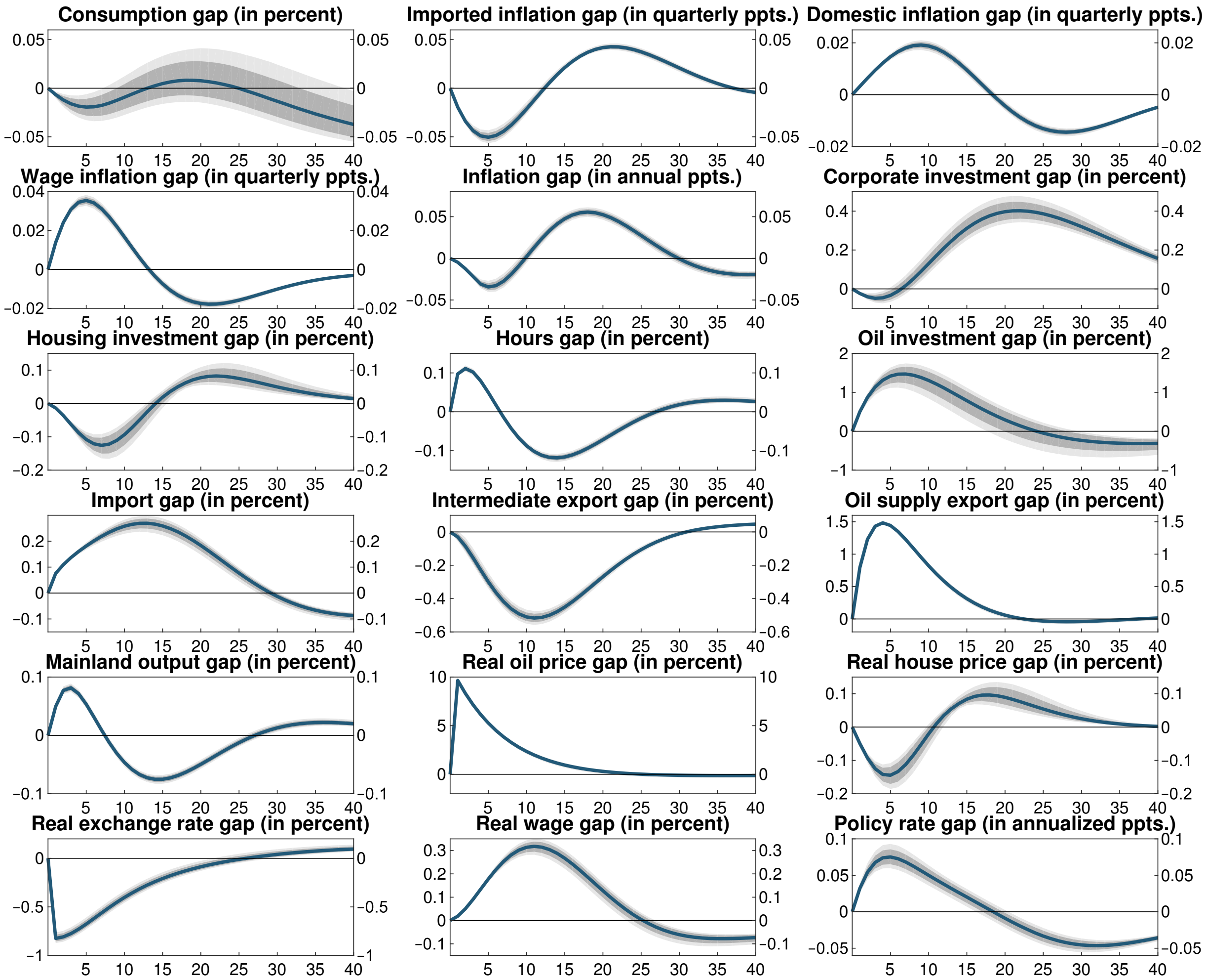

Figure 51: Impulse responses to a real oil price shock (not normalized)

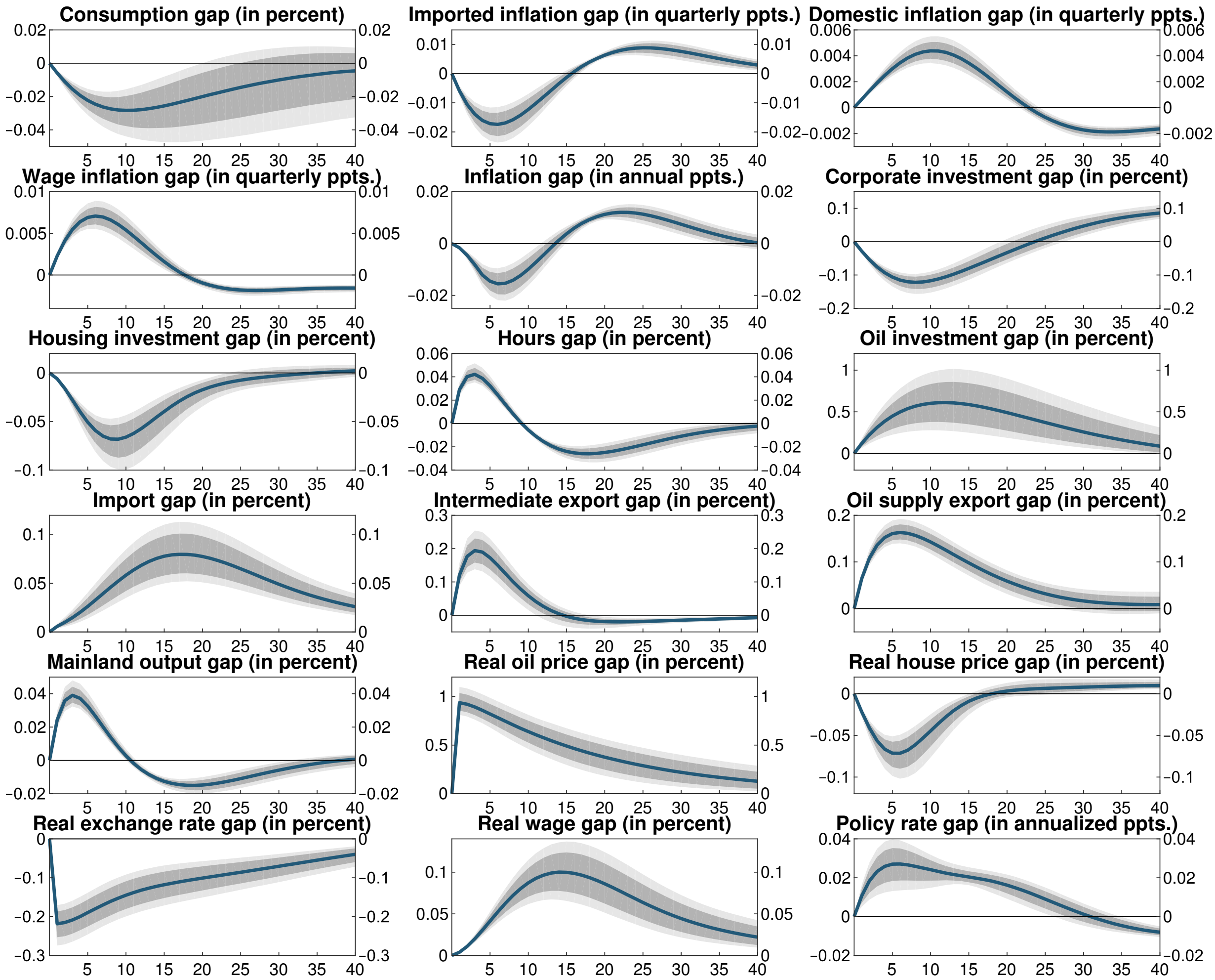

Figure 52: Impulse responses to a global demand shock (not normalized)

J Historical shock decompositions: Grouped shocks

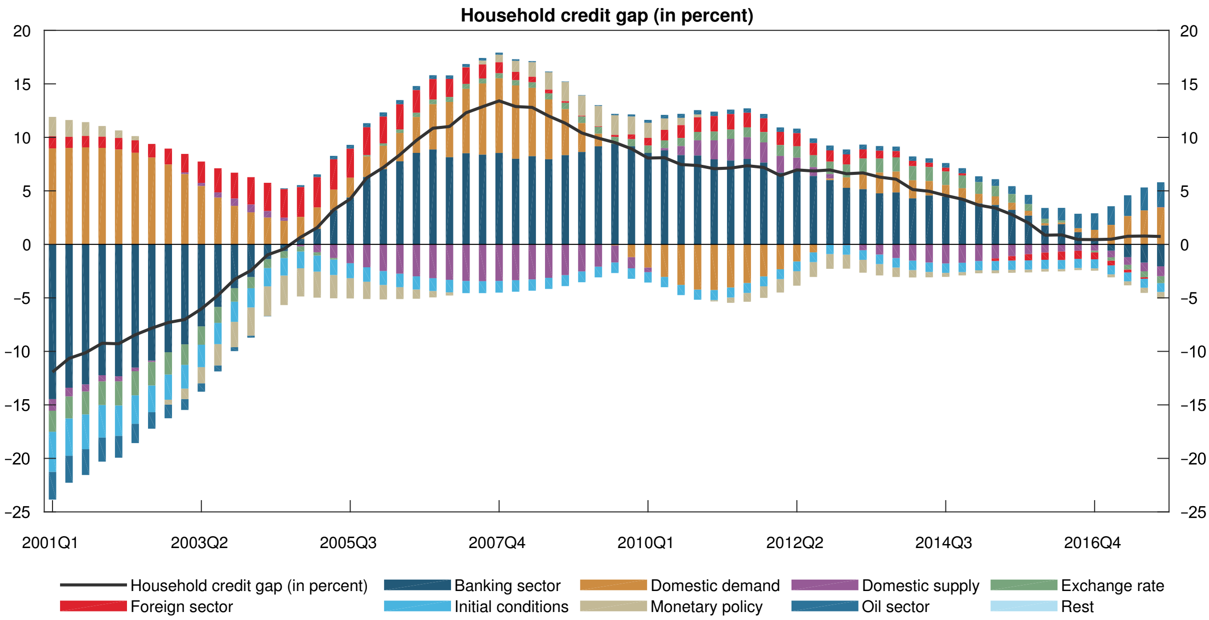

Figure 53: Historical shock decomposition of the household credit gap

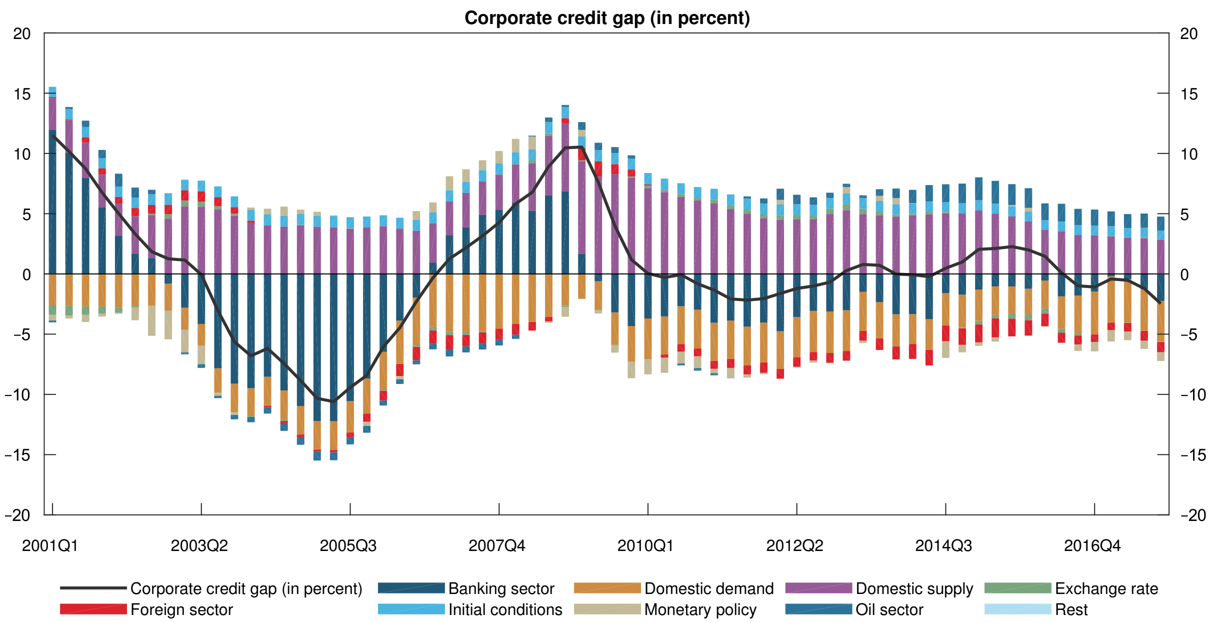

Figure 54: Historical shock decomposition of the corporate credit gap

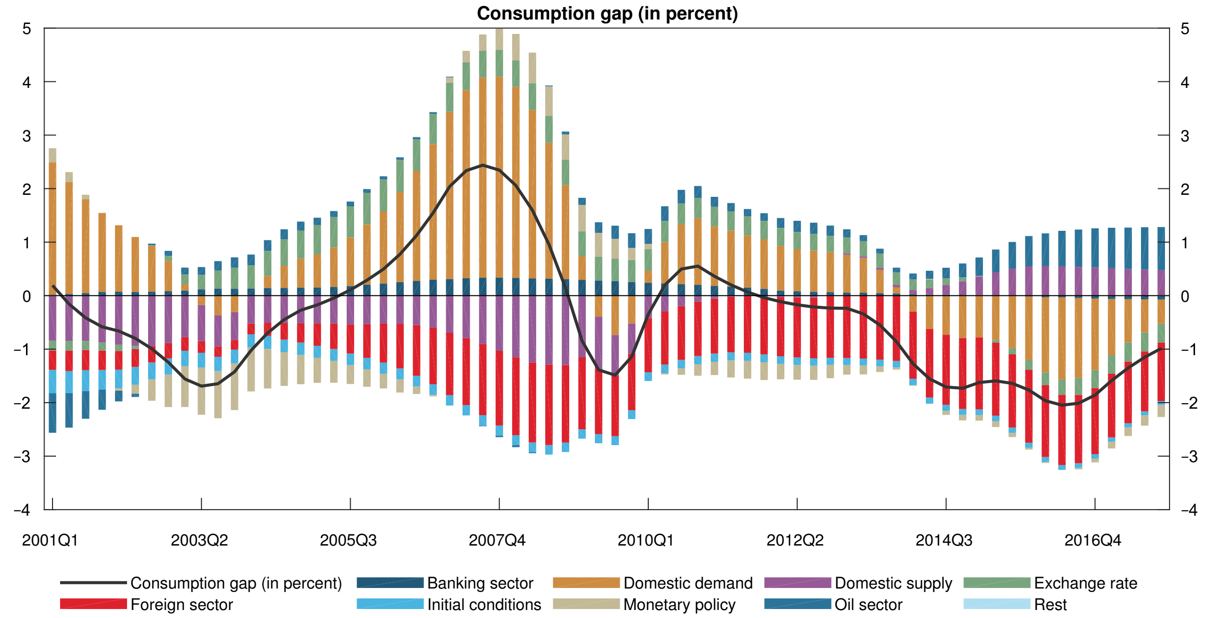

Figure 55: Historical shock decomposition of the consumption gap

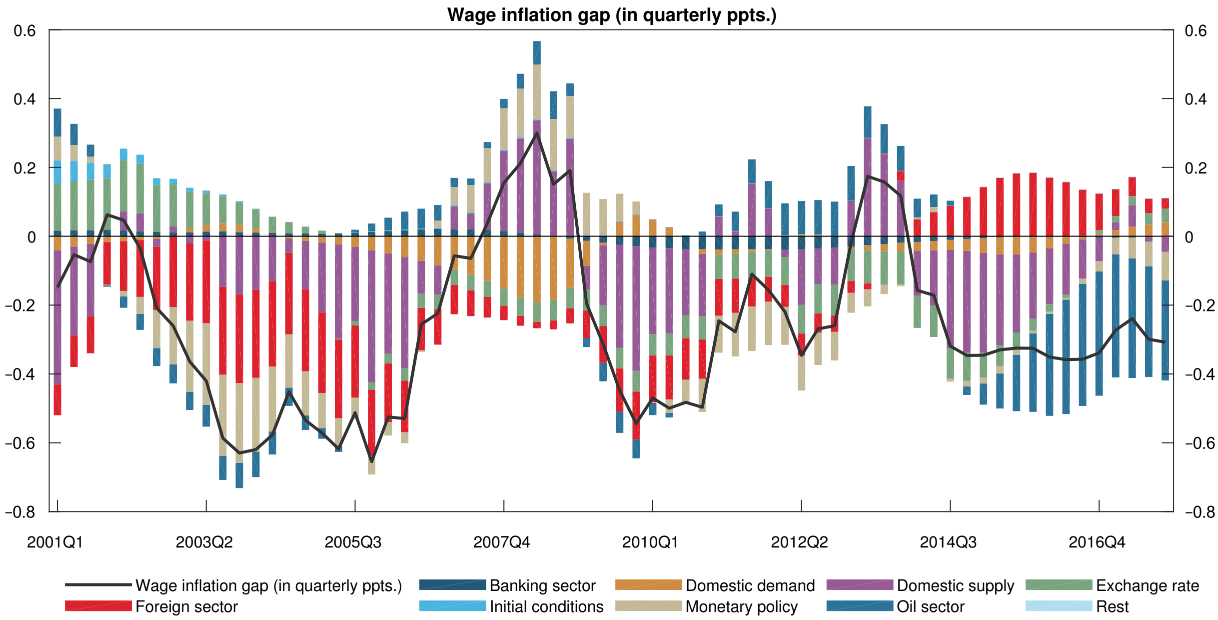

Figure 56: Historical shock decomposition of the wage inflation gap

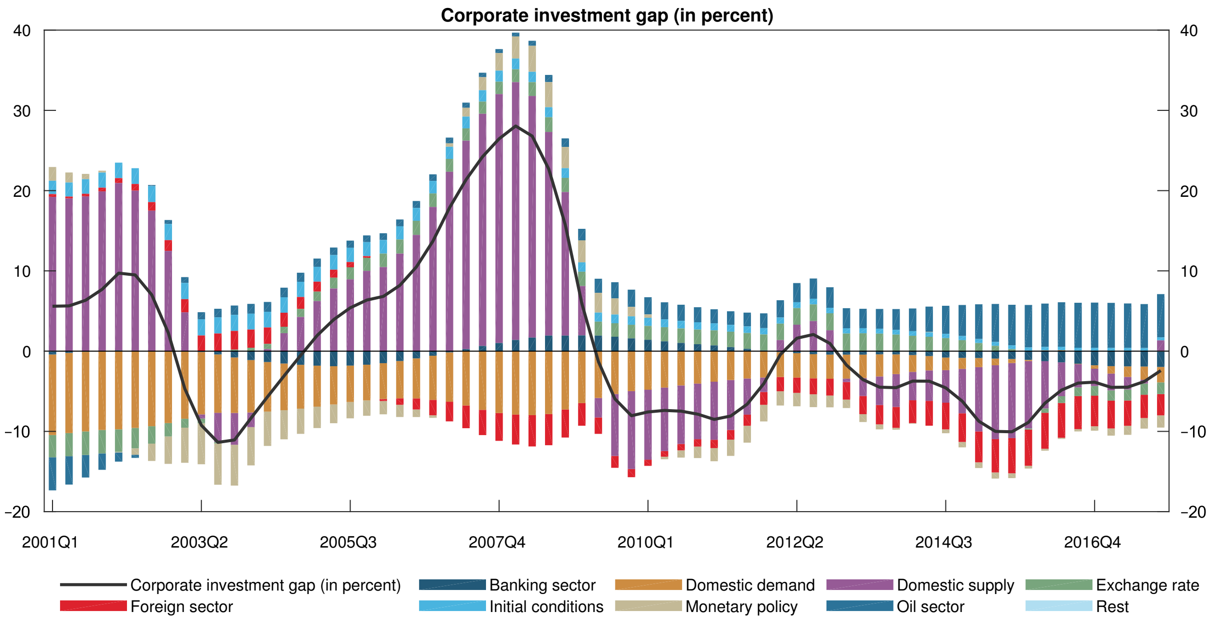

Figure 57: Historical shock decomposition of the corporate investment gap

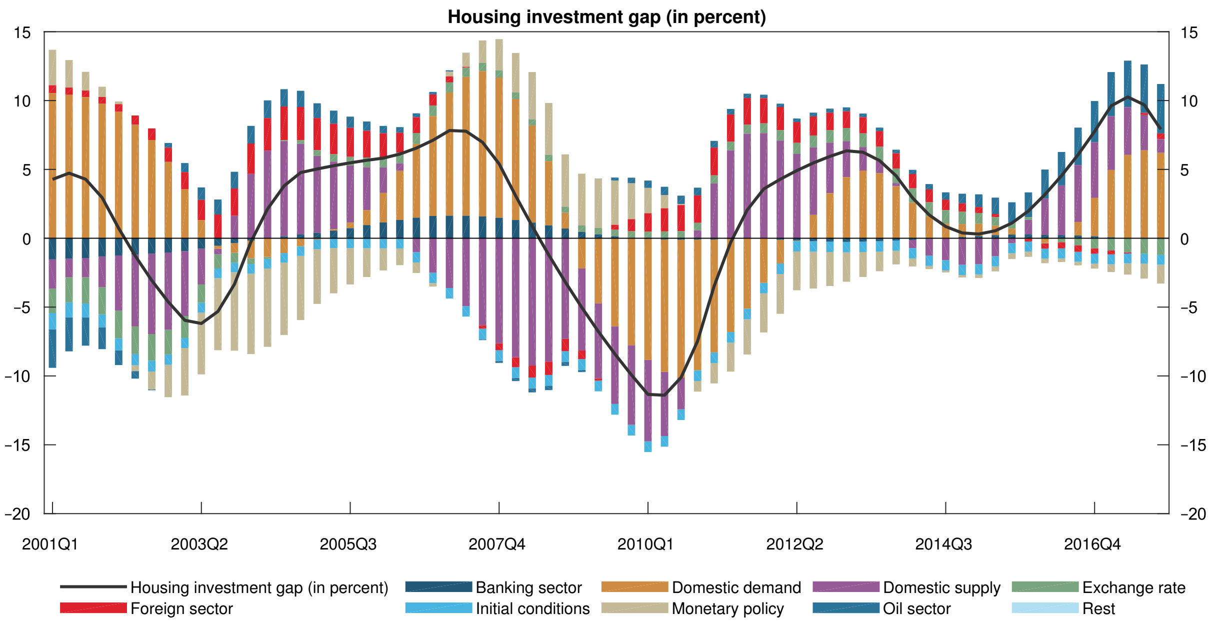

Figure 58: Historical shock decomposition of the housing investment gap

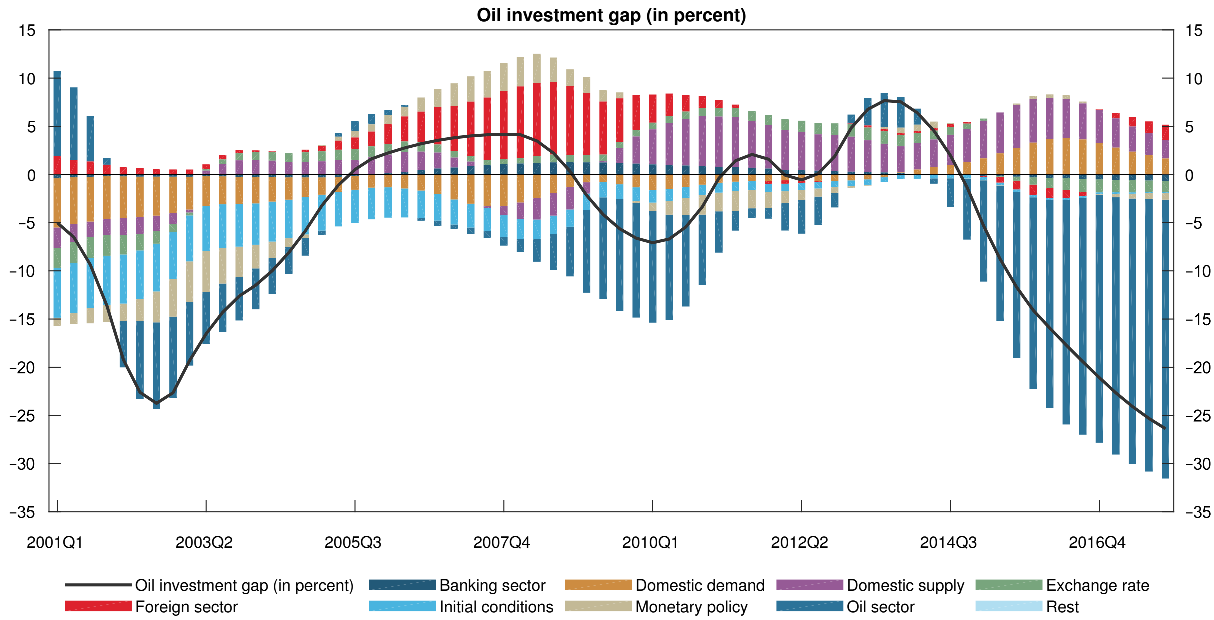

Figure 59: Historical shock decomposition of the oil investment gap

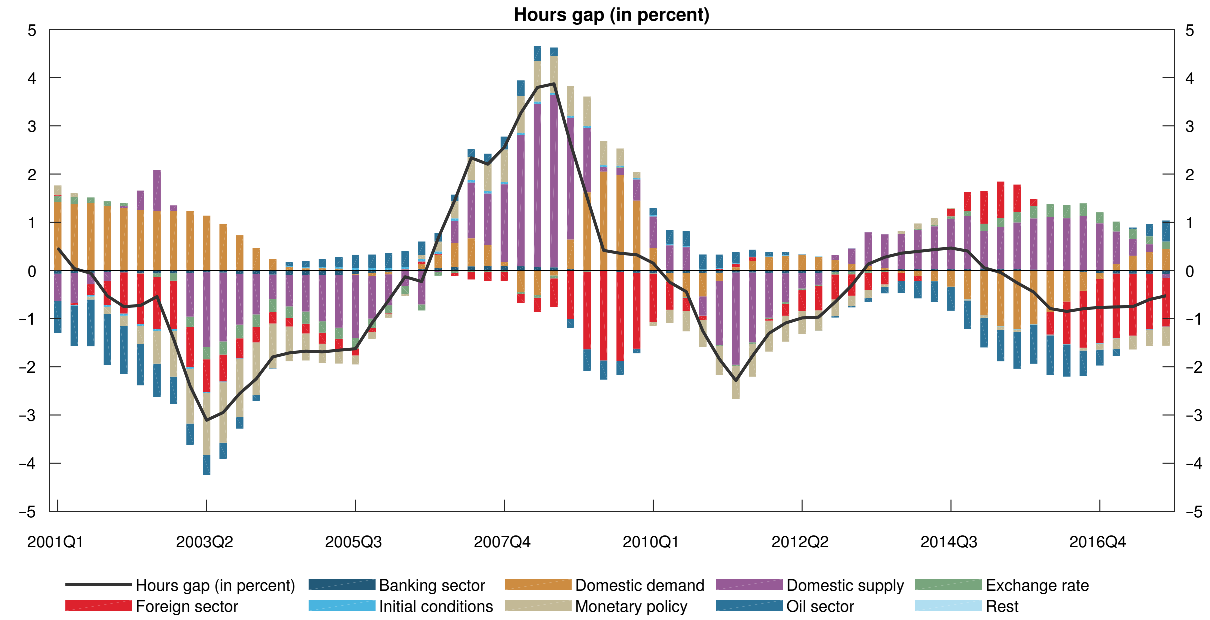

Figure 60: Historical shock decomposition of the hours worked gap

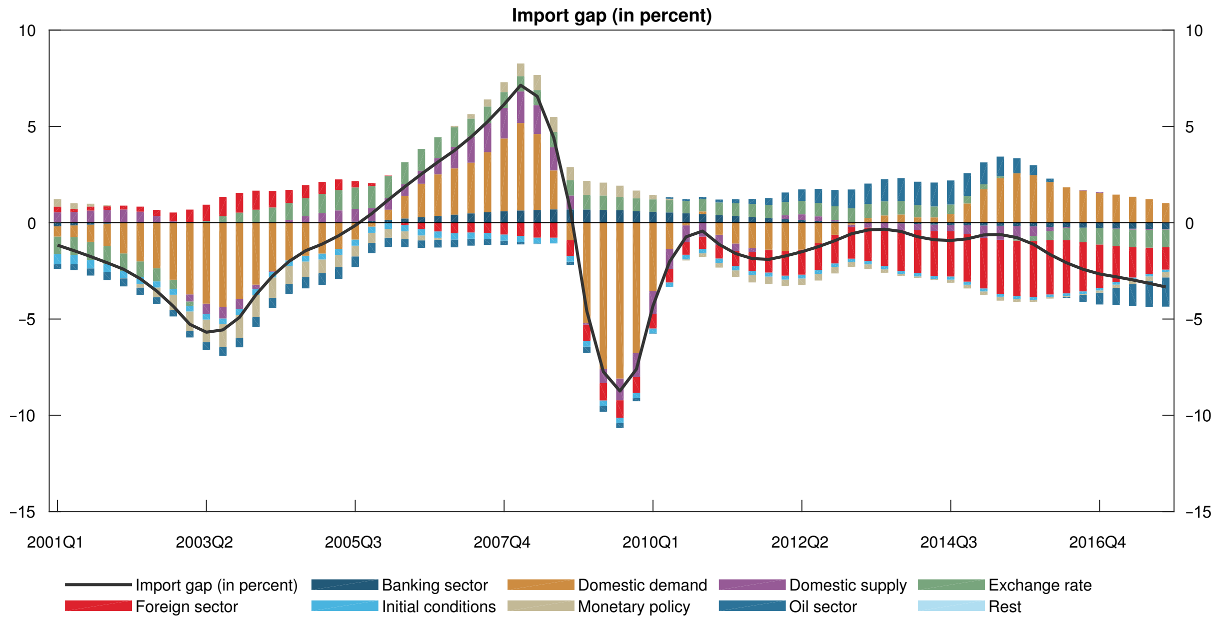

Figure 61: Historical shock decomposition of the import gap

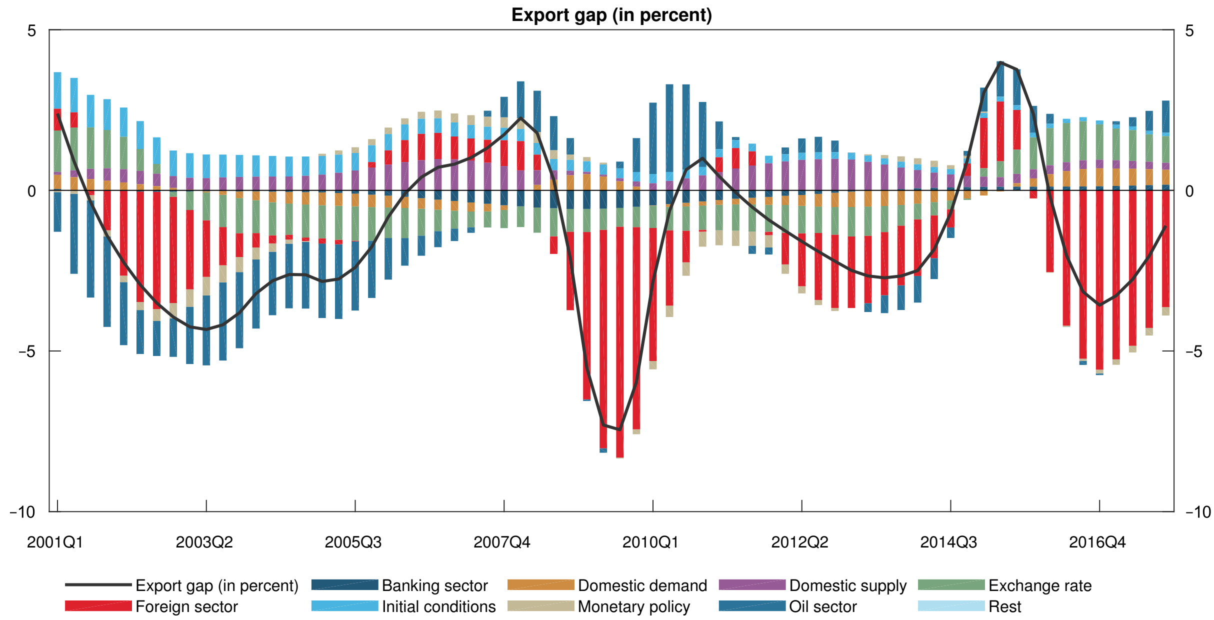

Figure 62: Historical shock decomposition of the export gap

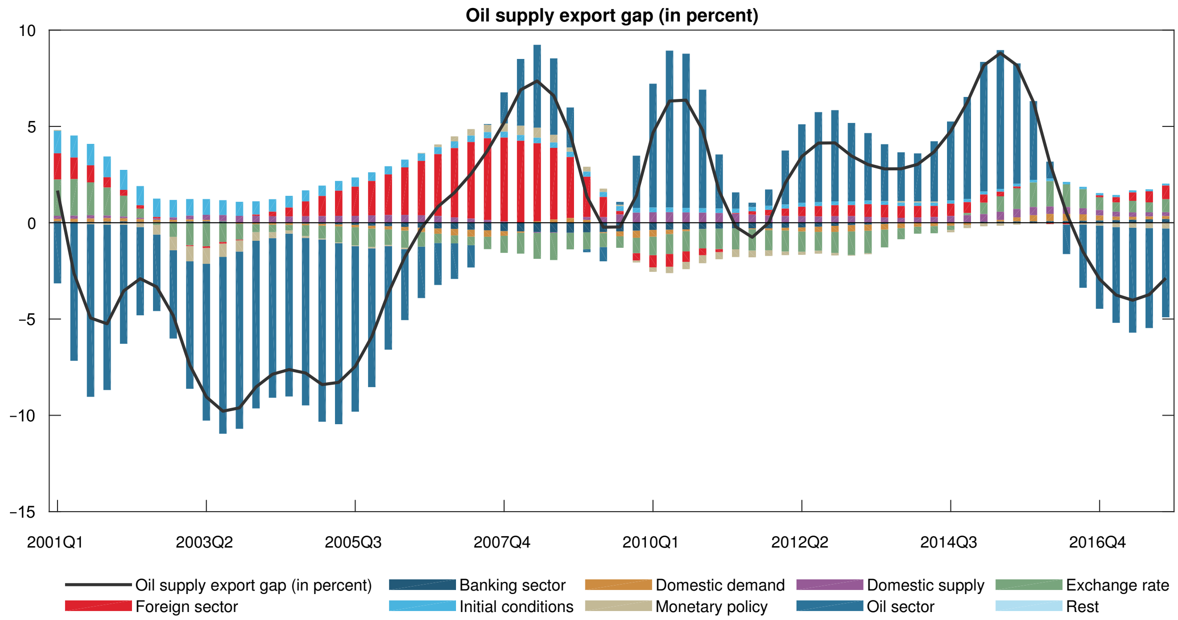

Figure 63: Historical shock decomposition of the oil supply export gap

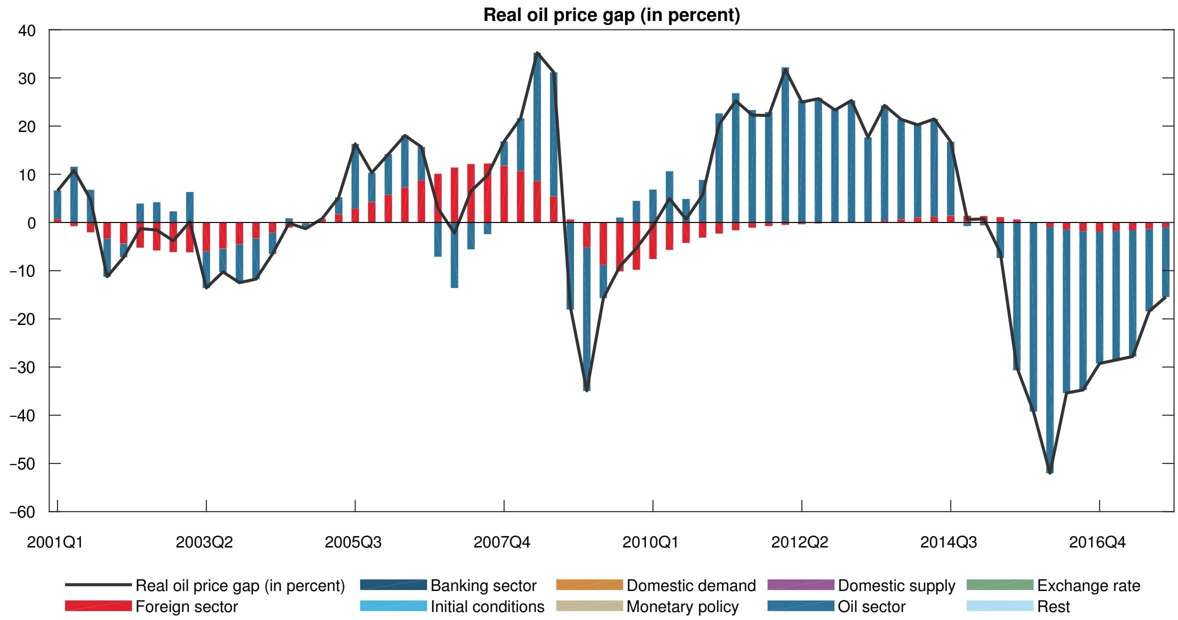

Figure 64: Historical shock decomposition of the real oil price gap

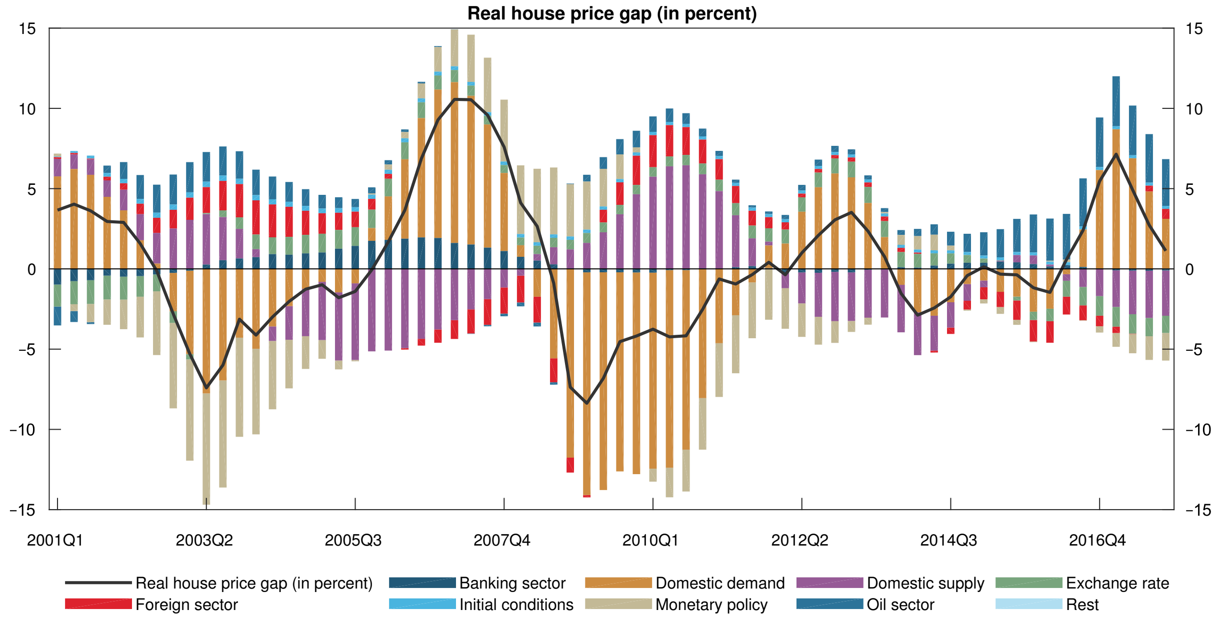

Figure 65: Historical shock decomposition of the real house price gap

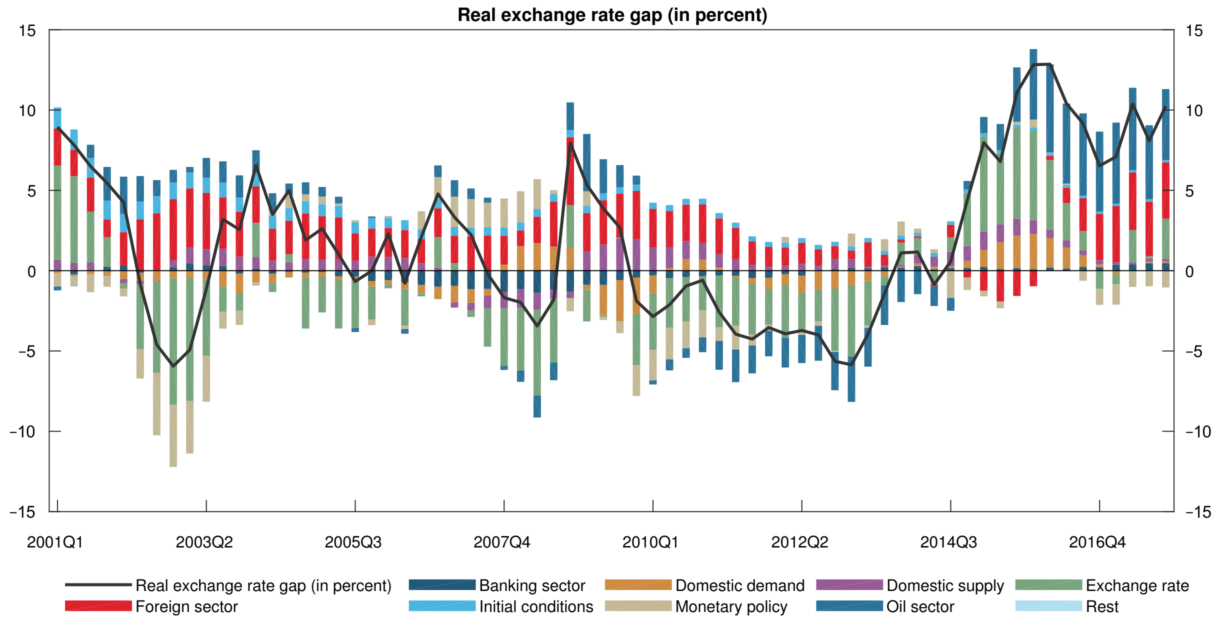

Figure 66: Historical shock decomposition of the real exchange rate gap

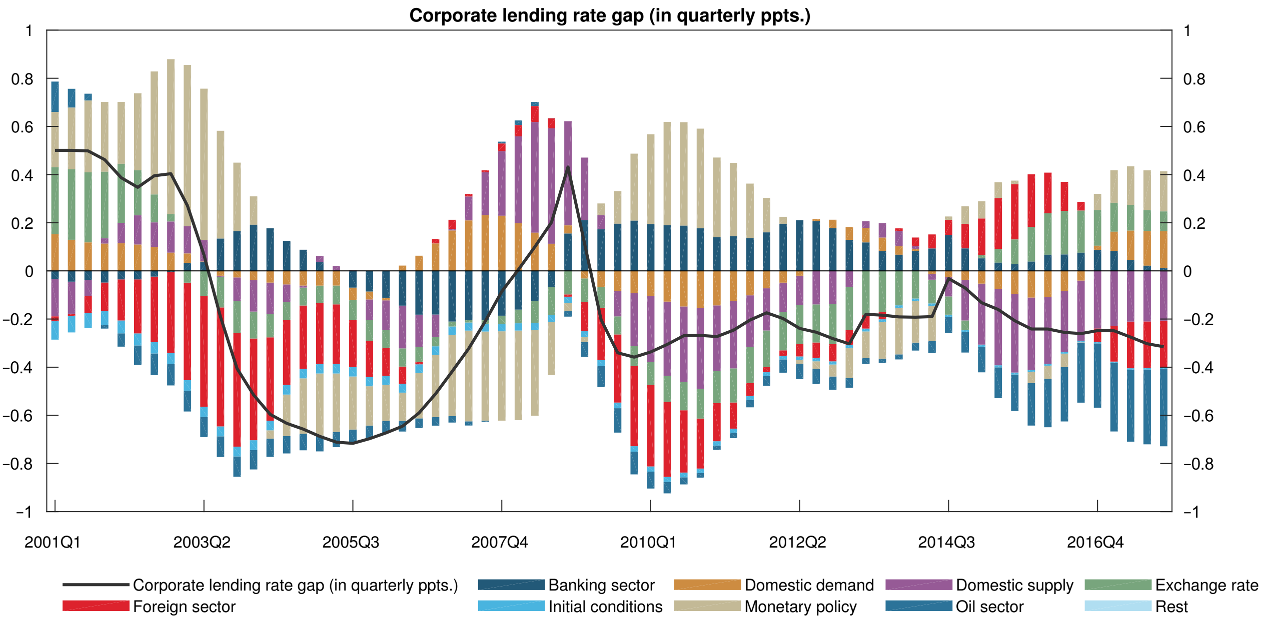

Figure 67: Historical shock decomposition of the corporate lending rate gap

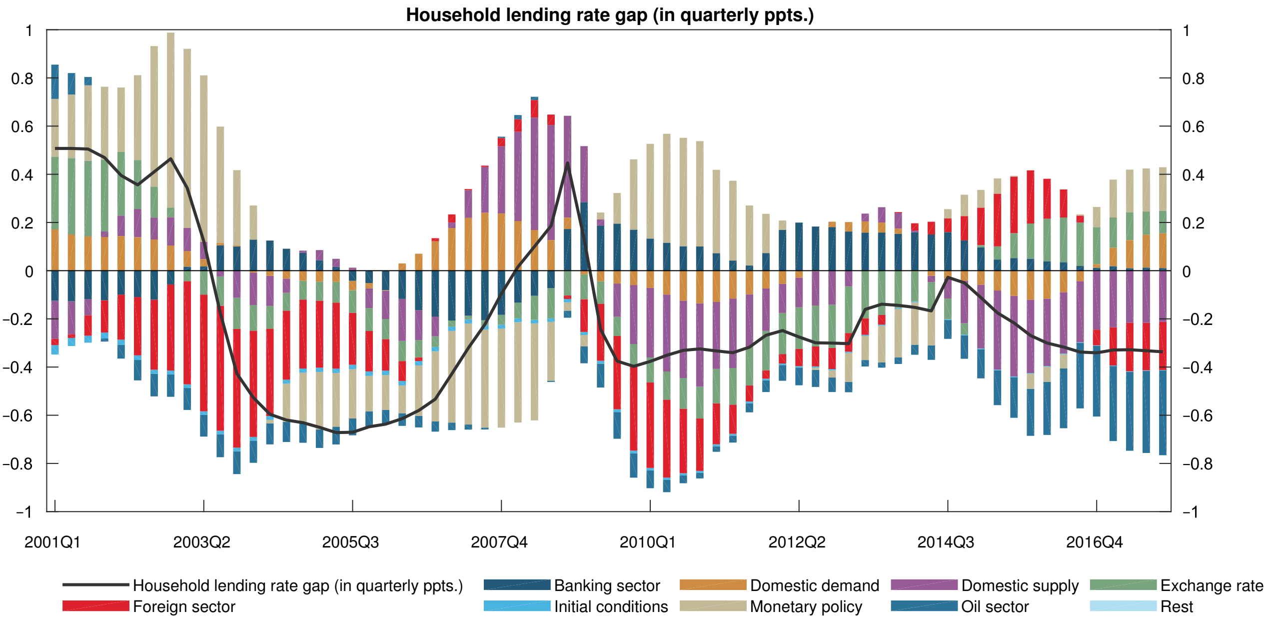

Figure 68: Historical shock decomposition of the household lending rate gap

K Historical shock decompositions: All shocks

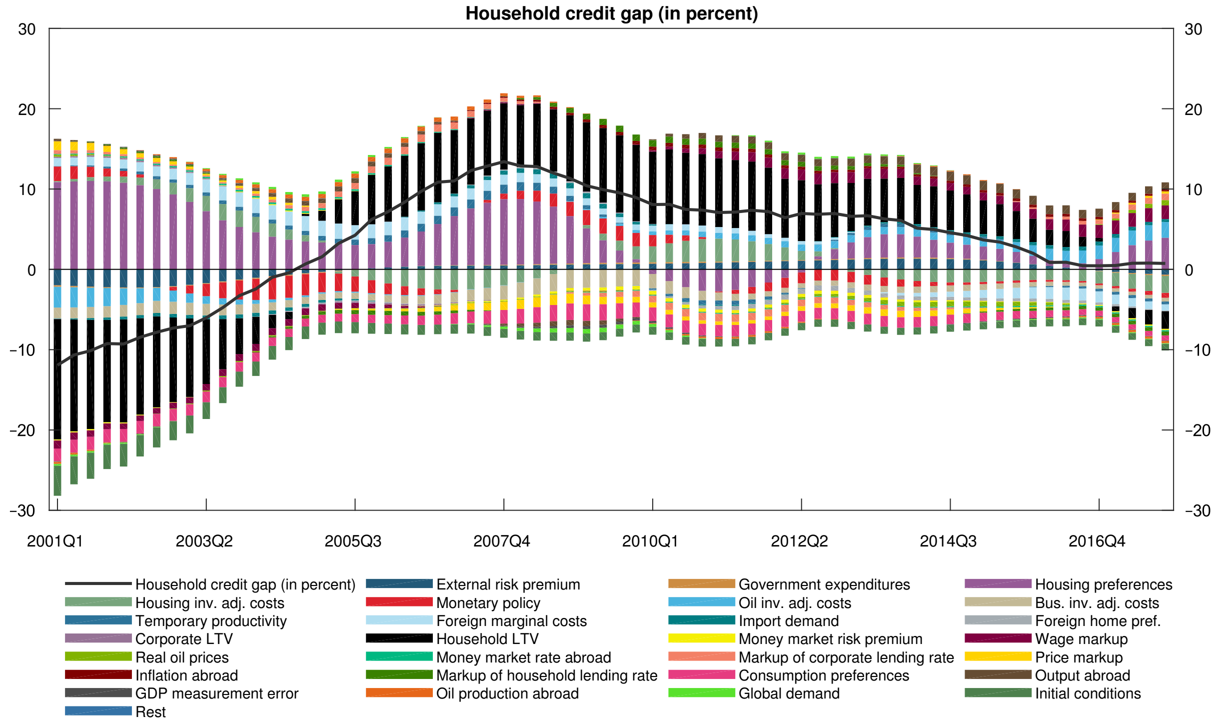

Figure 69: Historical shock decomposition of the household credit gap

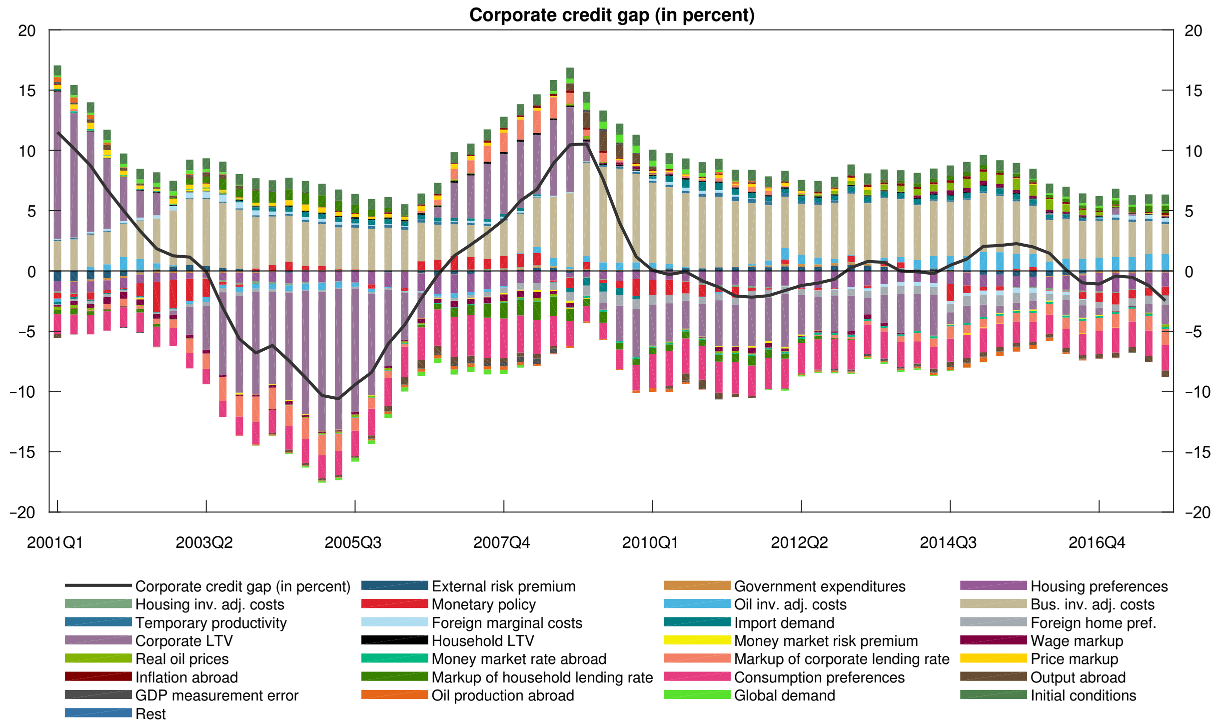

Figure 70: Historical shock decomposition of the corporate credit gap

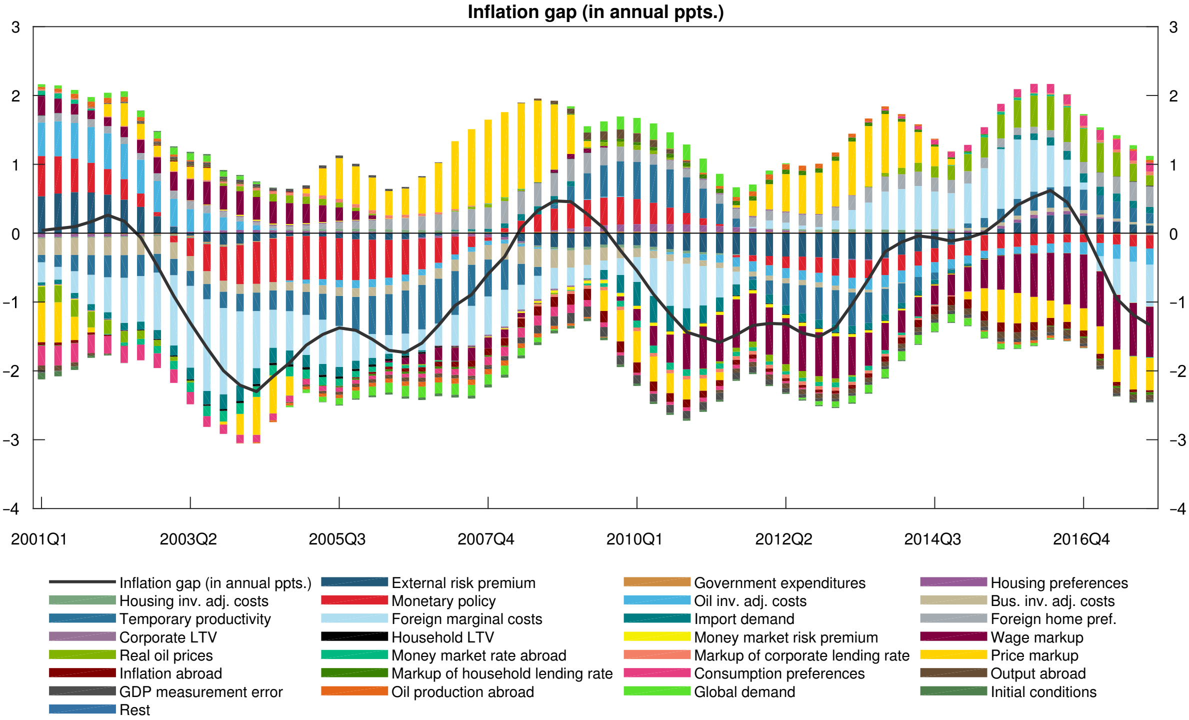

Figure 71: Historical shock decomposition of the inflation gap

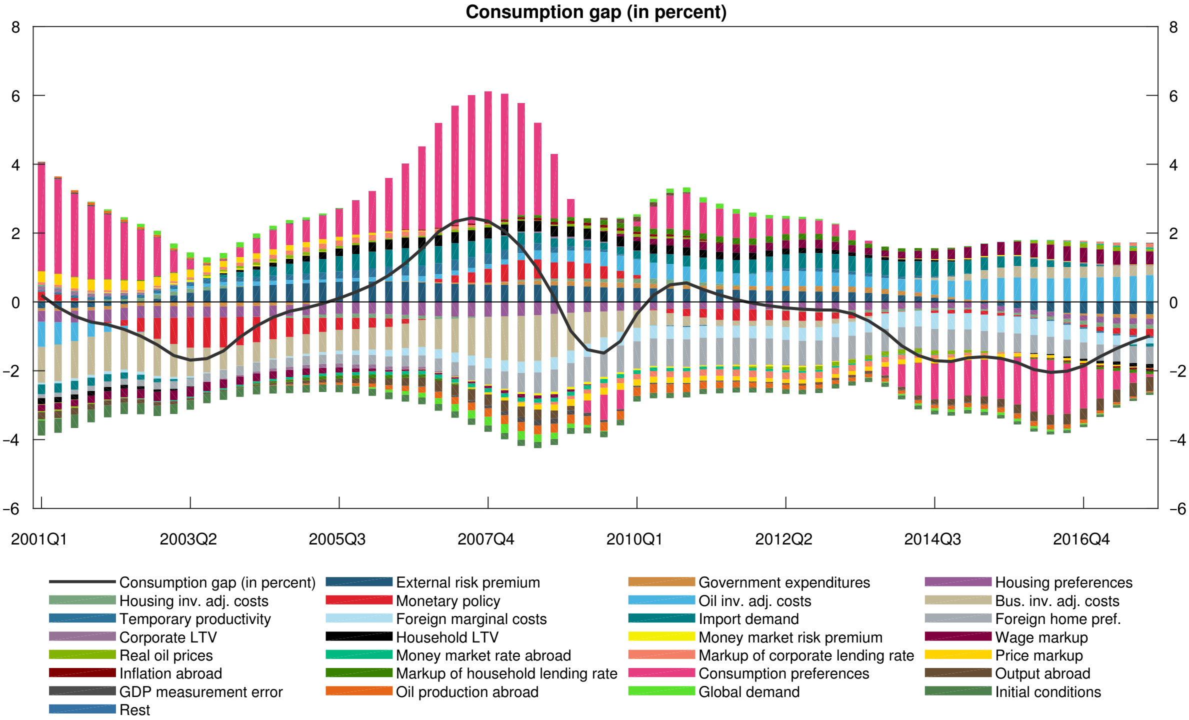

Figure 72: Historical shock decomposition of the consumption gap

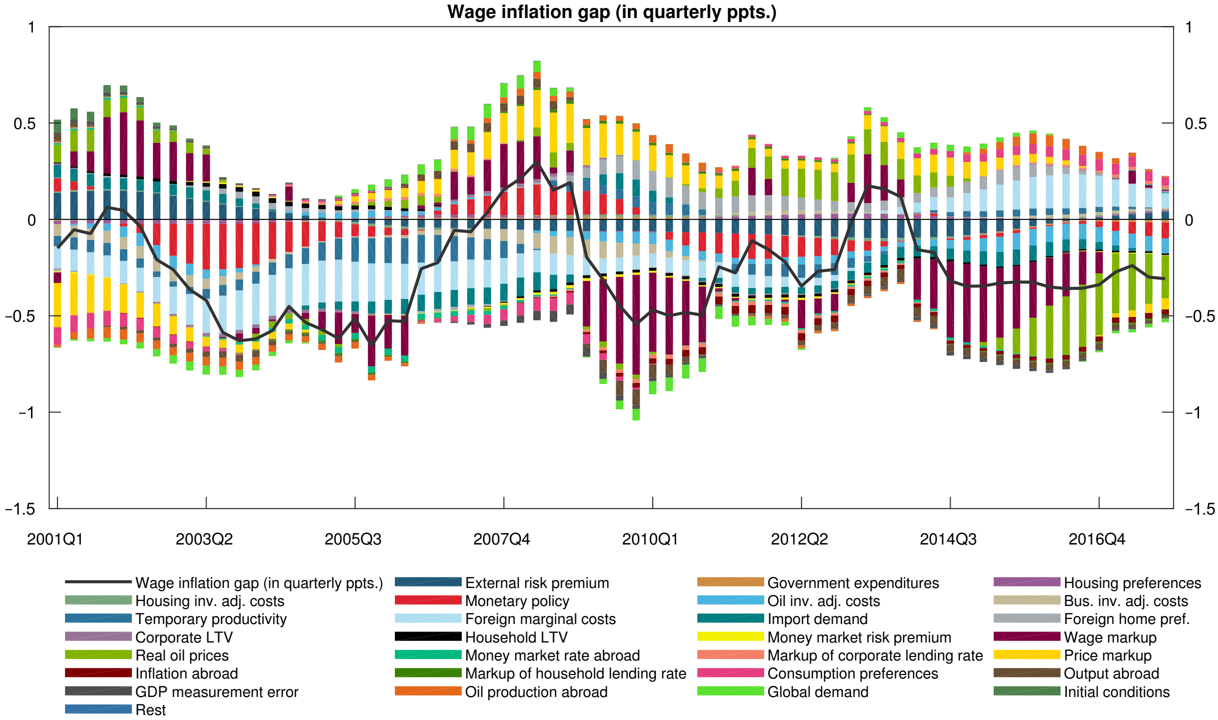

Figure 73: Historical shock decomposition of the wage inflation gap

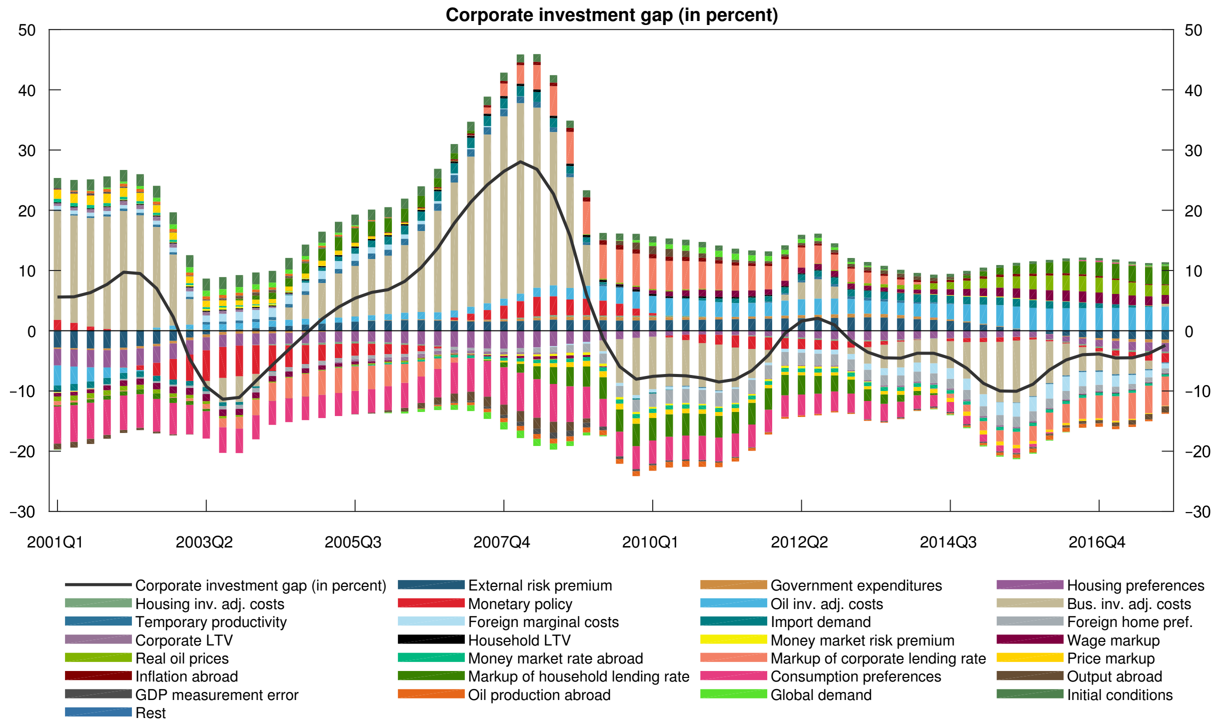

Figure 74: Historical shock decomposition of the corporate investment gap

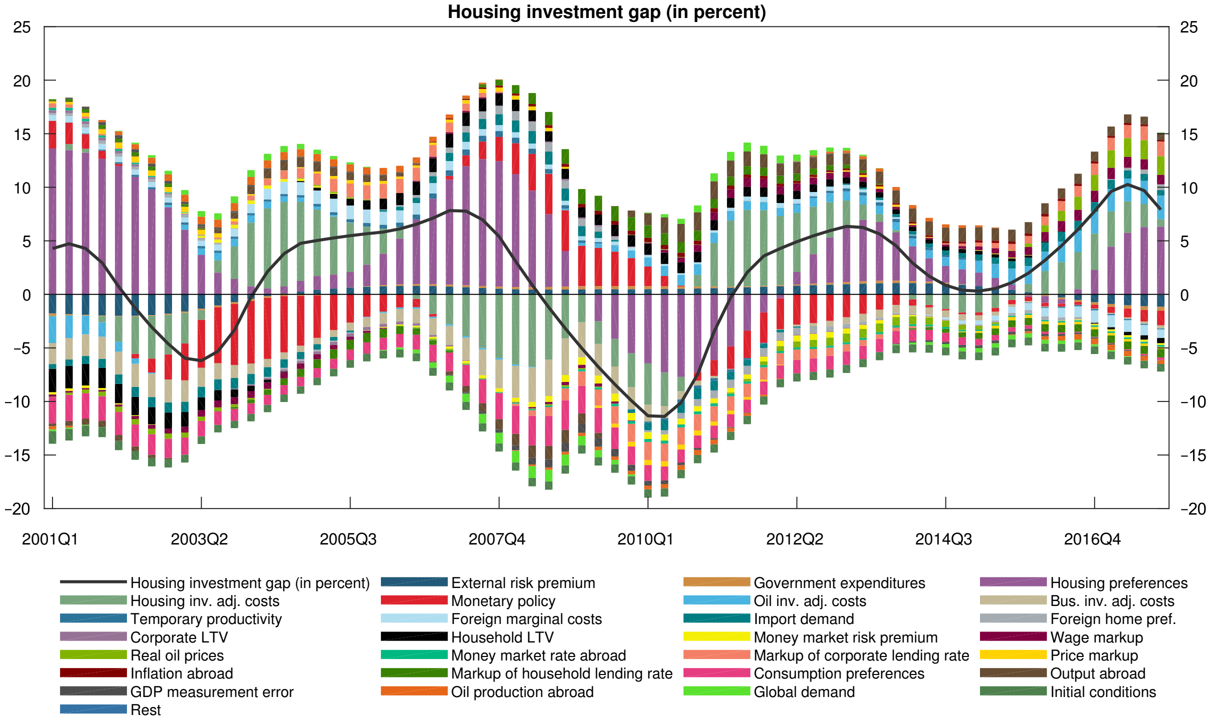

Figure 75: Historical shock decomposition of the housing investment gap

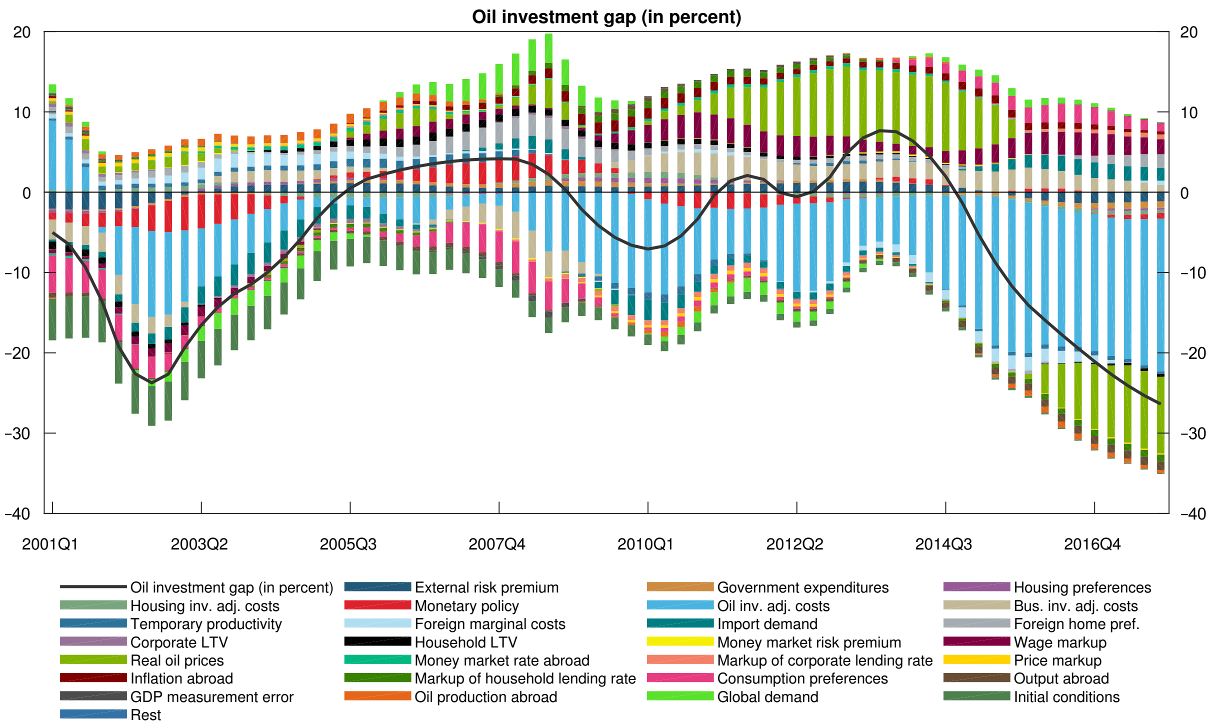

Figure 76: Historical shock decomposition of the oil investment gap

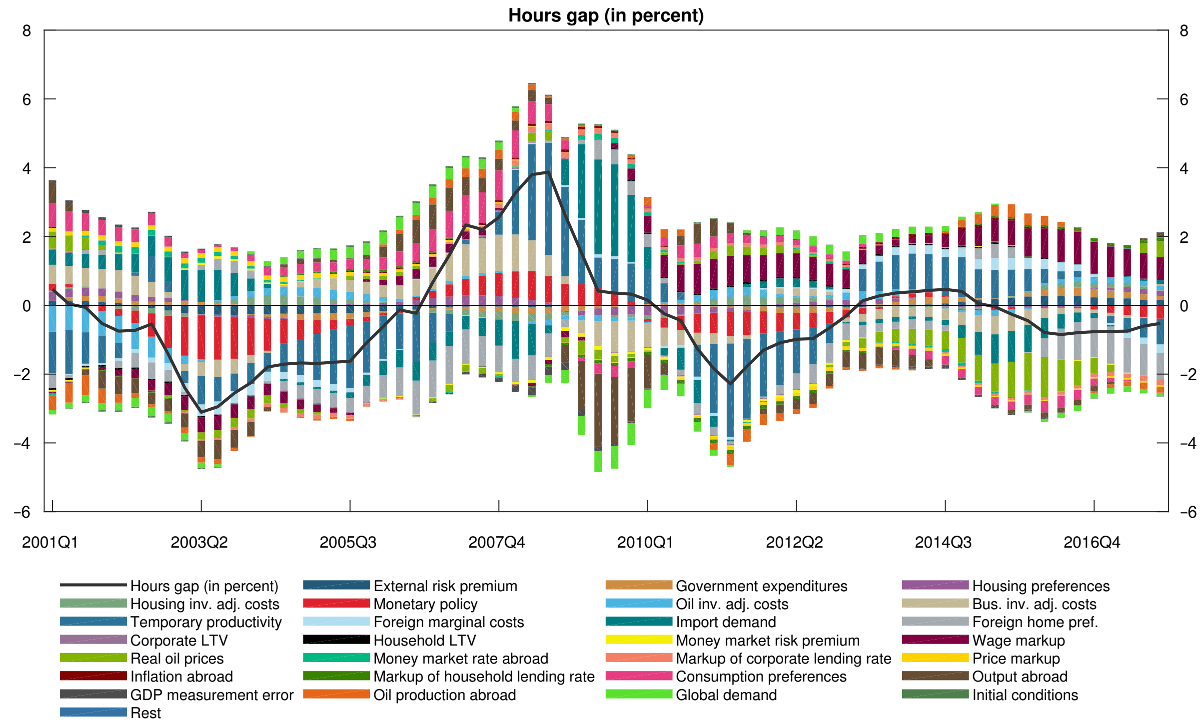

Figure 77: Historical shock decomposition of the hours worked gap

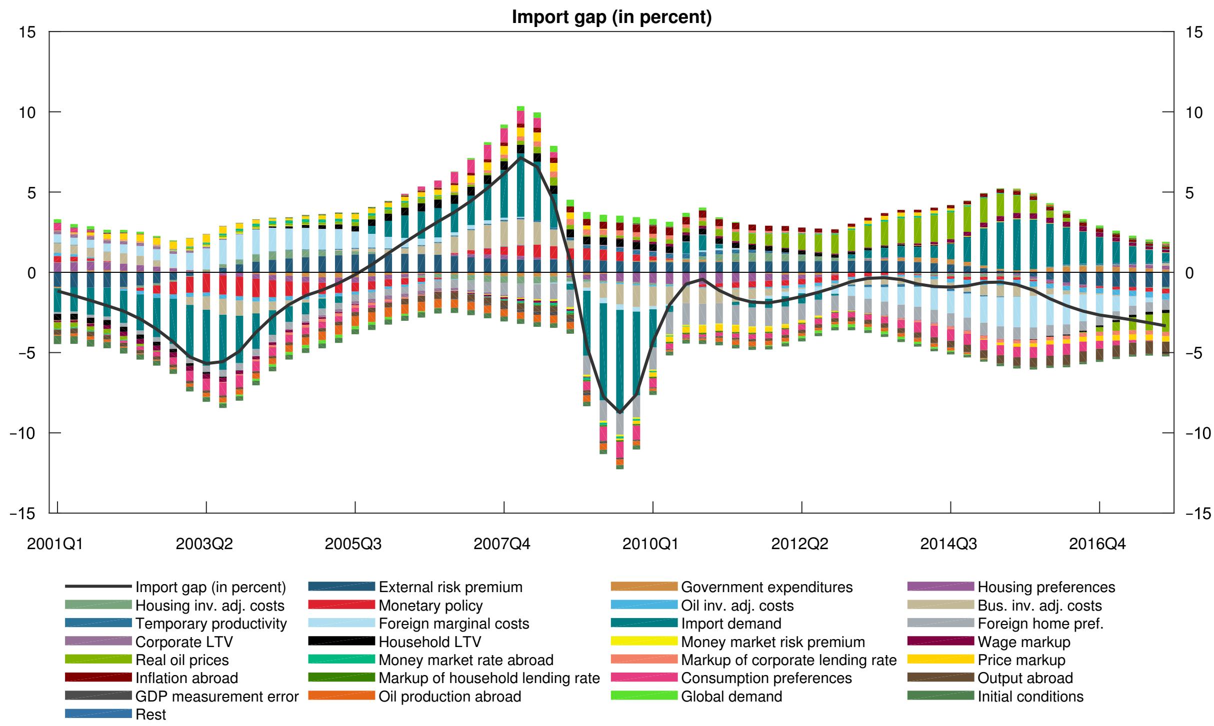

Figure 78: Historical shock decomposition of the import gap

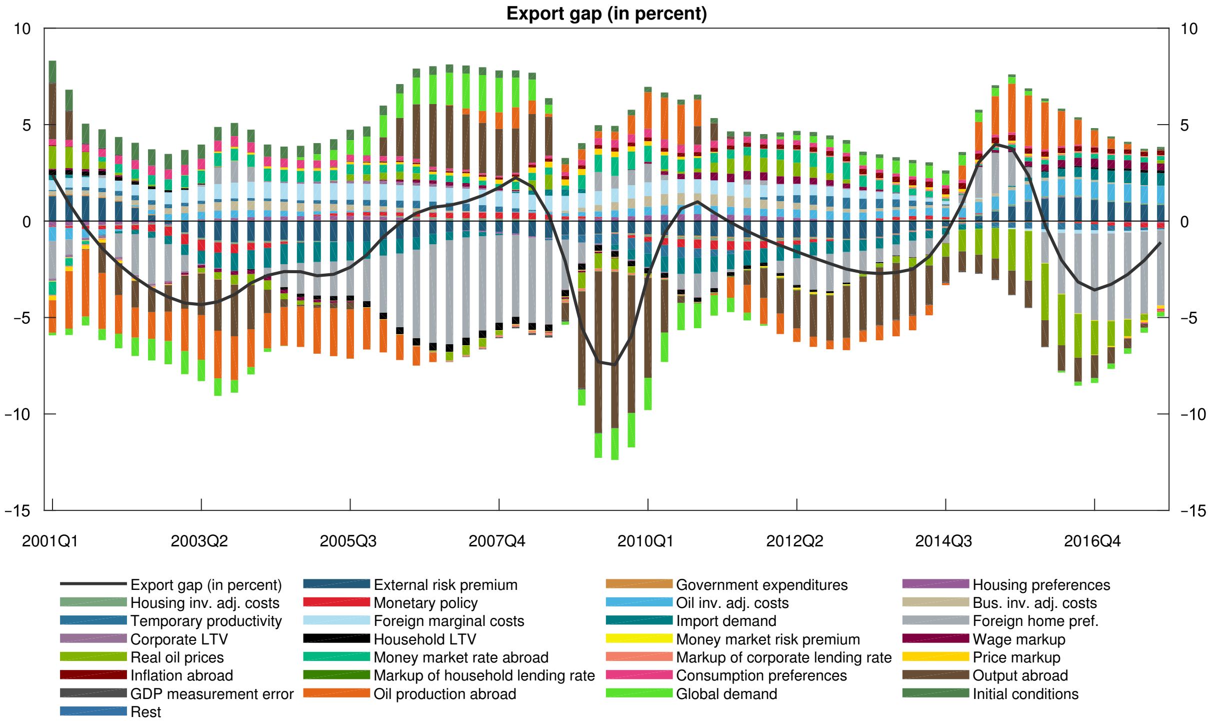

Figure 79: Historical shock decomposition of the export gap

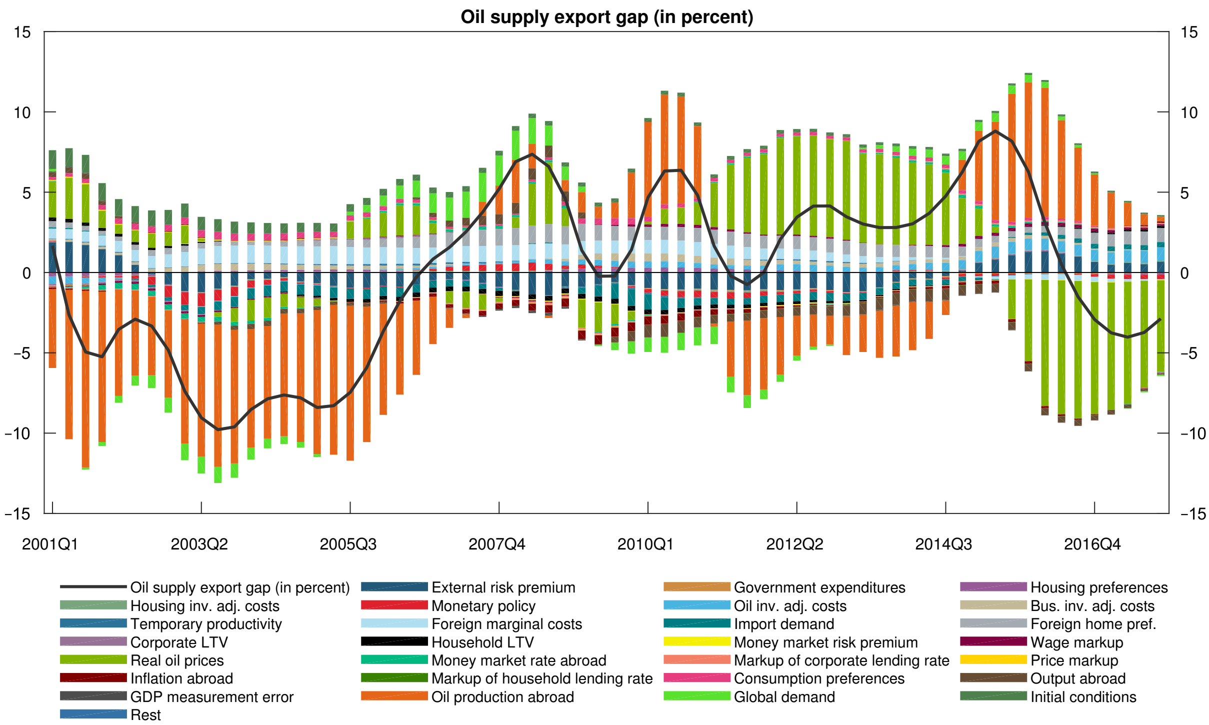

Figure 80: Historical shock decomposition of the oil supply export gap

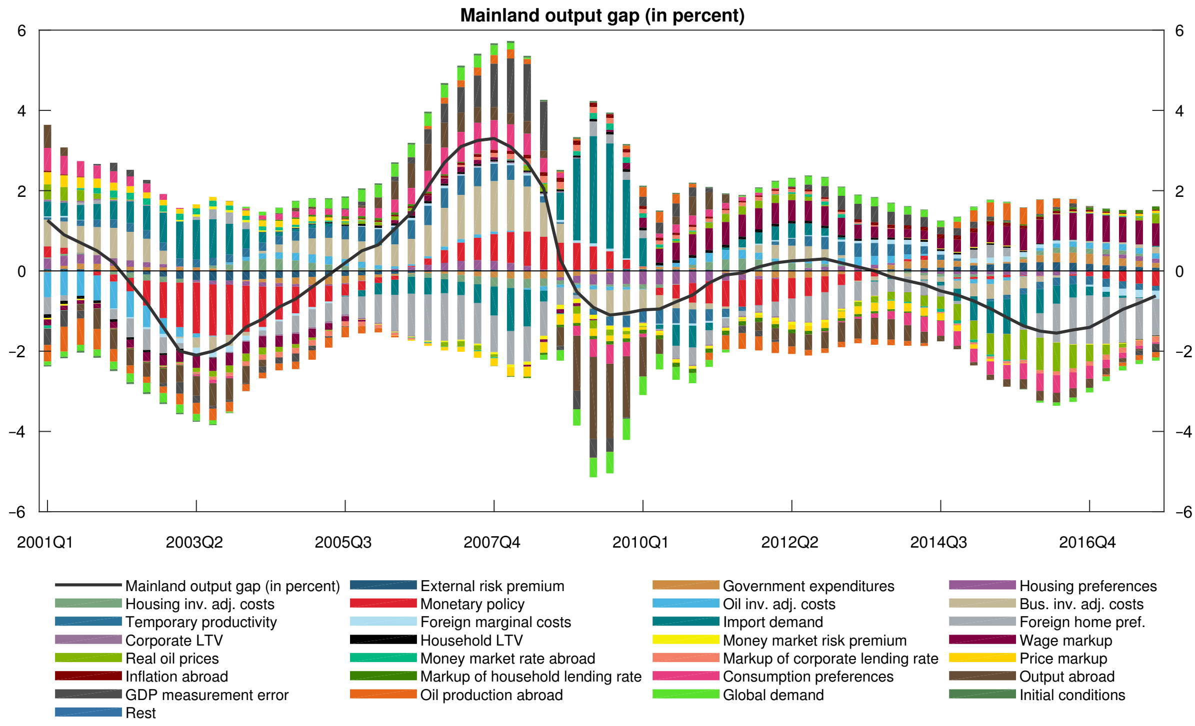

Figure 81: Historical shock decomposition of the mainland output gap

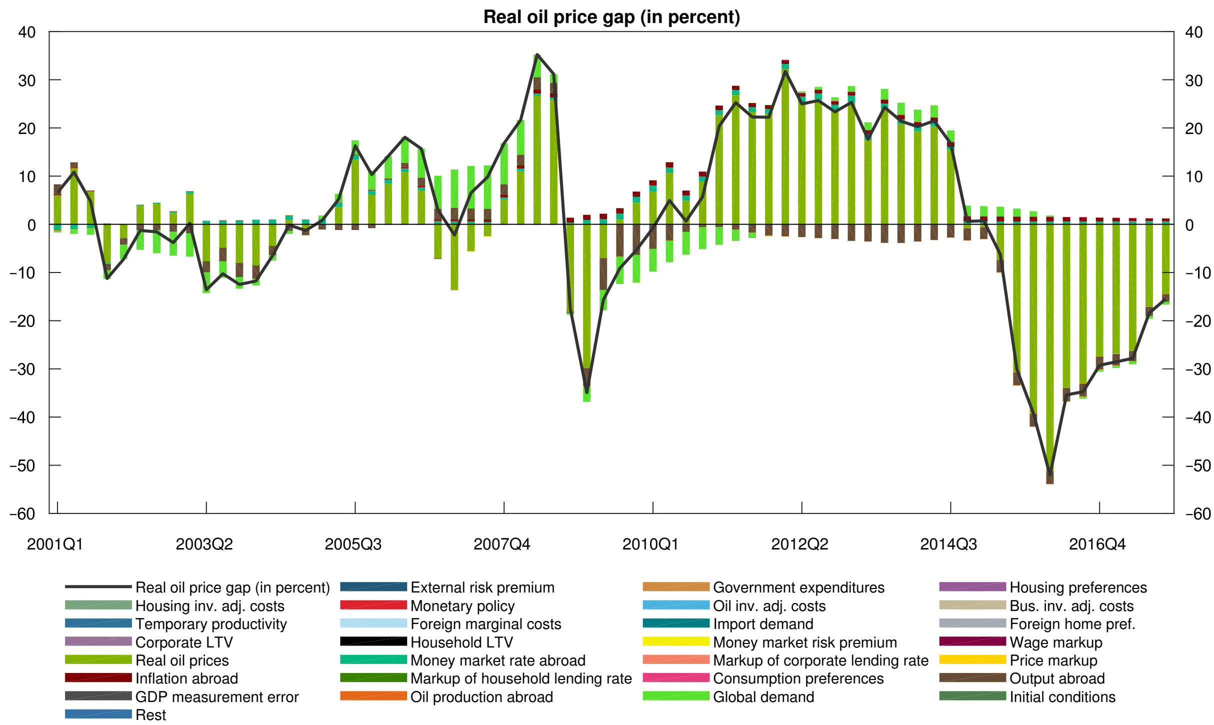

Figure 82: Historical shock decomposition of the real oil price gap

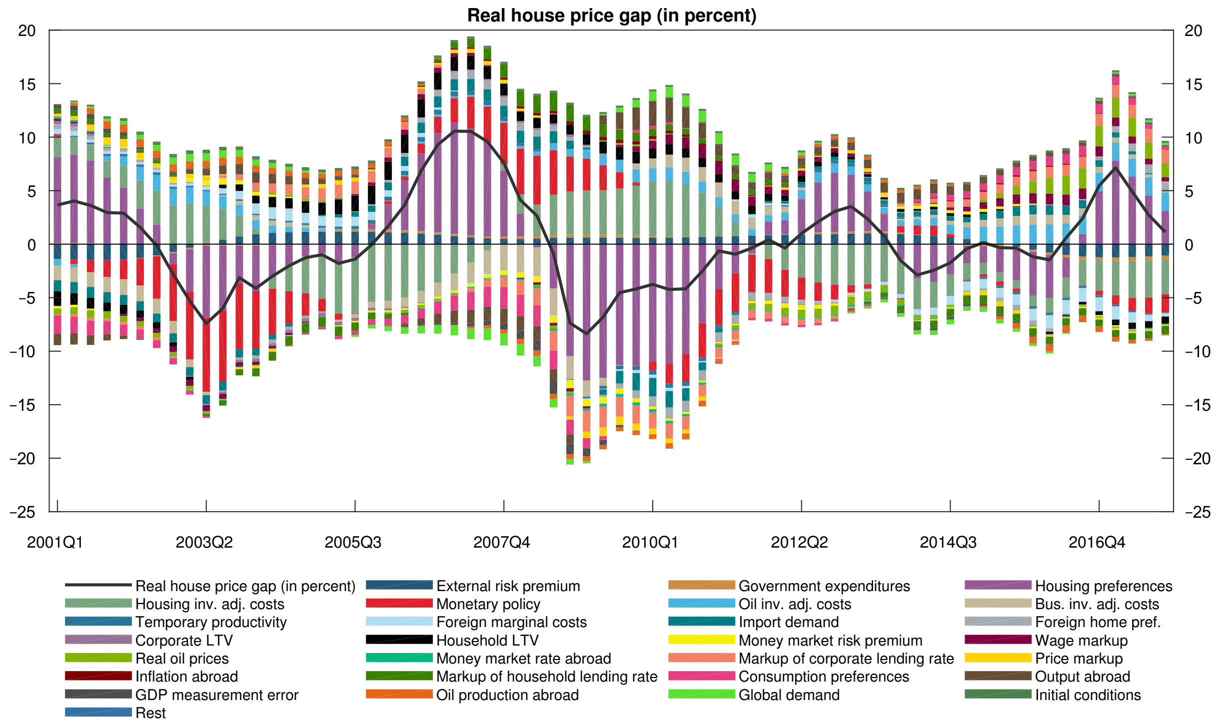

Figure 83: Historical shock decomposition of the real house price gap

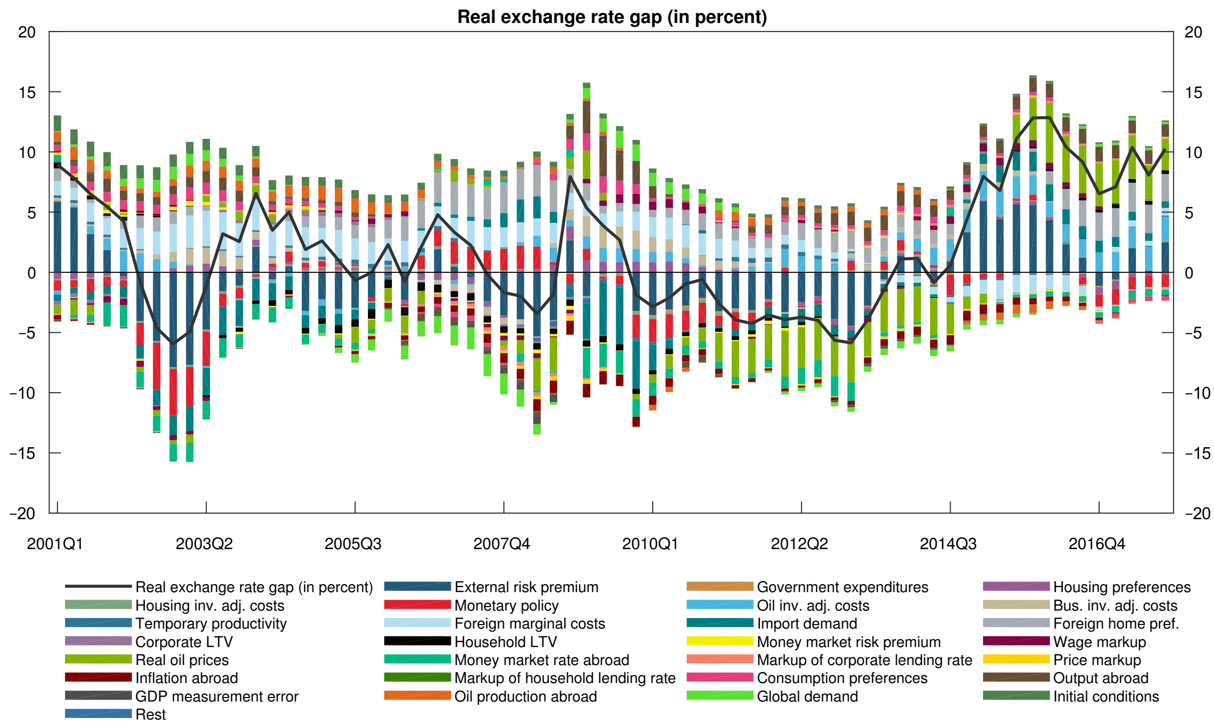

Figure 84: Historical shock decomposition of the real exchange rate gap

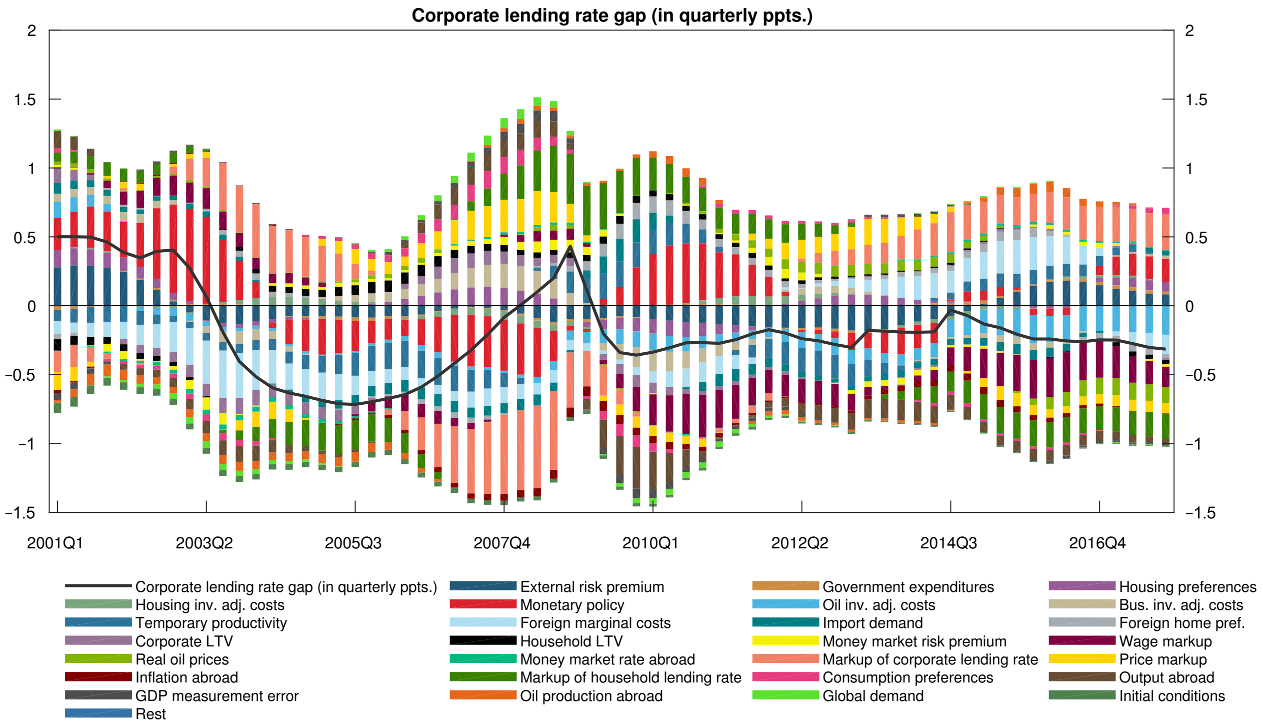

Figure 85: Historical shock decomposition of the corporate lending rate gap

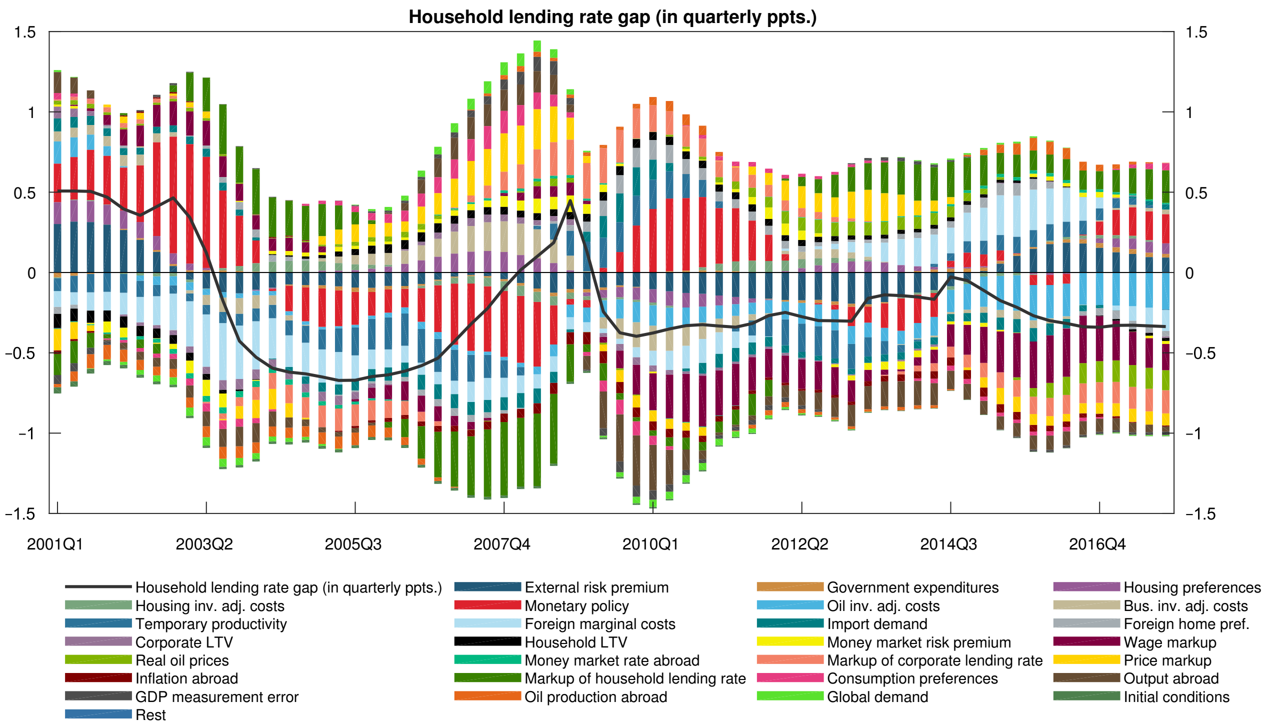

Figure 86: Historical shock decomposition of the household lending rate gap

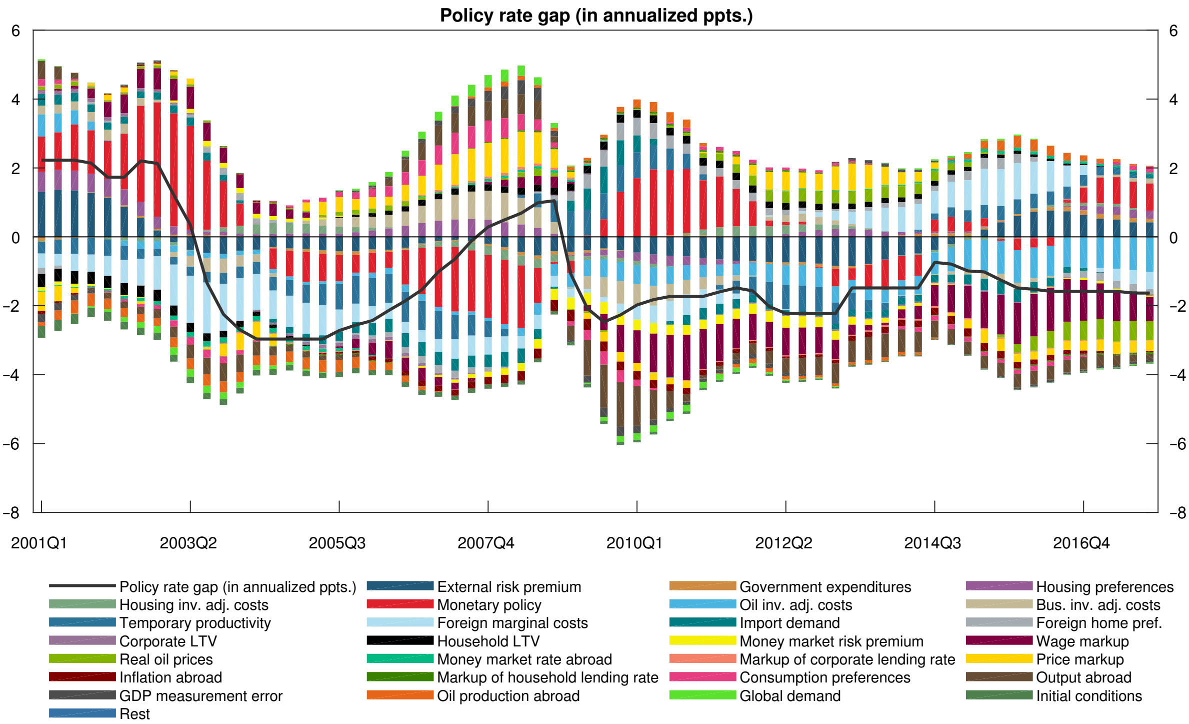

Figure 87: Historical shock decomposition of the policy rate gap

L Forecast-error-variance decompositions: Grouped shocks

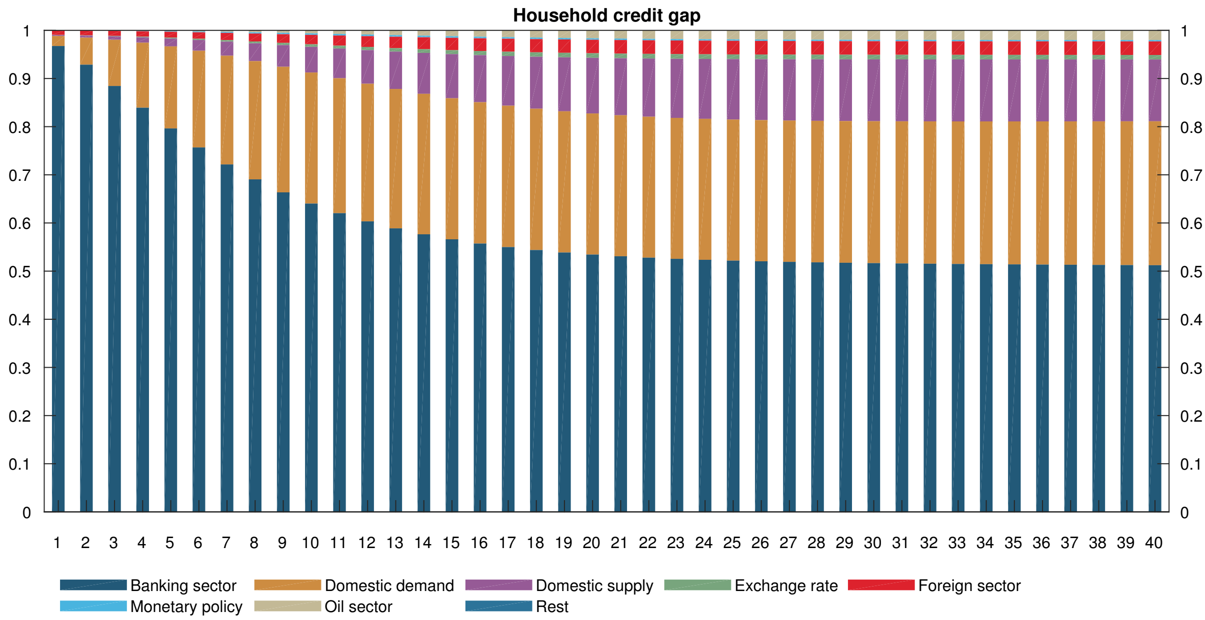

Figure 88: Forecast-error-variance decomposition of the household credit gap

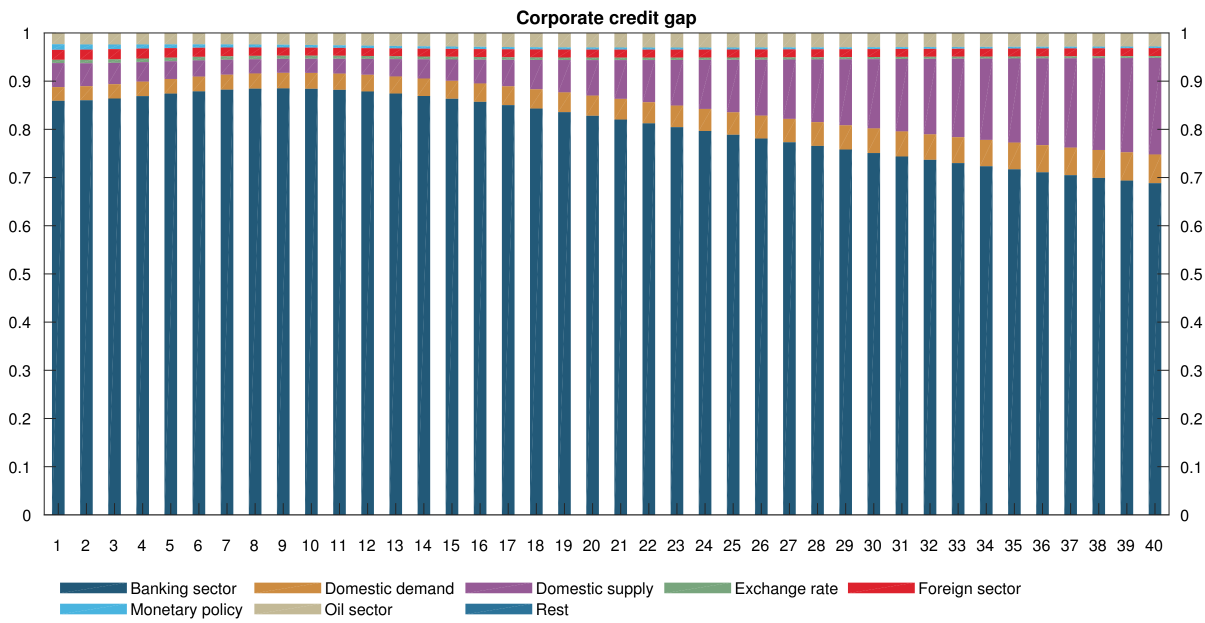

Figure 89: Forecast-error-variance decomposition of the corporate credit gap

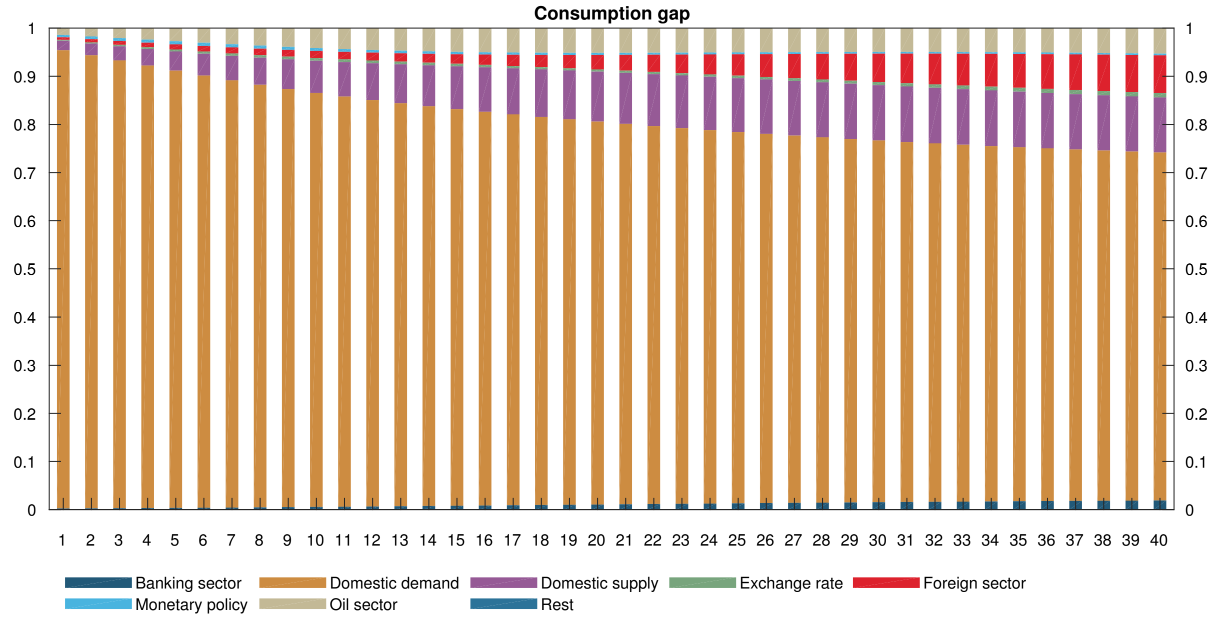

Figure 90: Forecast-error-variance decomposition of the consumption gap

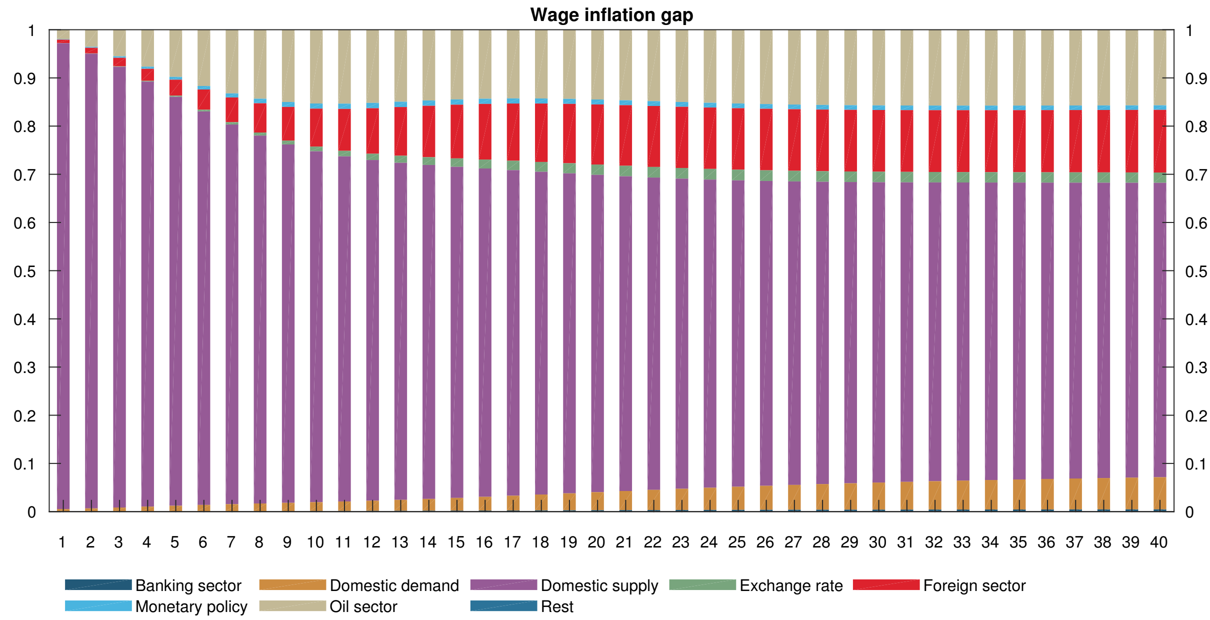

Figure 91: Forecast-error-variance decomposition of the wage inflation gap

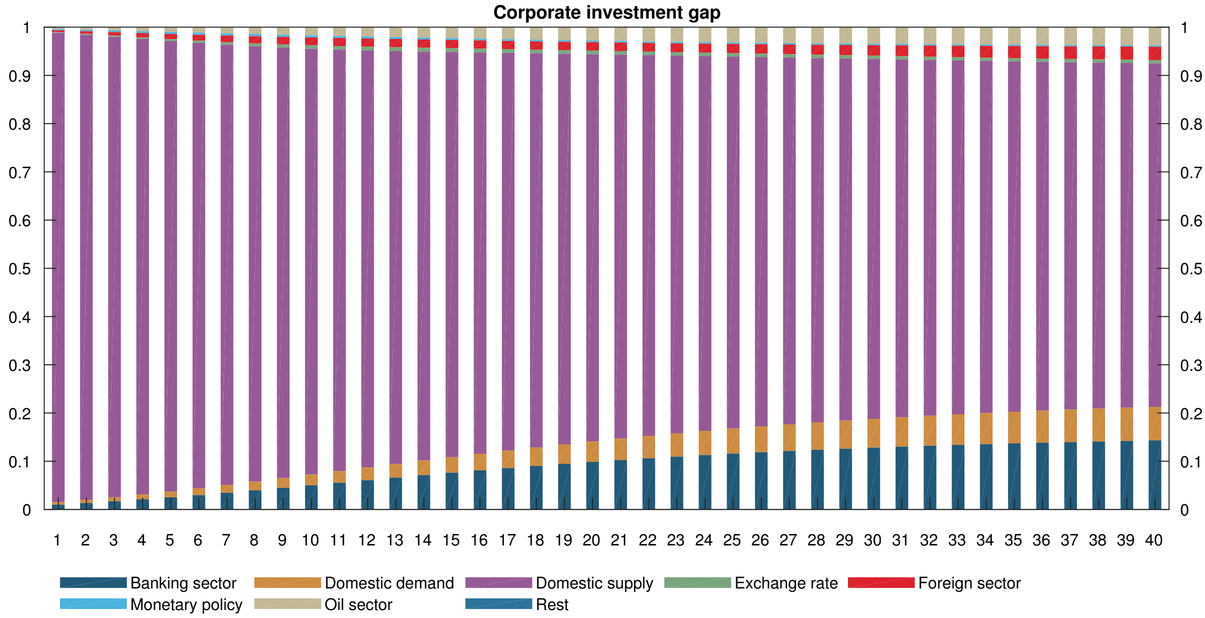

Figure 92: Forecast-error-variance decomposition of the corporate investment gap

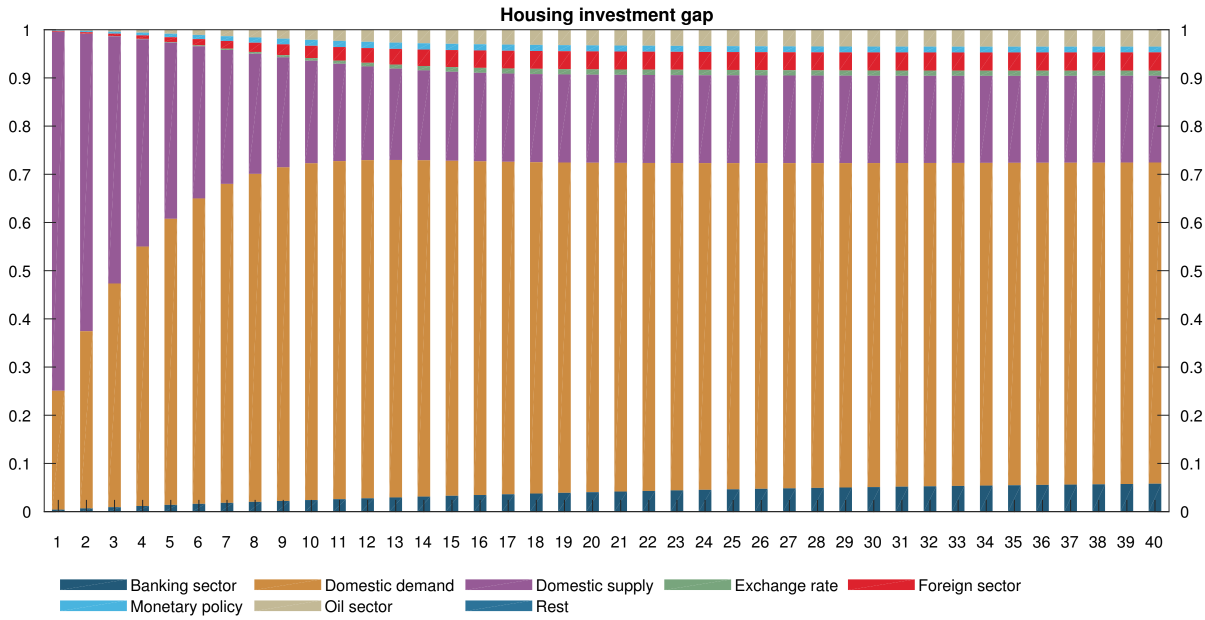

Figure 93: Forecast-error-variance decomposition of the housing investment gap

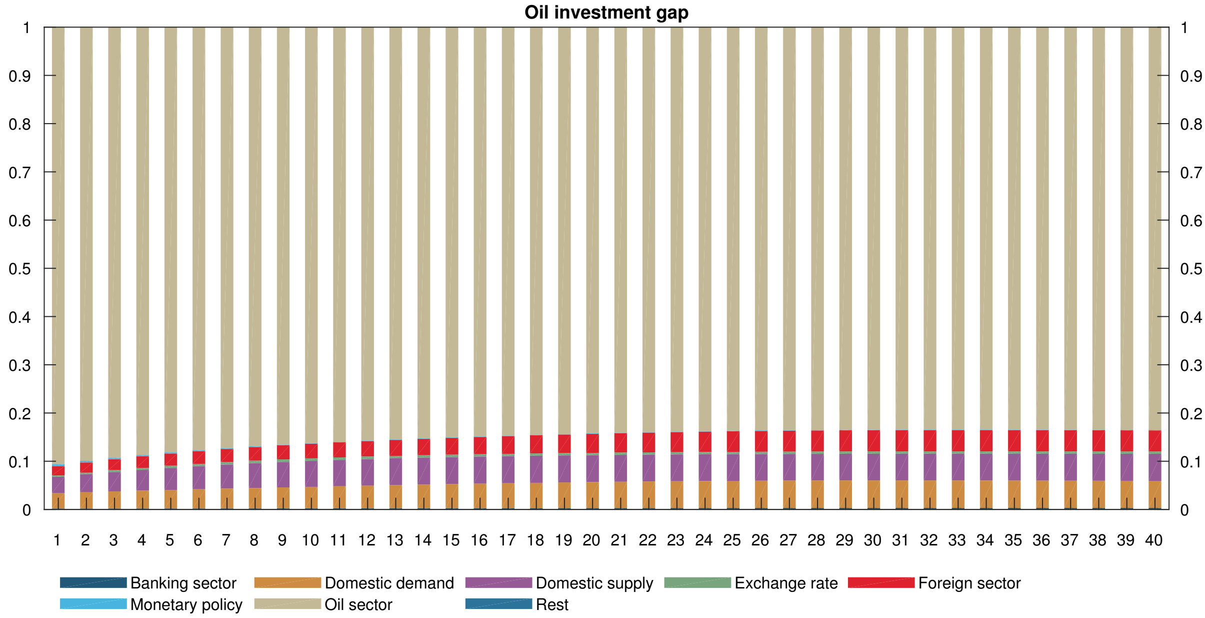

Figure 94: Forecast-error-variance decomposition of the oil investment gap

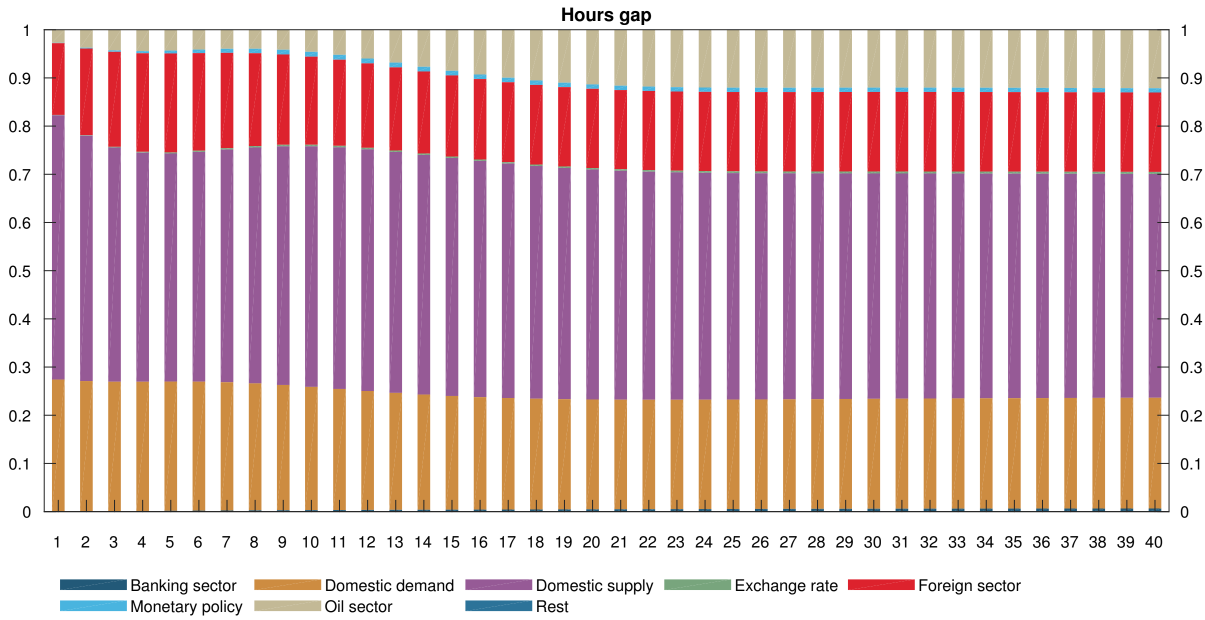

Figure 95: Forecast-error-variance decomposition of the hours worked gap

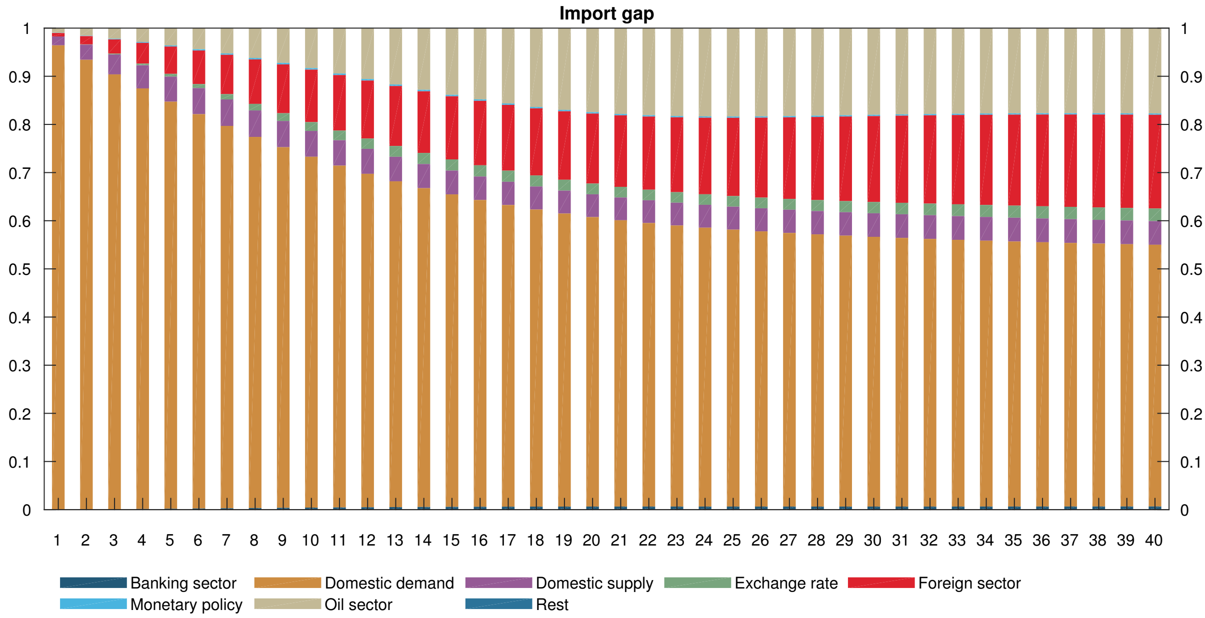

Figure 96: Forecast-error-variance decomposition of the import gap

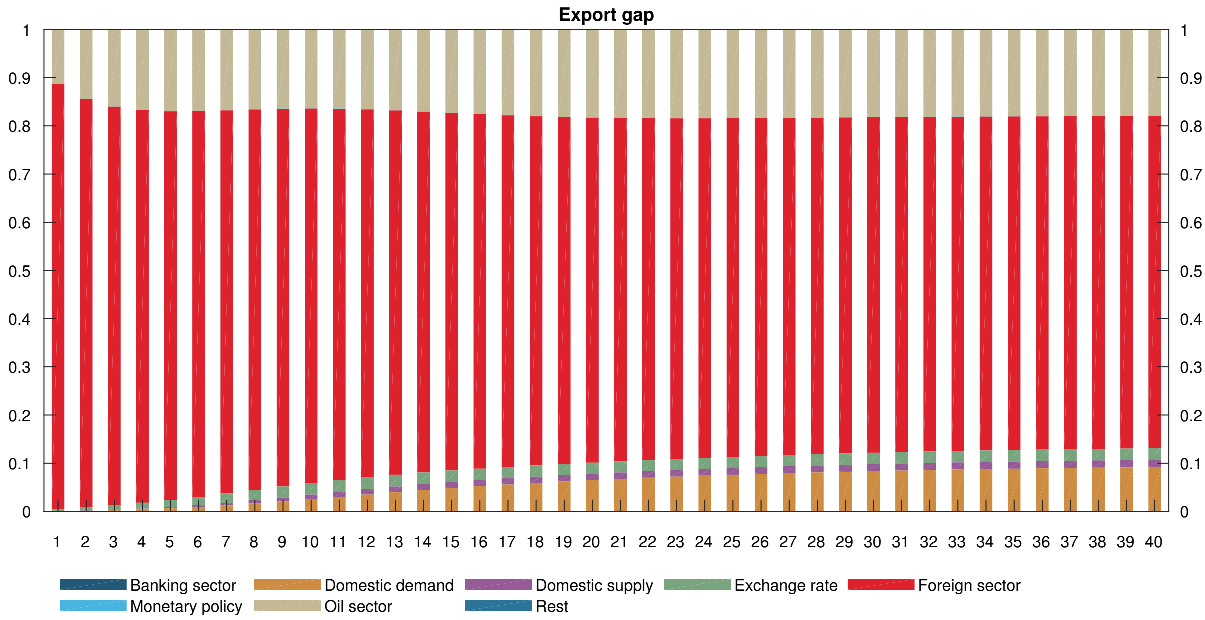

Figure 97: Forecast-error-variance decomposition of the export gap

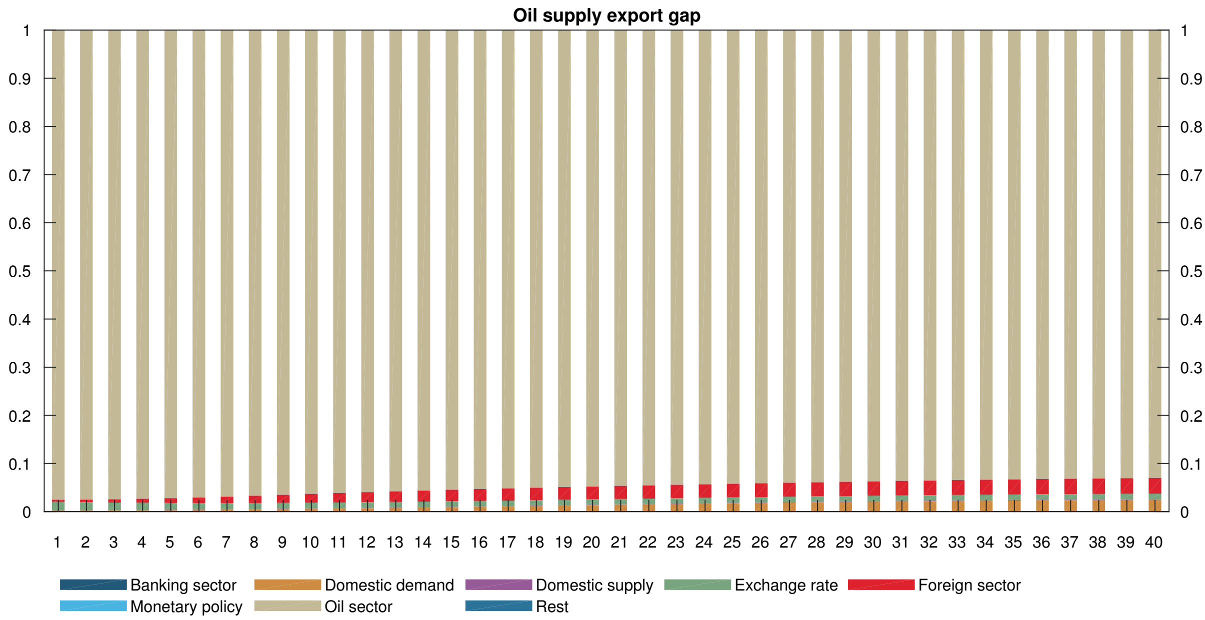

Figure 98: Forecast-error-variance decomposition of the oil supply export gap

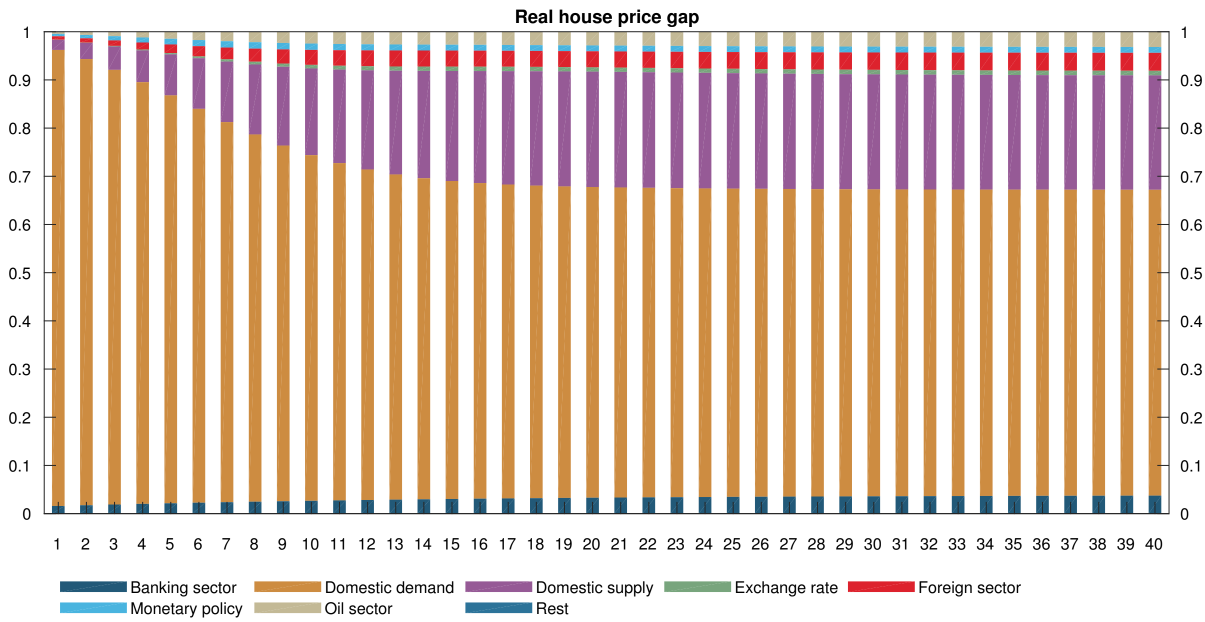

Figure 99: Forecast-error-variance decomposition of the real house price gap

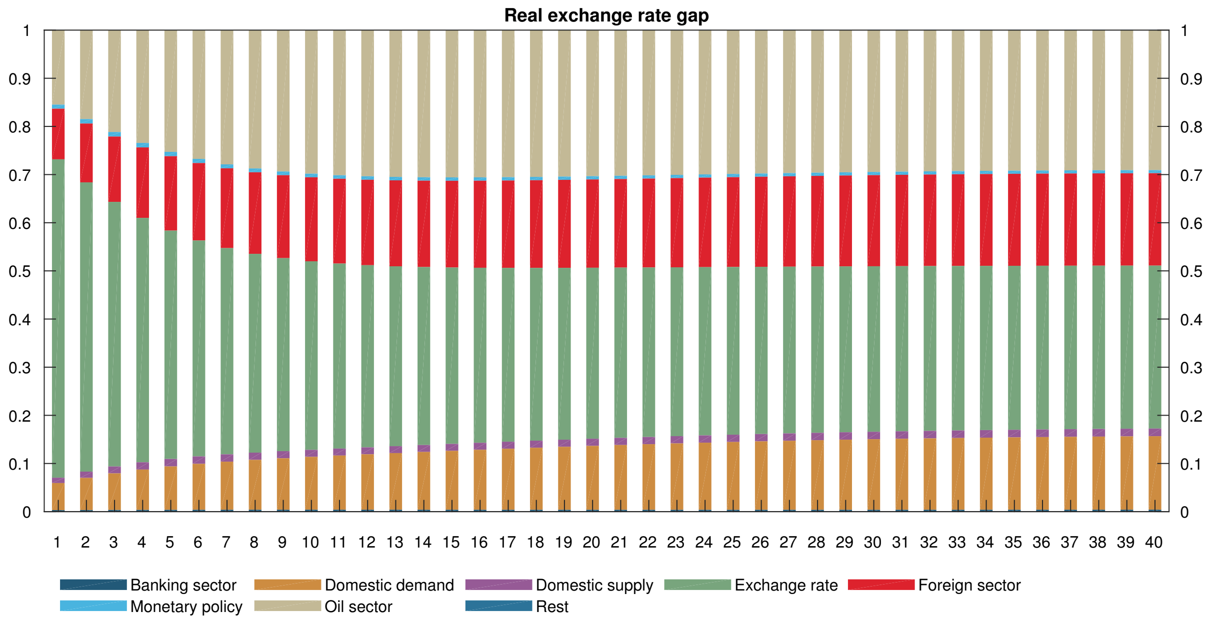

Figure 100: Forecast-error-variance decomposition of the real exchange rate gap

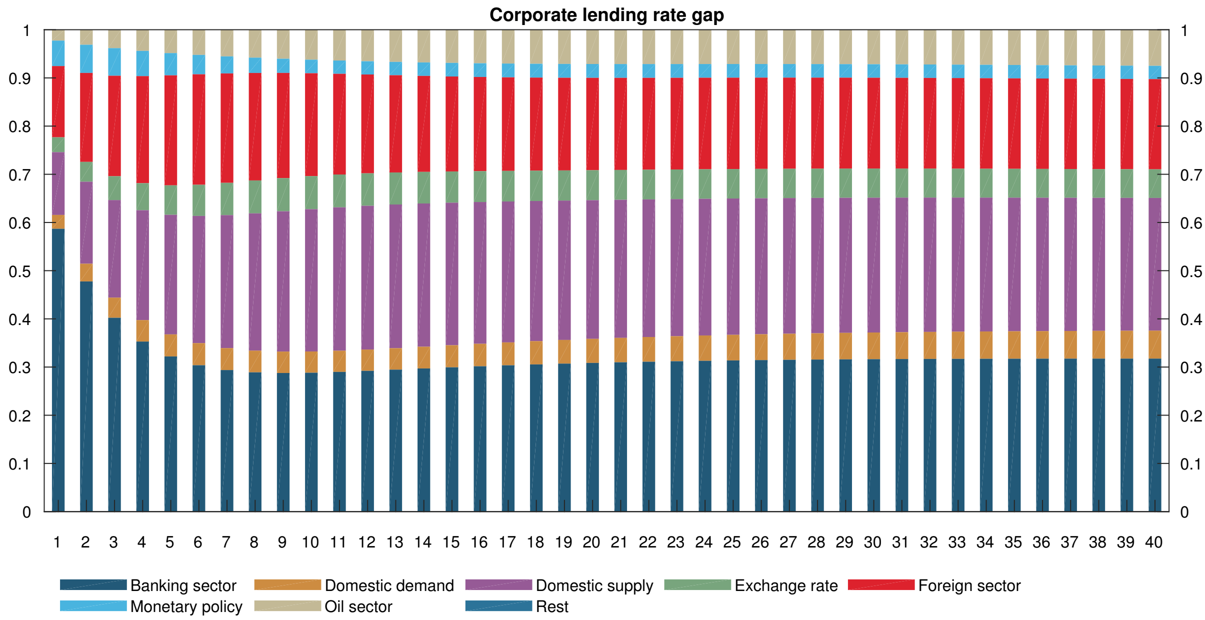

Figure 101: Forecast-error-variance decomposition of the corporate lending rate gap

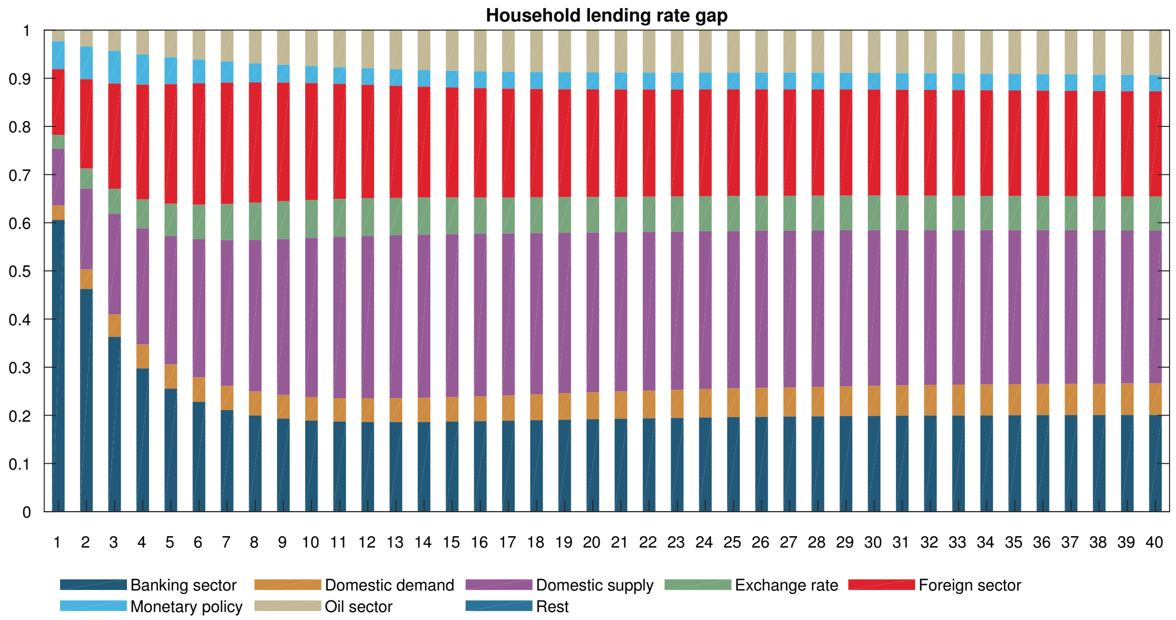

Figure 102: Forecast-error-variance decomposition of the household lending rate gap

M Forecast-error-variance decompositions: All shocks

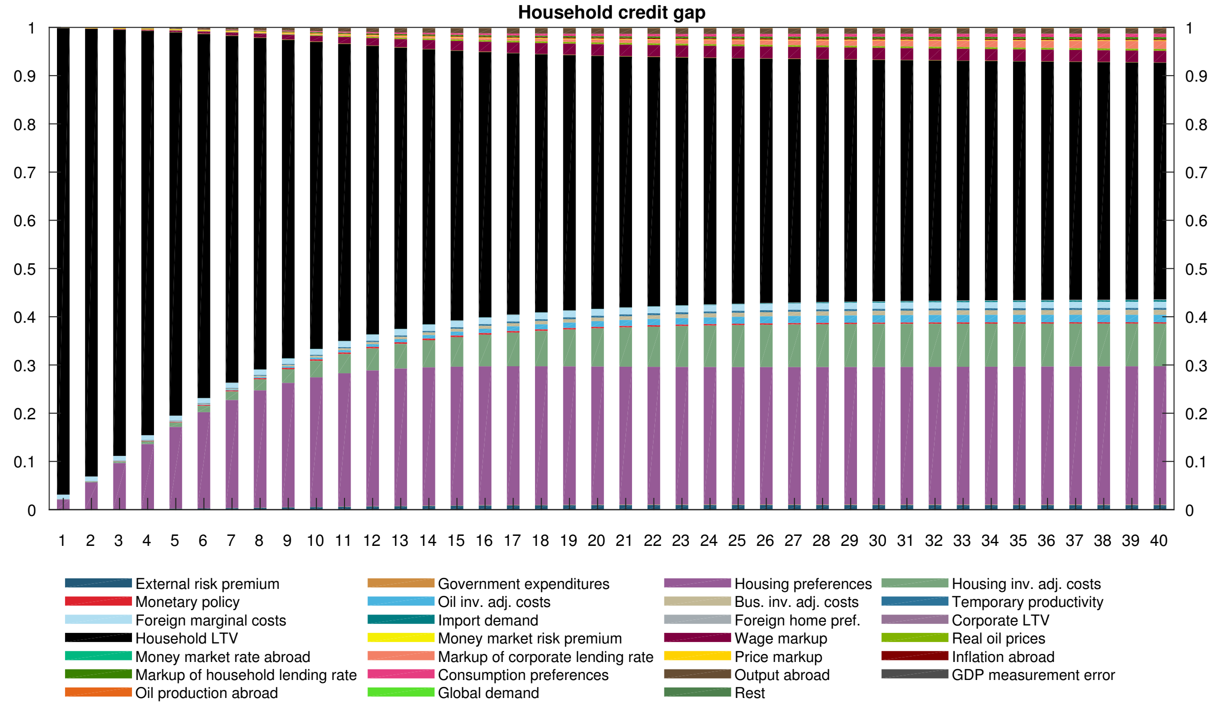

Figure 103: Forecast-error-variance decomposition of the household credit gap

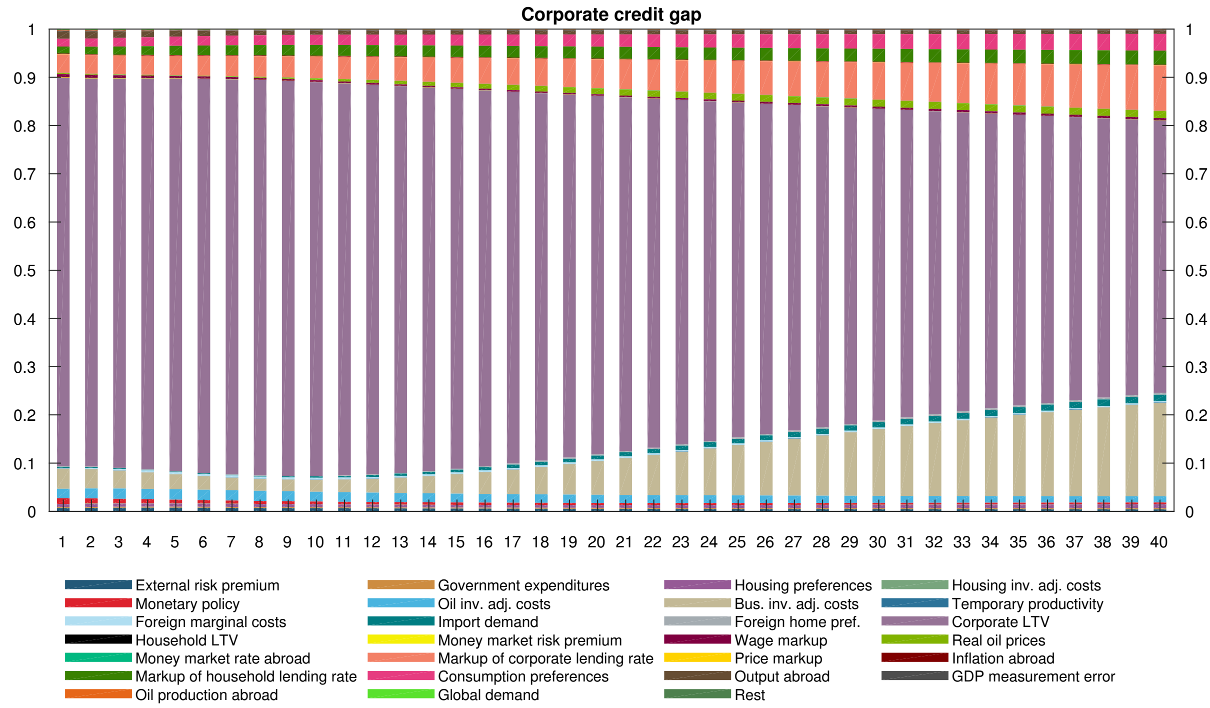

Figure 104: Forecast-error-variance decomposition of the corporate credit gap

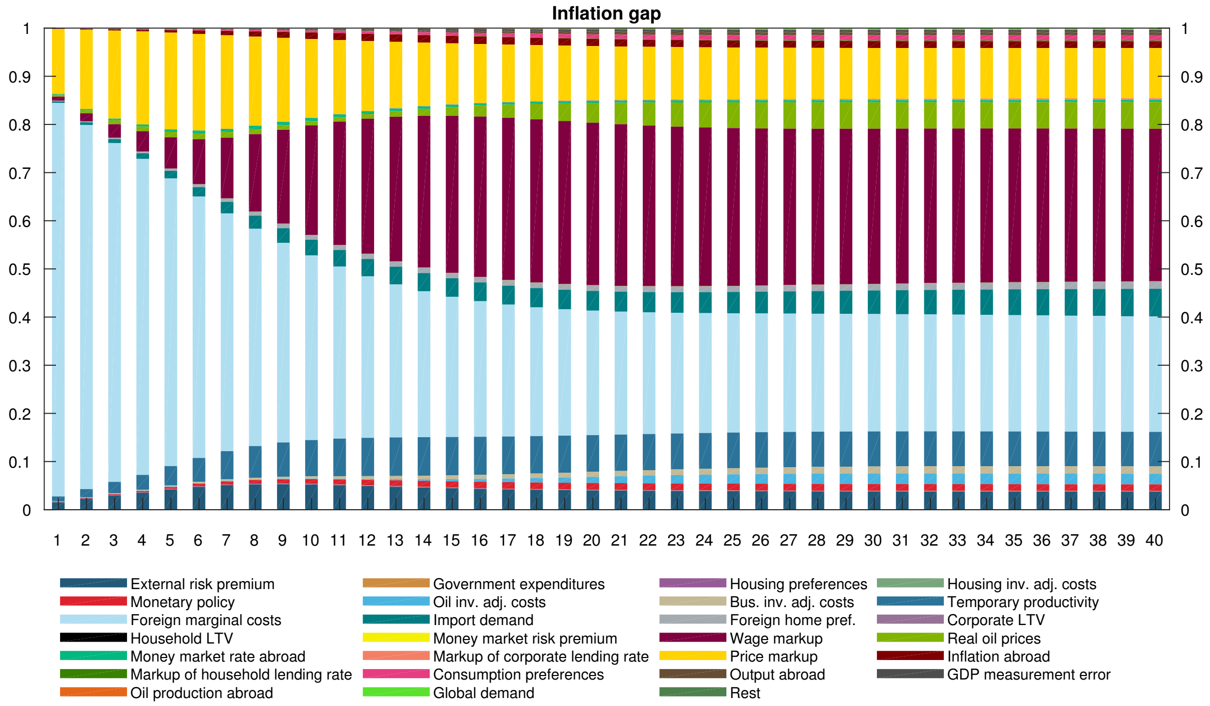

Figure 105: Forecast-error-variance decomposition of the inflation gap

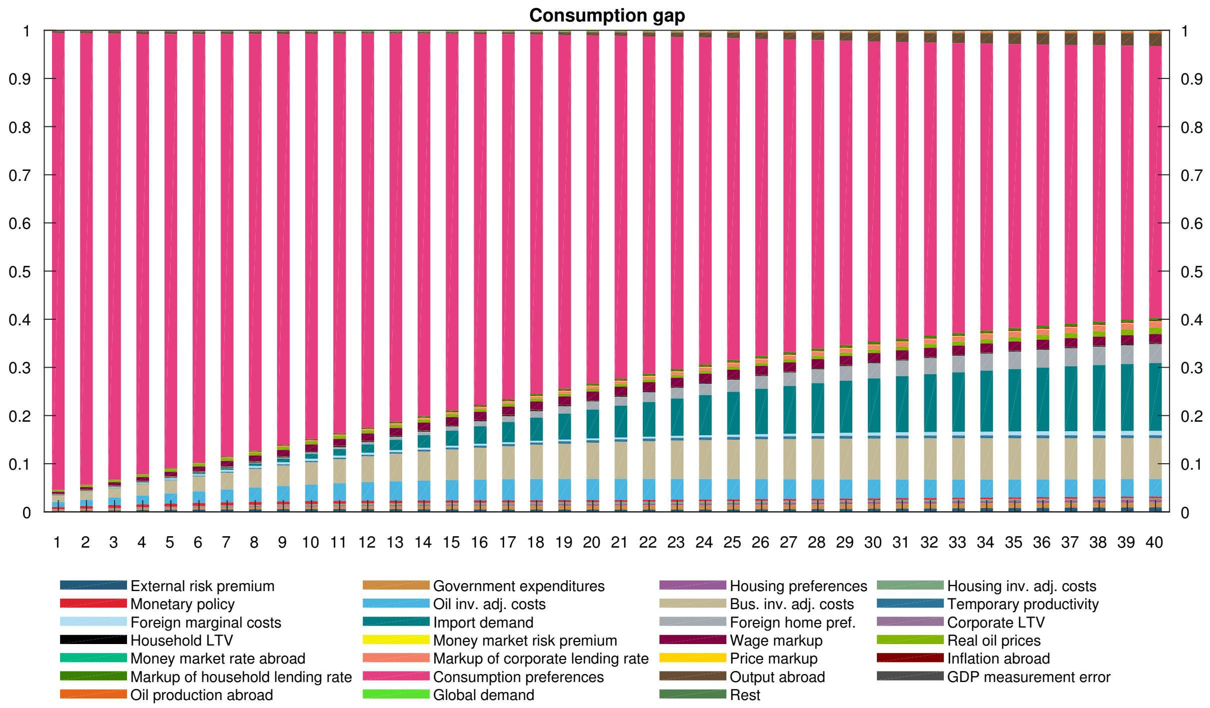

Figure 106: Forecast-error-variance decomposition of the consumption gap

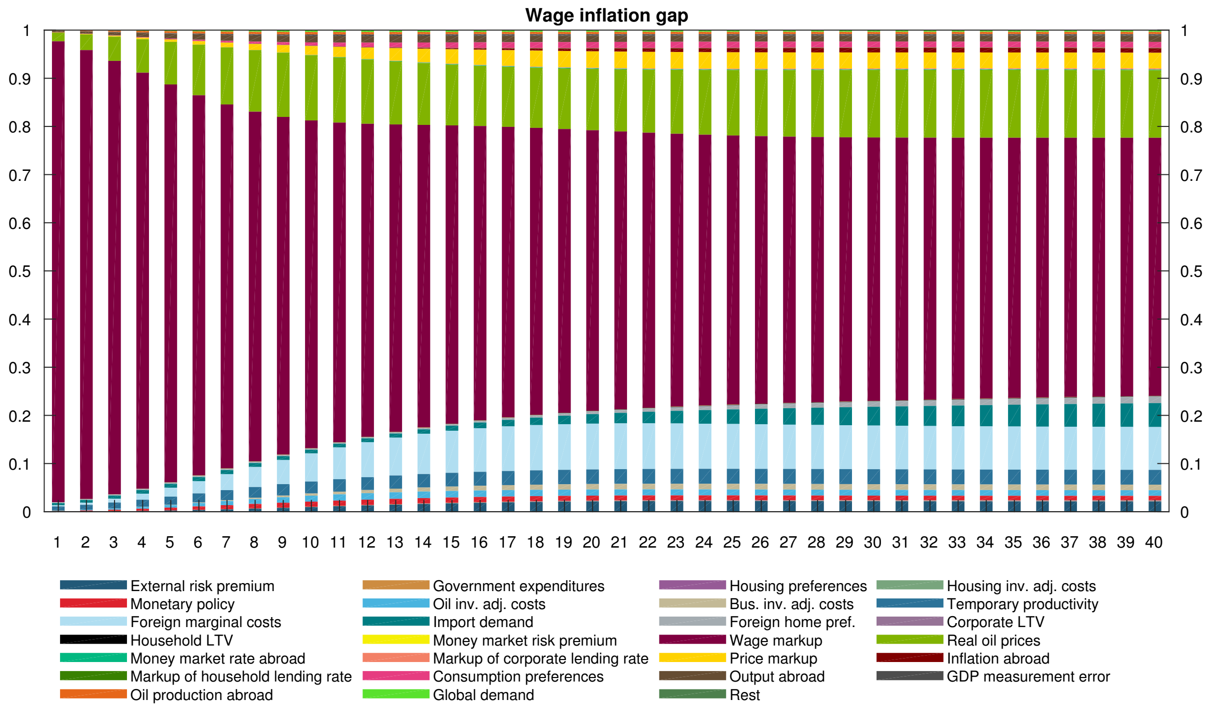

Figure 107: Forecast-error-variance decomposition of the wage inflation gap

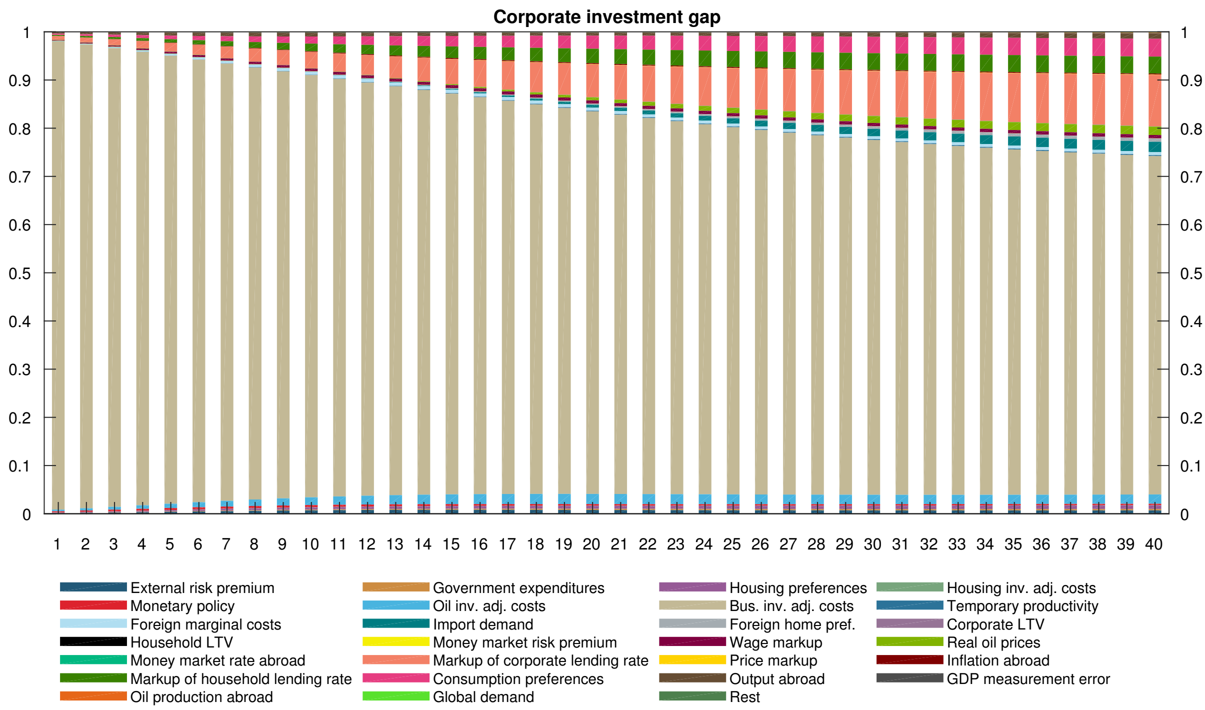

Figure 108: Forecast-error-variance decomposition of the corporate investment gap

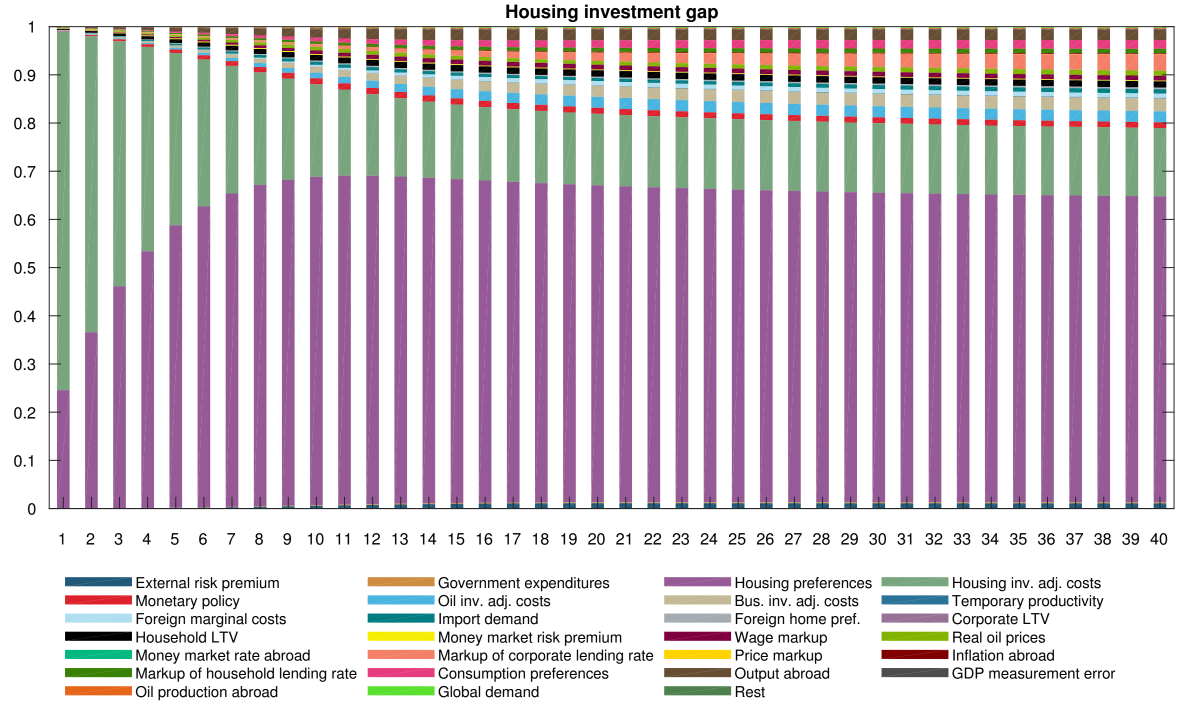

Figure 109: Forecast-error-variance decomposition of the housing investment gap

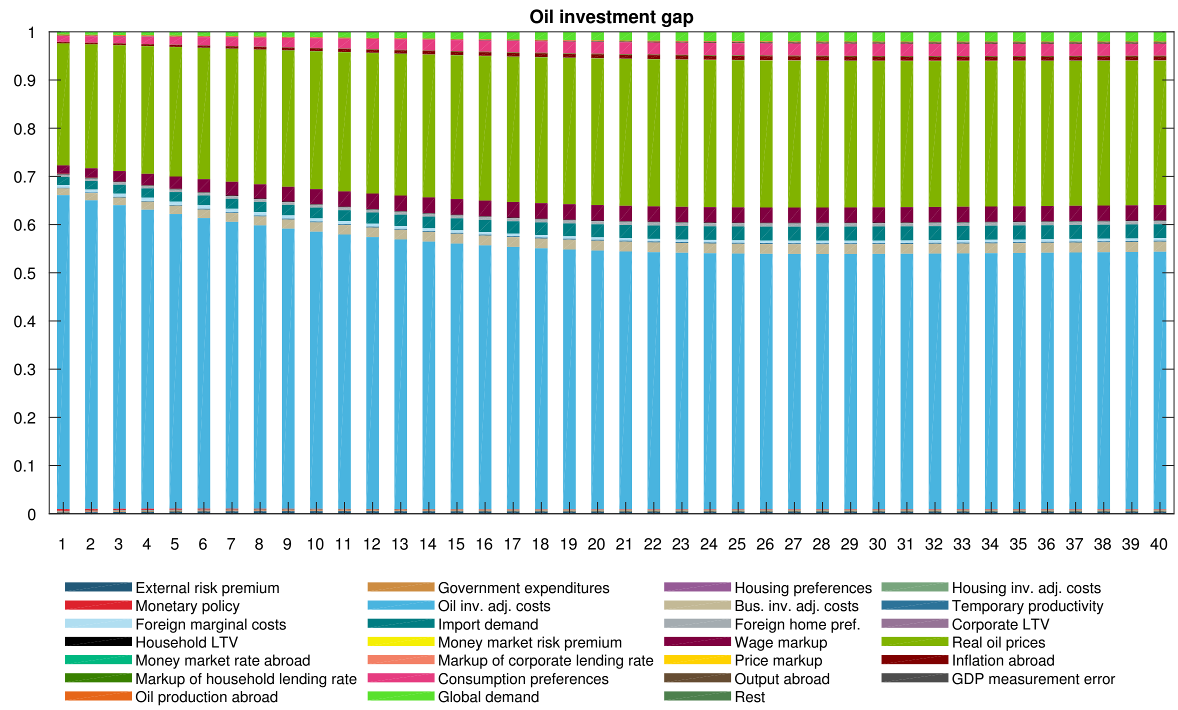

Figure 110: Forecast-error-variance decomposition of the oil investment gap

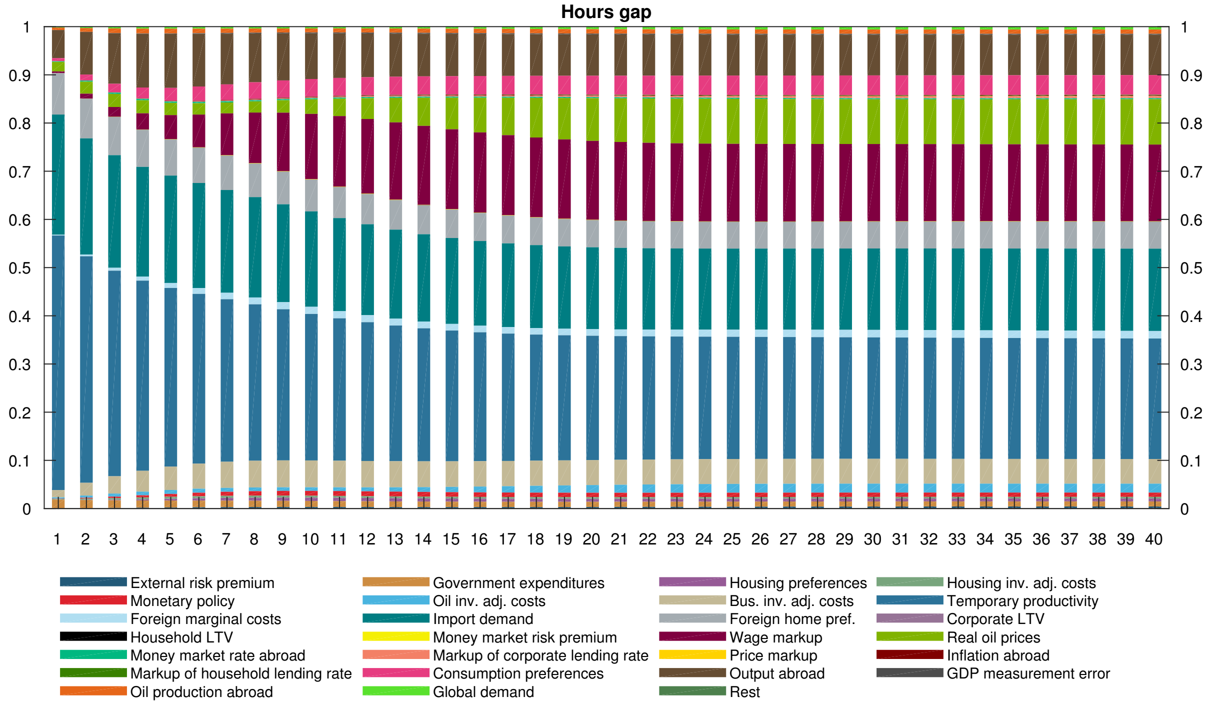

Figure 111: Forecast-error-variance decomposition of the hours worked gap

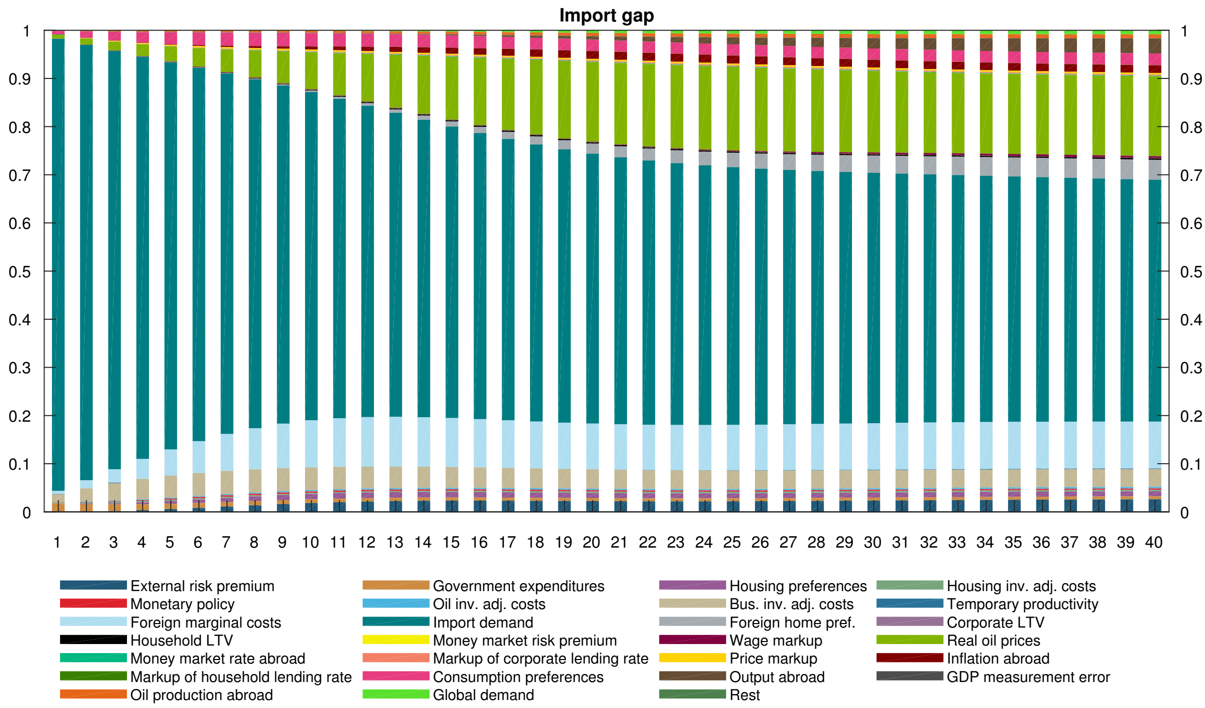

Figure 112: Forecast-error-variance decomposition of the import gap

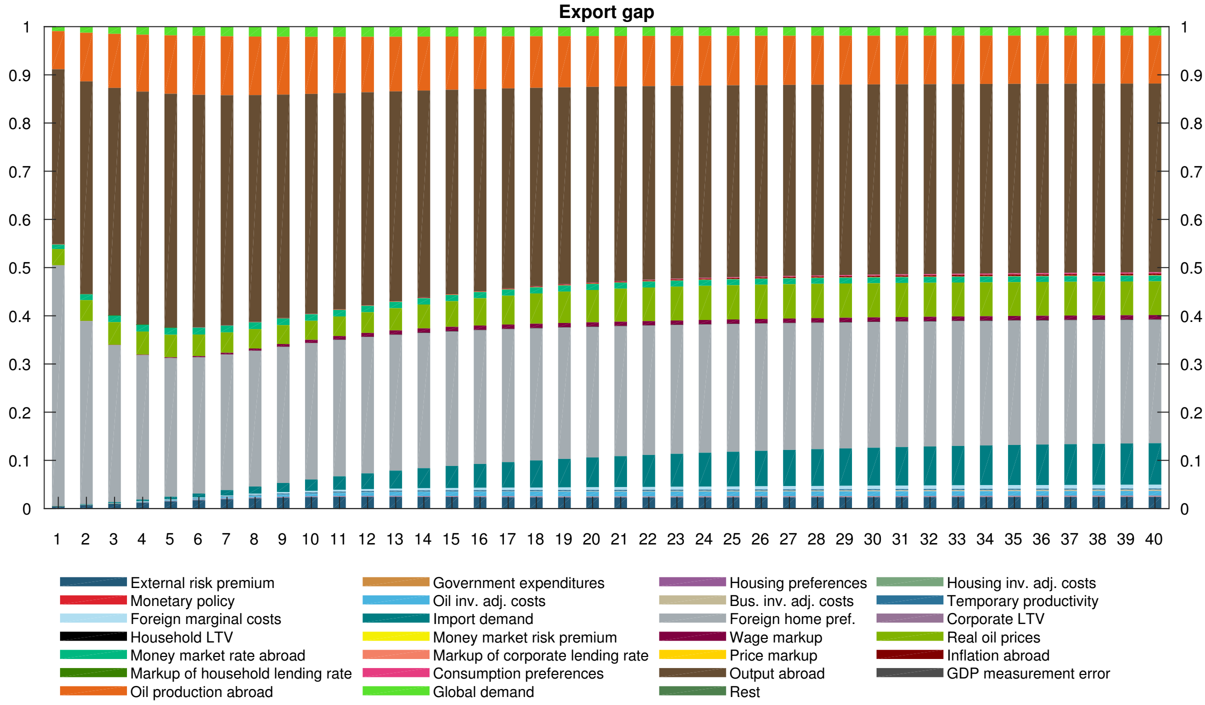

Figure 113: Forecast-error-variance decomposition of the export gap

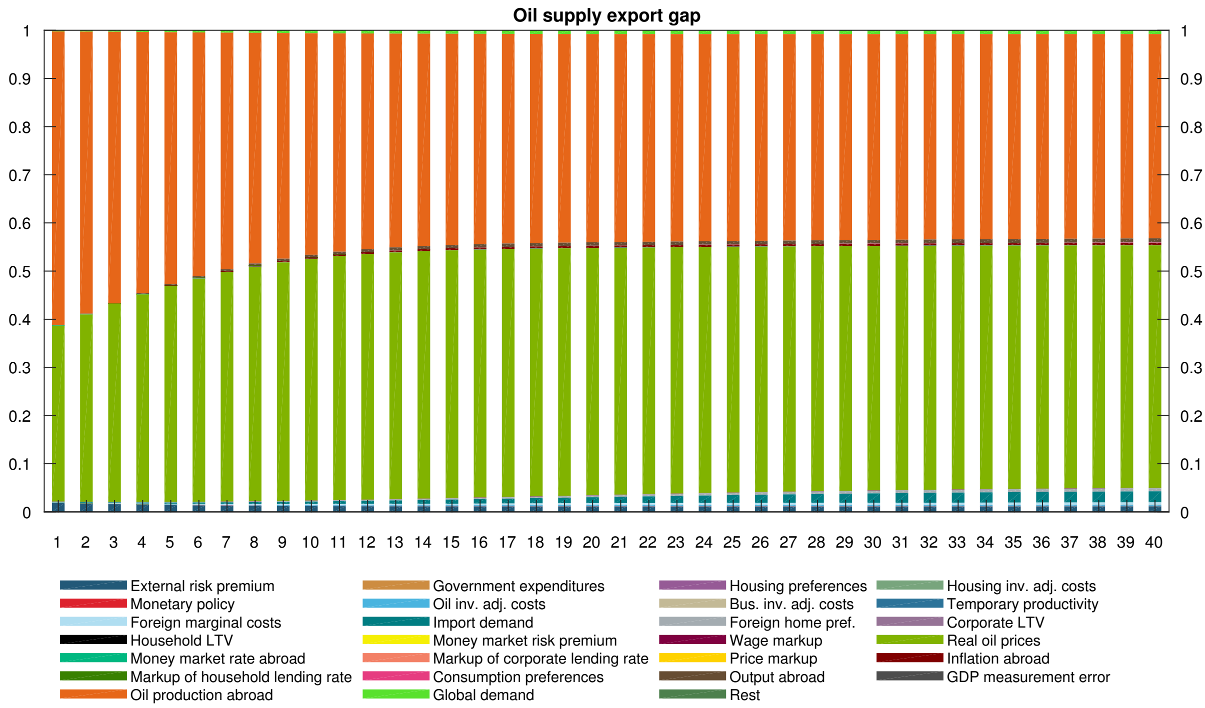

Figure 114: Forecast-error-variance decomposition of the oil supply export gap

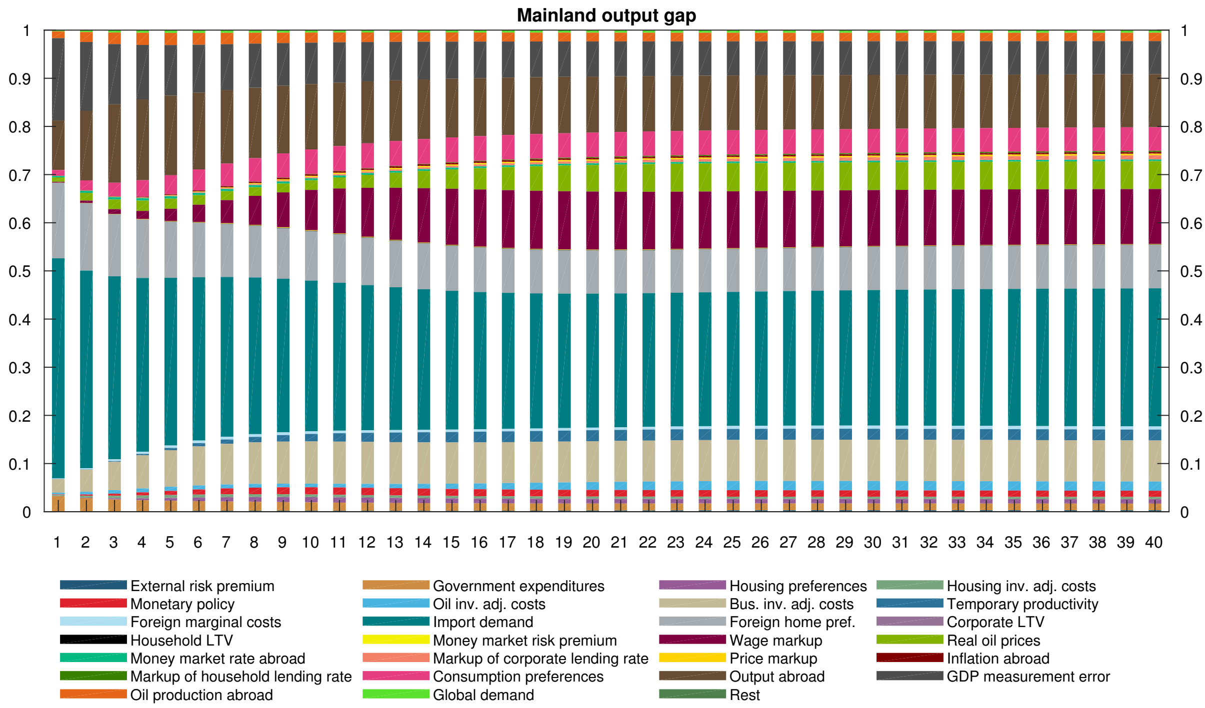

Figure 115: Forecast-error-variance decomposition of the mainland output gap

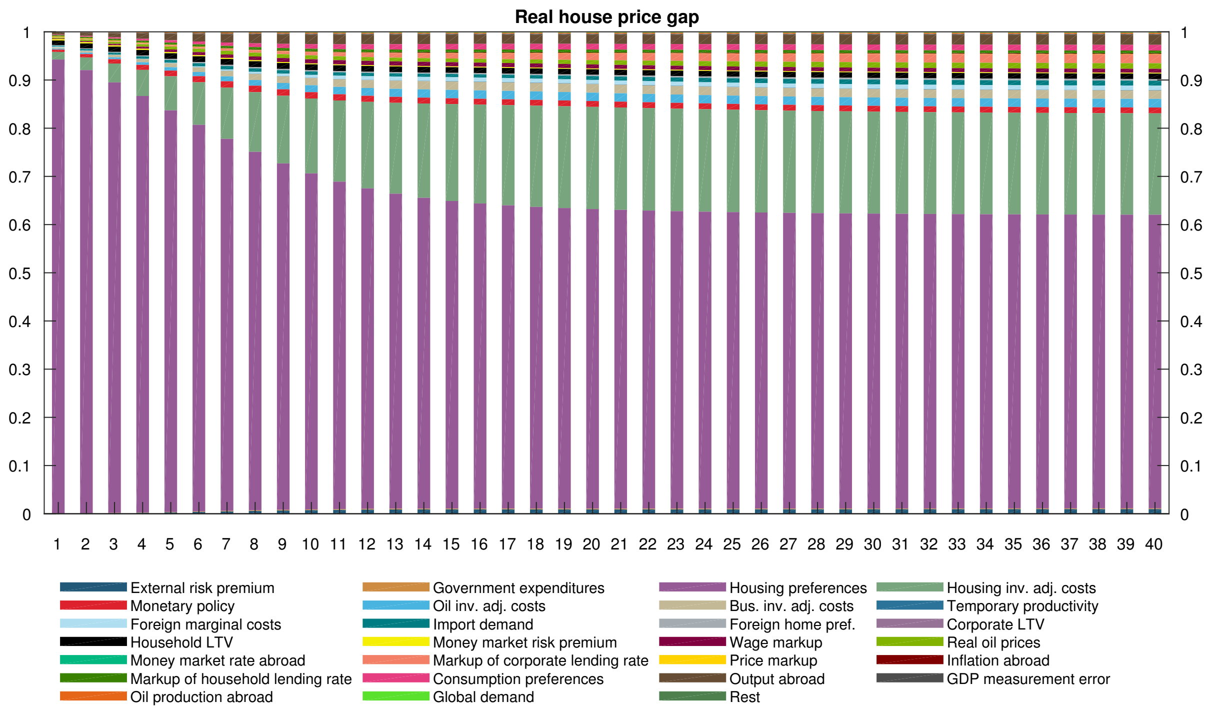

Figure 116: Forecast-error-variance decomposition of the real house price gap

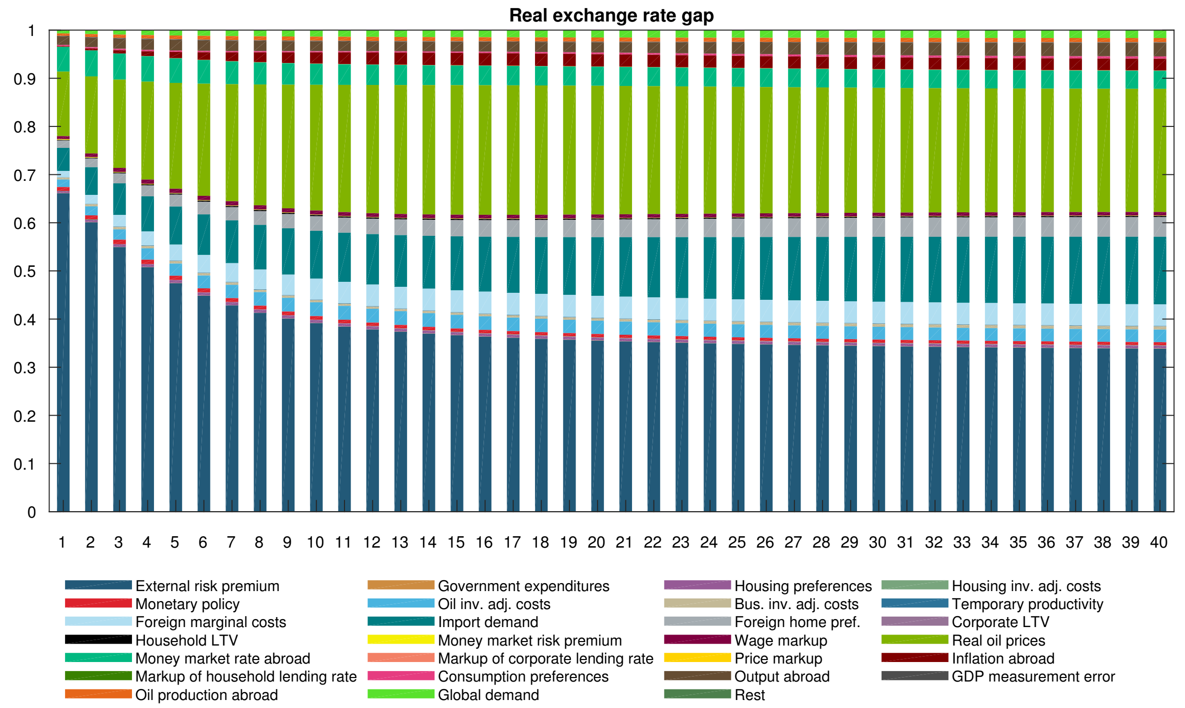

Figure 117: Forecast-error-variance decomposition of the real exchange rate gap

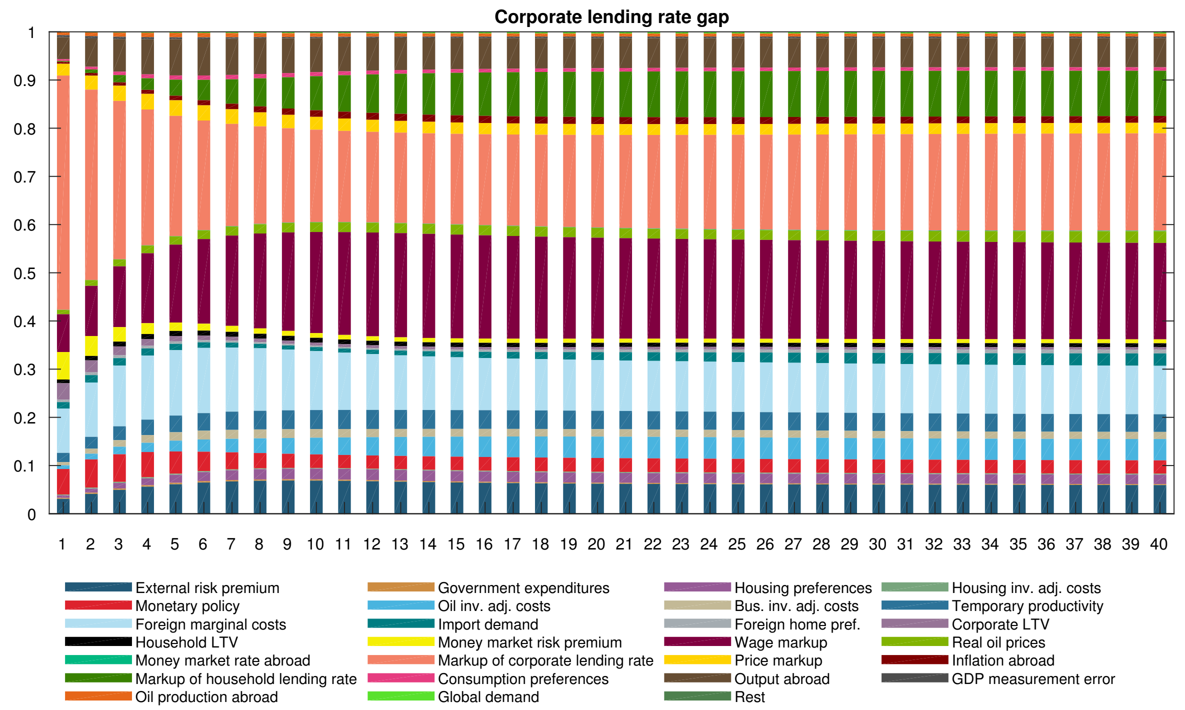

Figure 118: Forecast-error-variance decomposition of the corporate lending rate gap

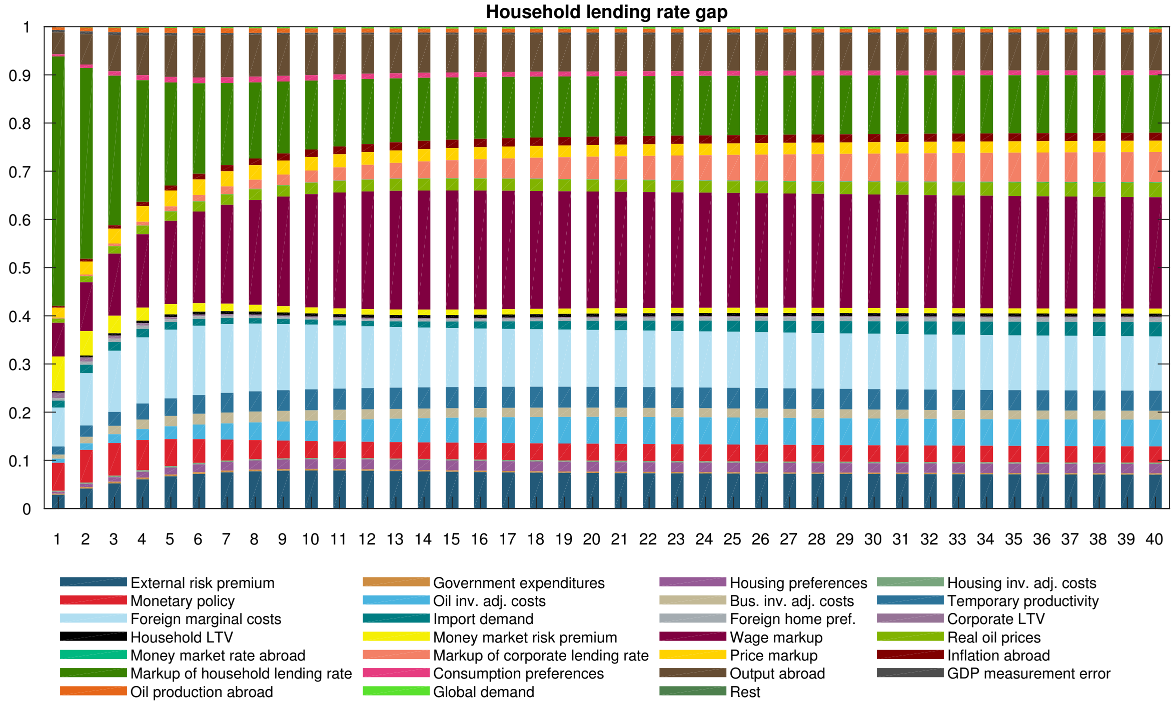

Figure 119: Forecast-error-variance decomposition of the household lending rate gap

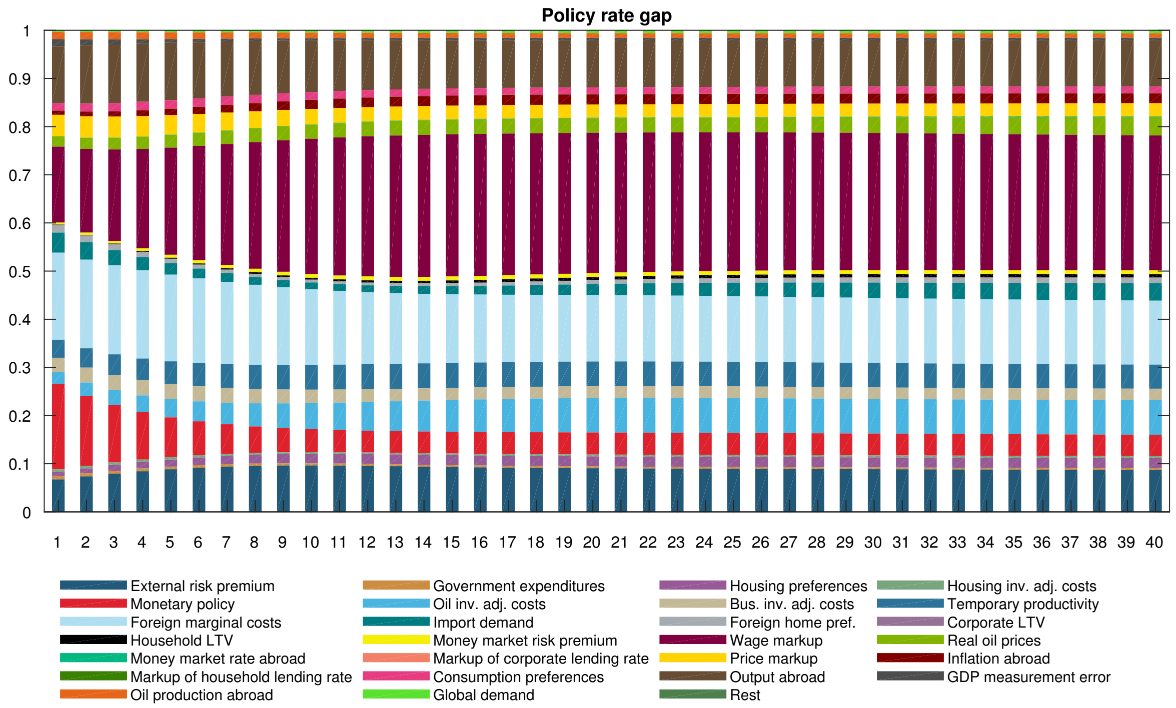

Figure 120: Forecast-error-variance decomposition of the policy rate gap

N Recursive forecasts for selected macro variables

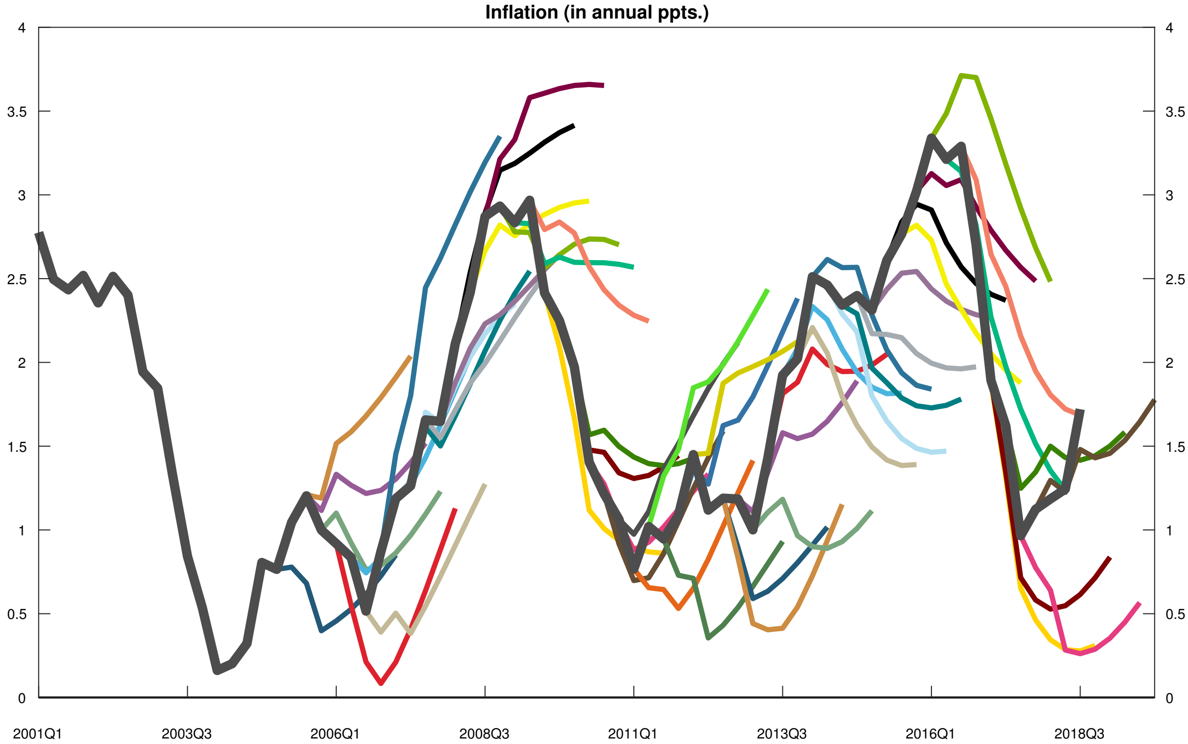

Figure 121: Unconditional out-of-sample forecast of the inflation gap in NEMO: Four-quarter change

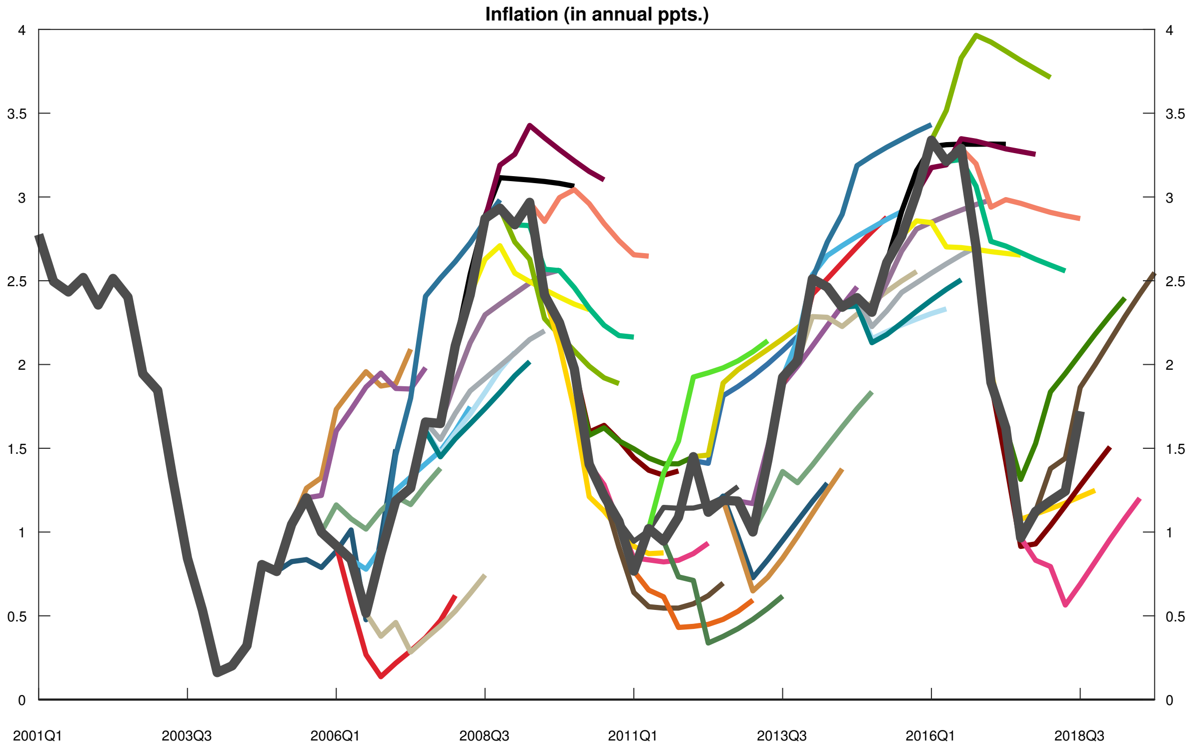

Figure 122: Unconditional out-of-sample forecast of the inflation gap in VAR models: Four-quarter change

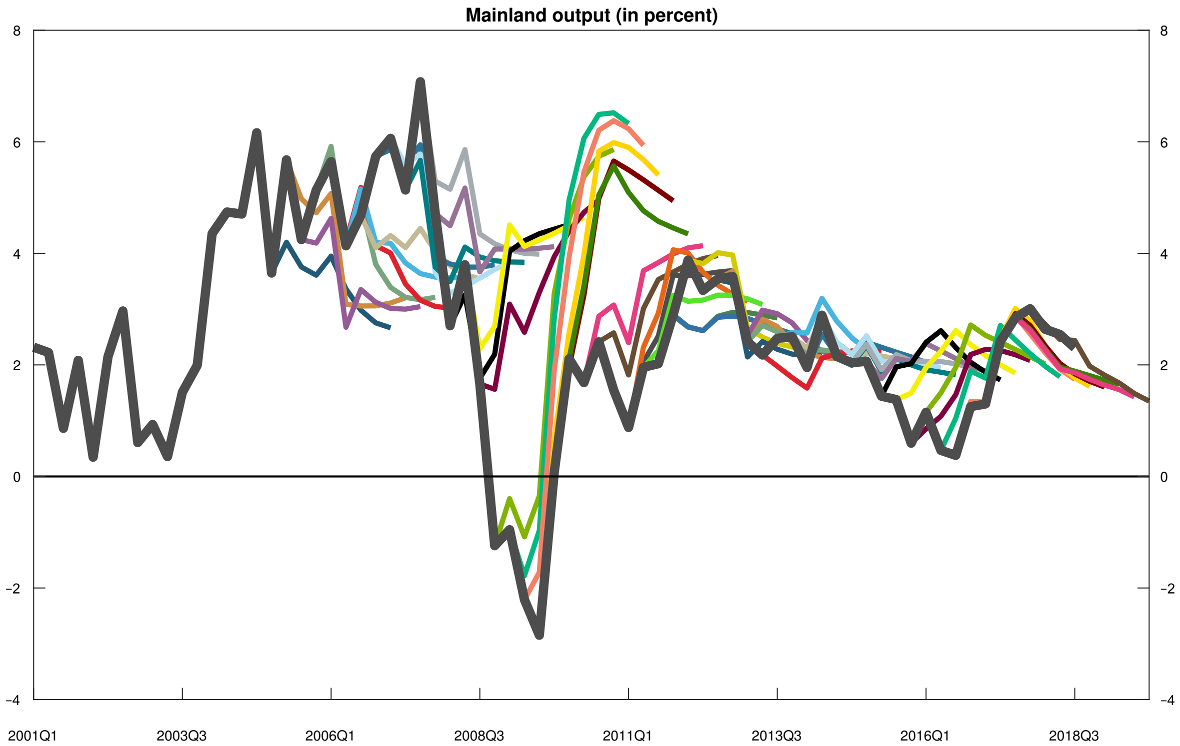

Figure 123: Unconditional out-of-sample forecast of the mainland output gap in NEMO: Four-quarter growth

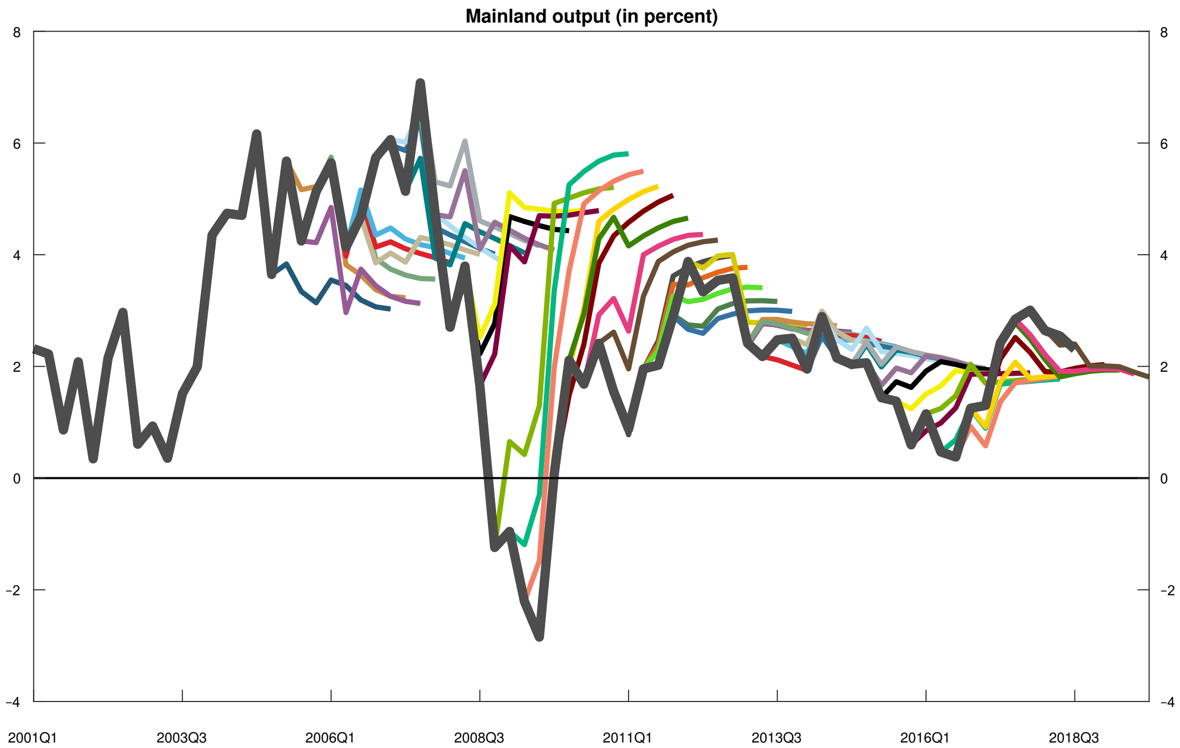

Figure 124: Unconditional out-of-sample forecast of the mainland output gap in VAR models: Four-quarter growth

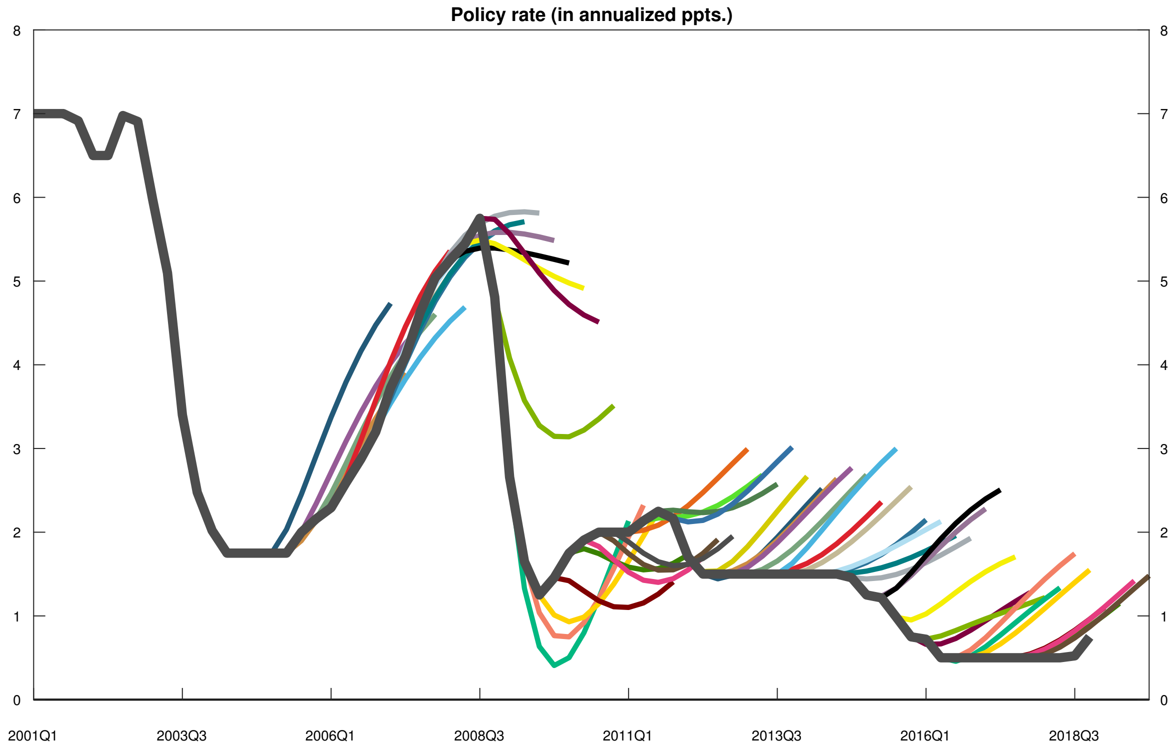

Figure 125: Unconditional out-of-sample forecast of the policy rate in NEMO (in levels)

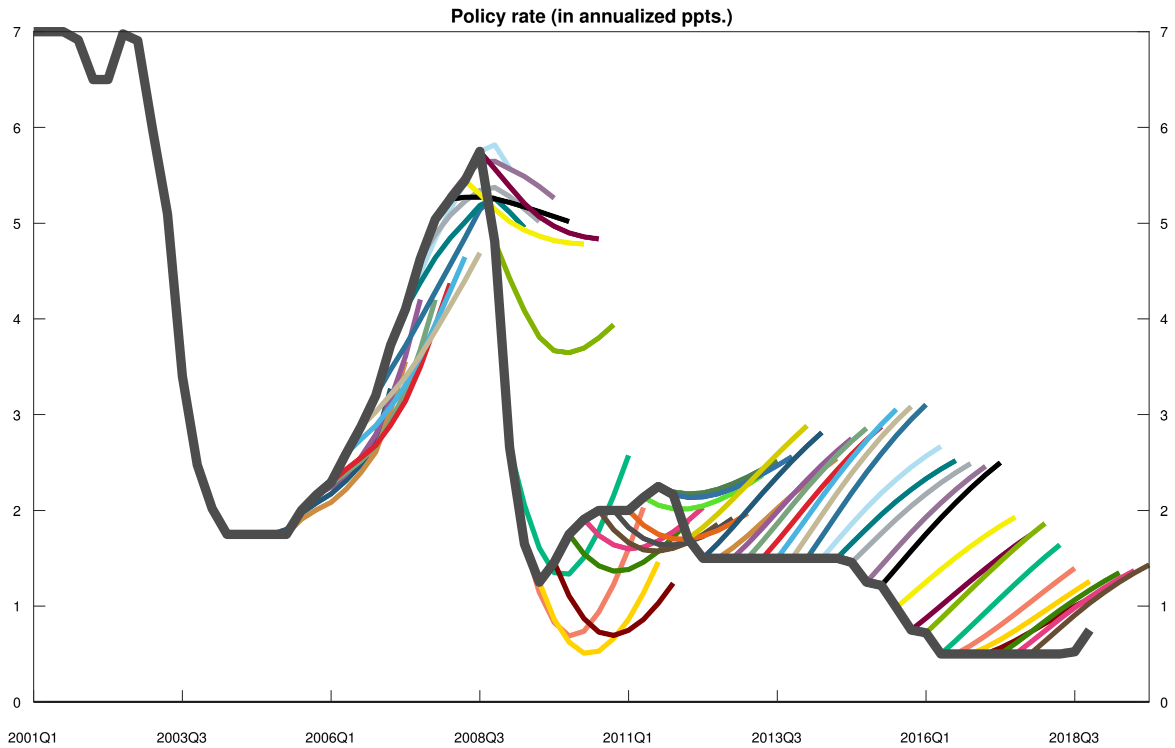

Figure 126: Unconditional out-of-sample forecast of the policy rate in VAR models (in levels)

O Smoothed estimates of shocks and innovations

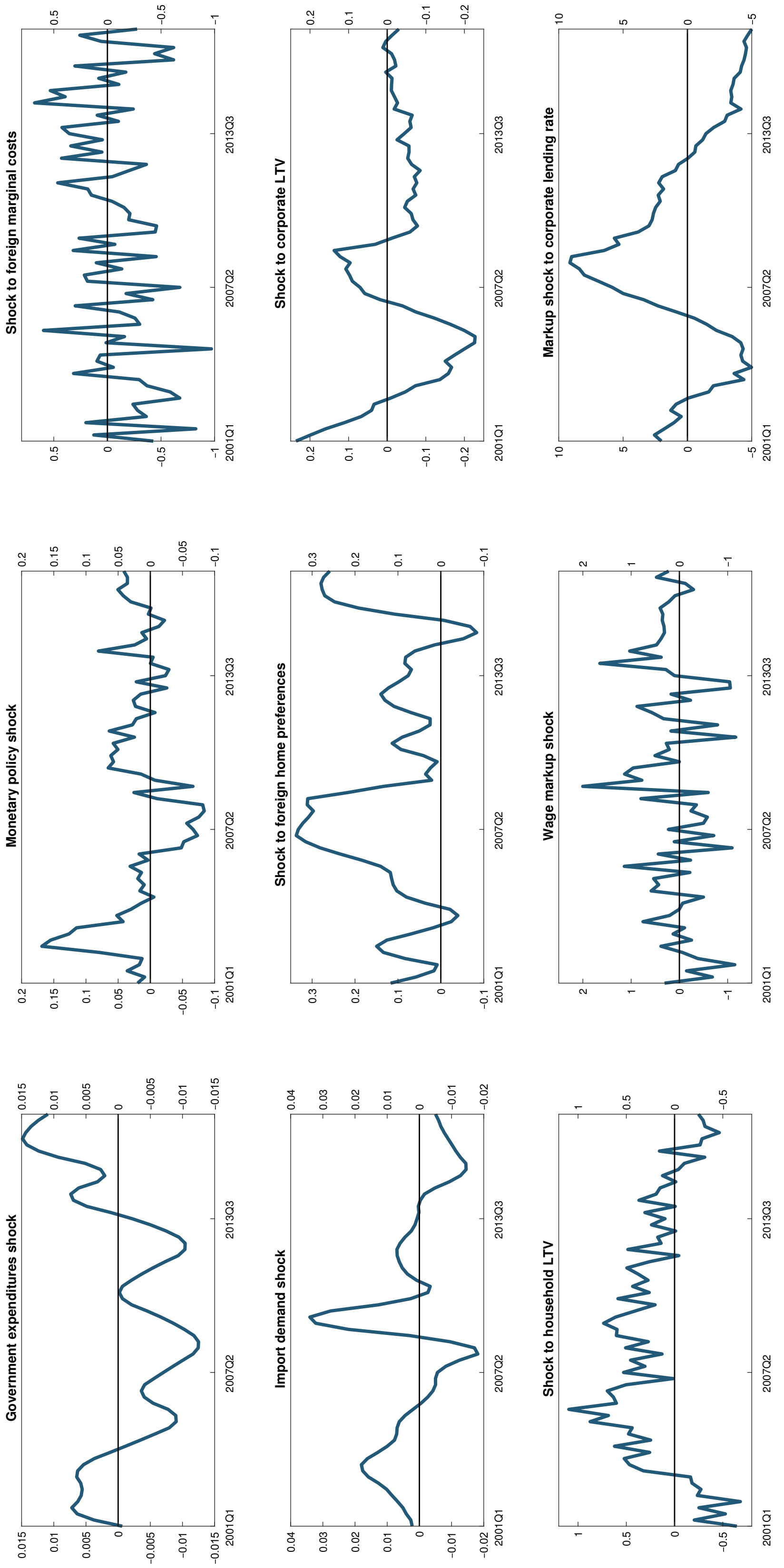

Figure 127: Smoothed estimates of shocks

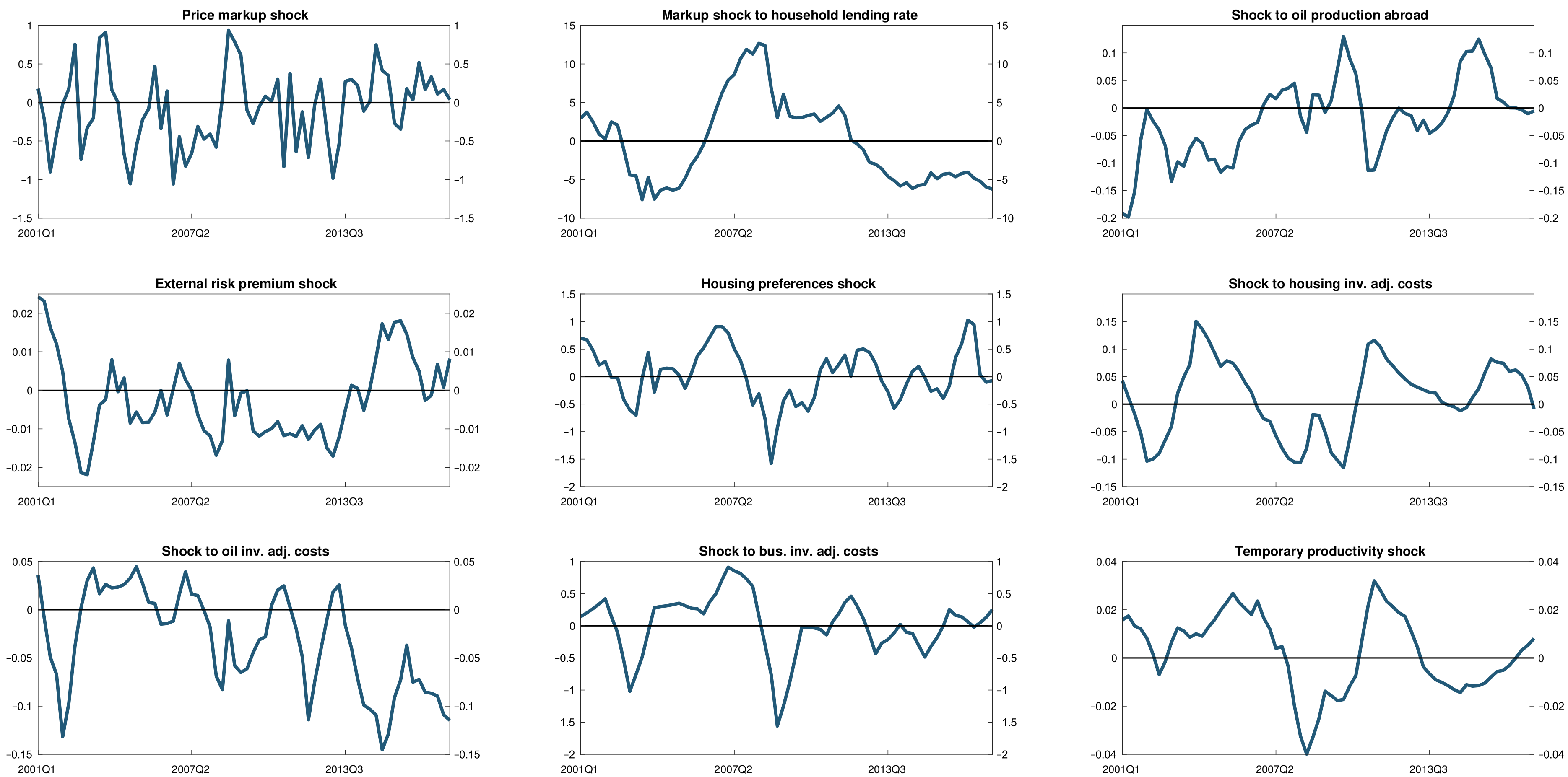

Figure 128: Smoothed estimates of shocks

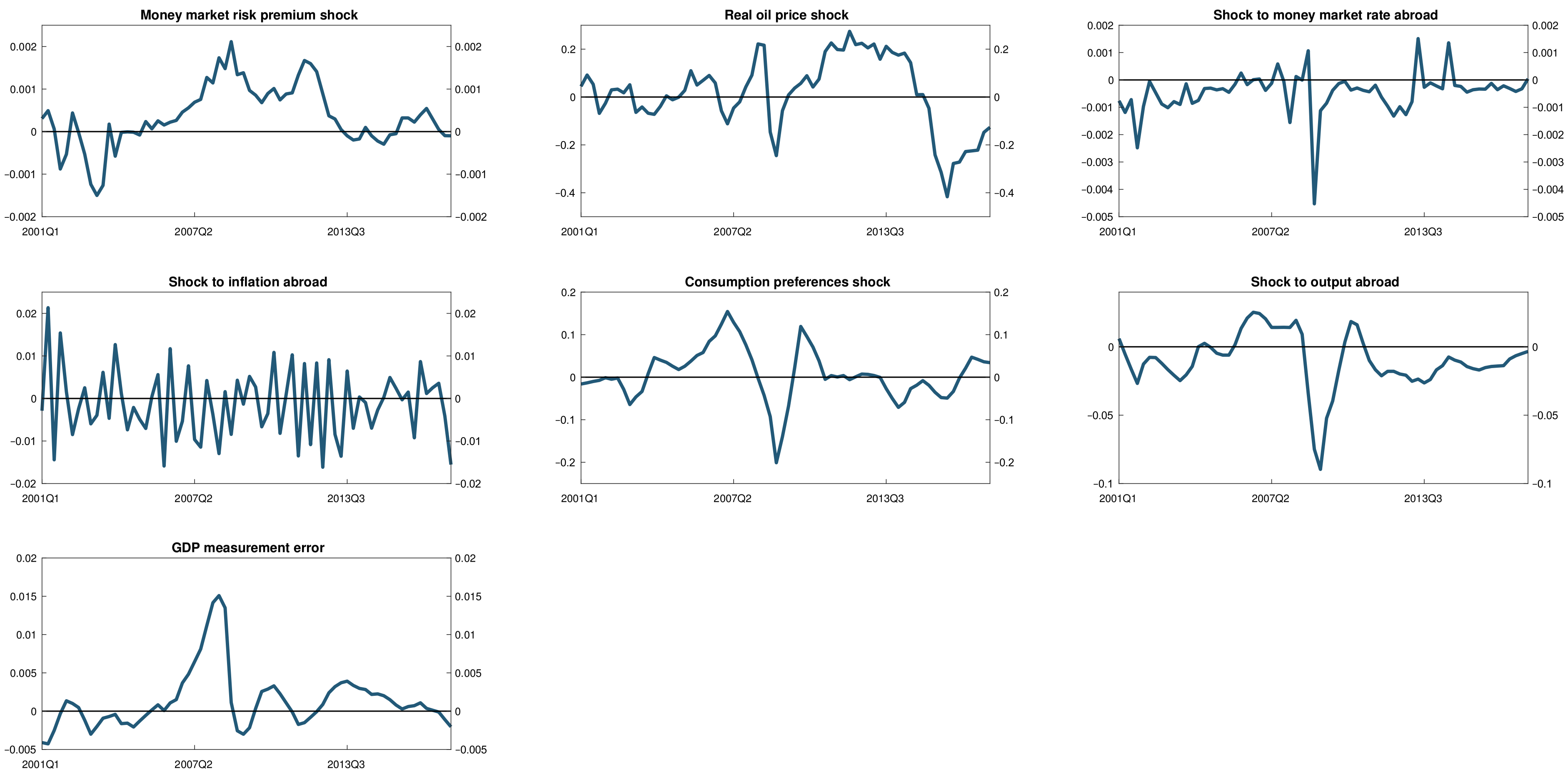

Figure 129: Smoothed estimates of shocks

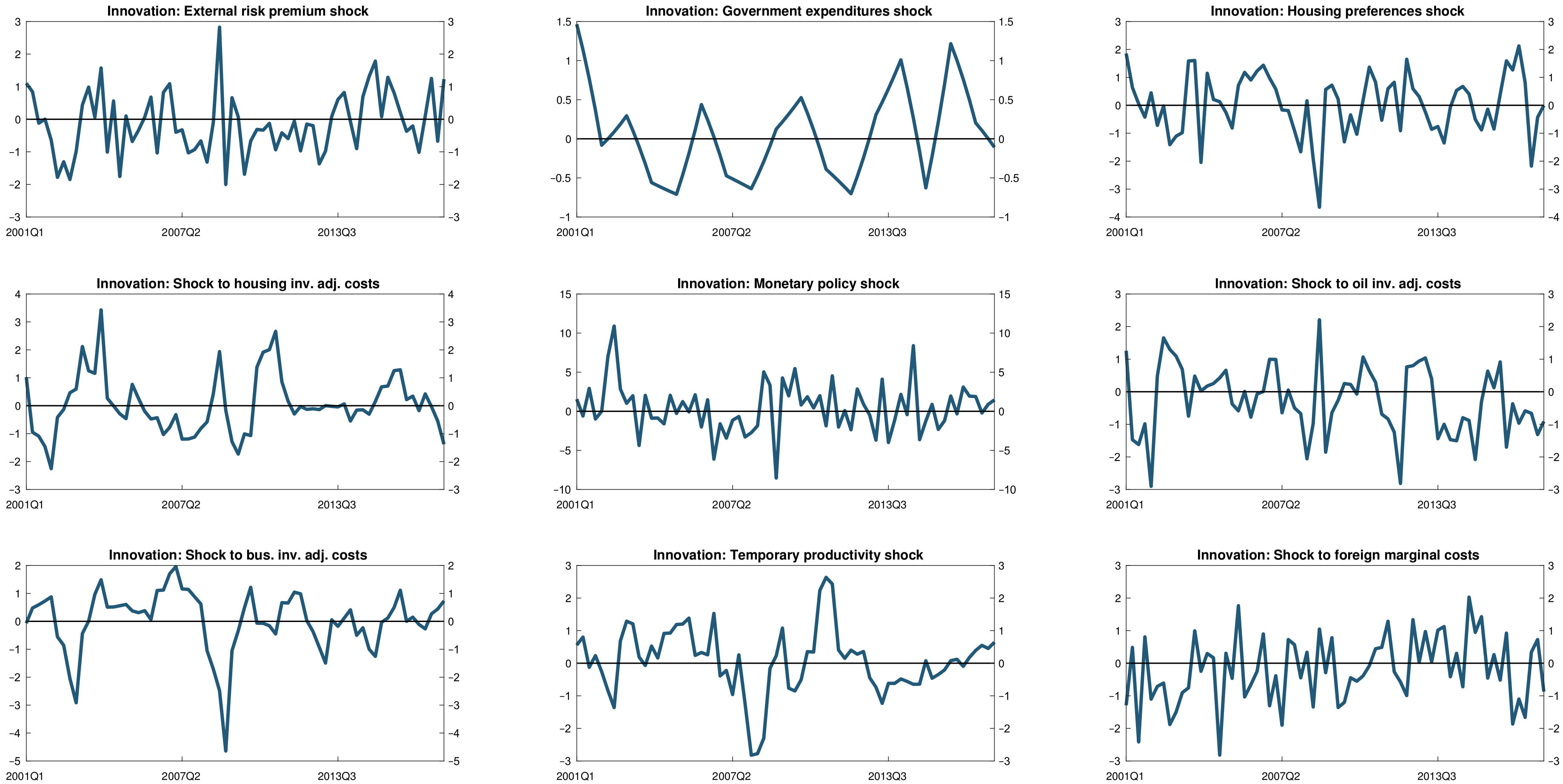

Figure 130: Smoothed estimates of innovation component of shocks

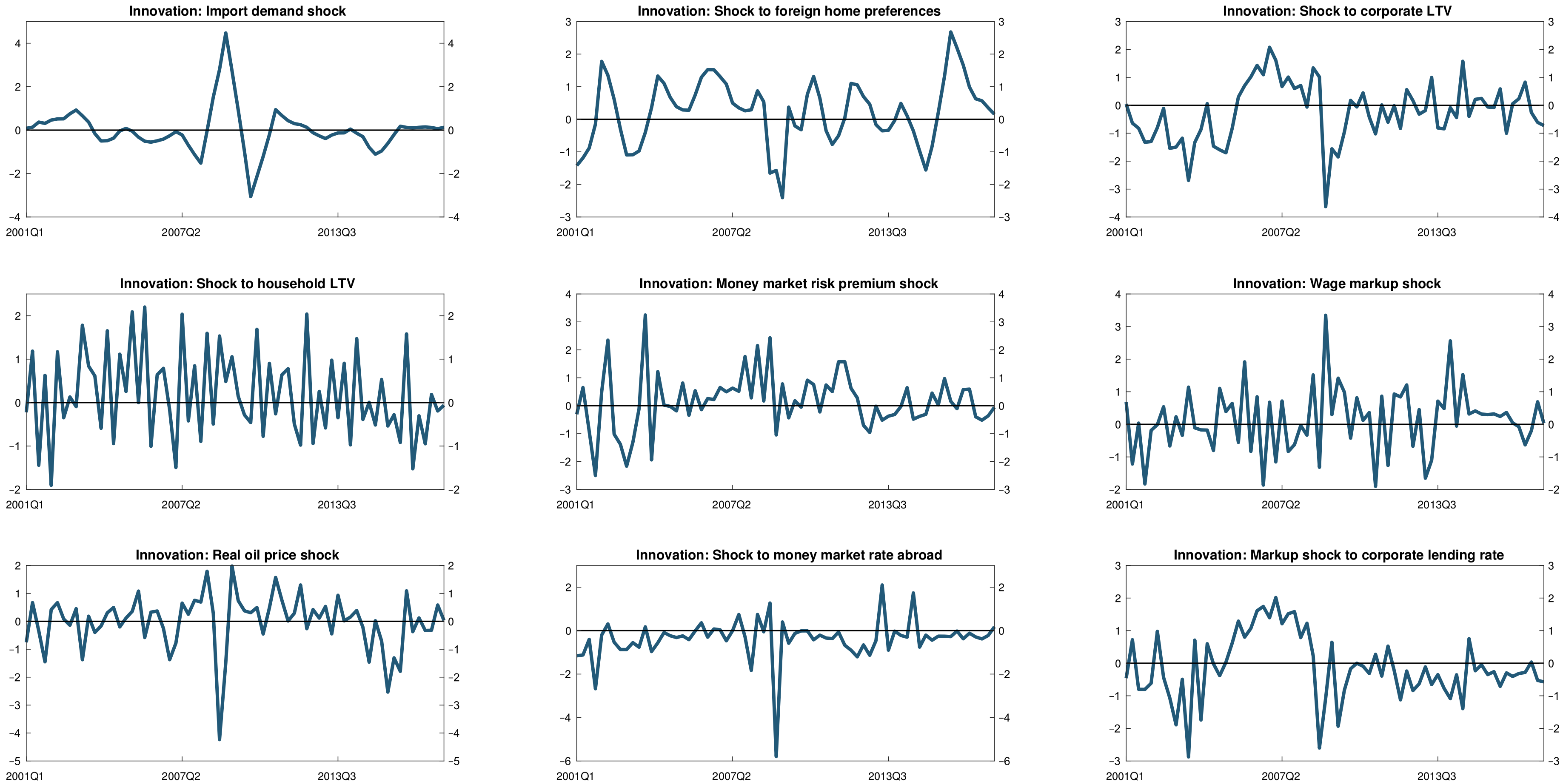

Figure 131: Smoothed estimates of innovation component of shocks

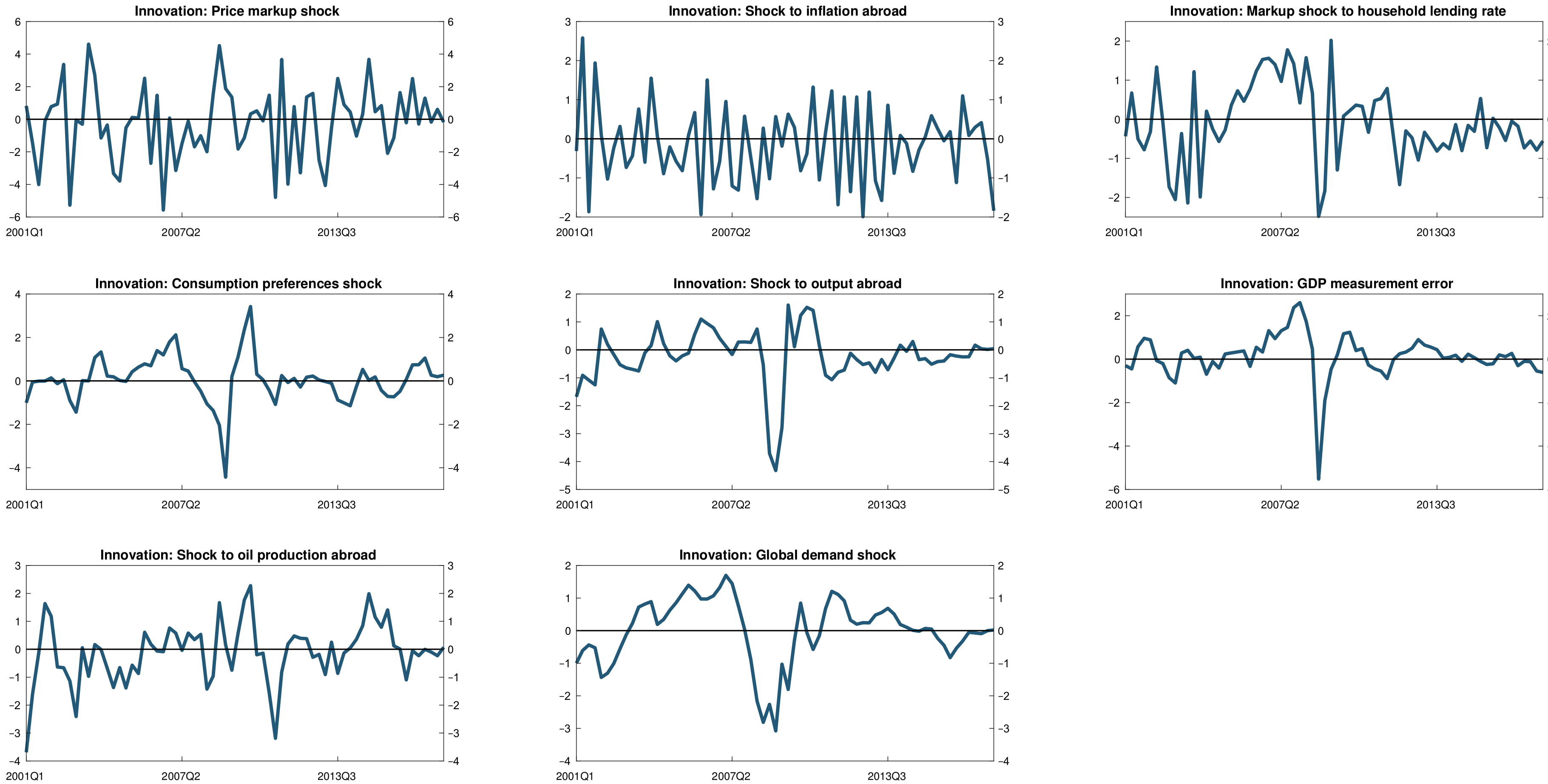

Figure 132: Smoothed estimates of innovation component of shocks

P Impulse responses: Old vs. new model

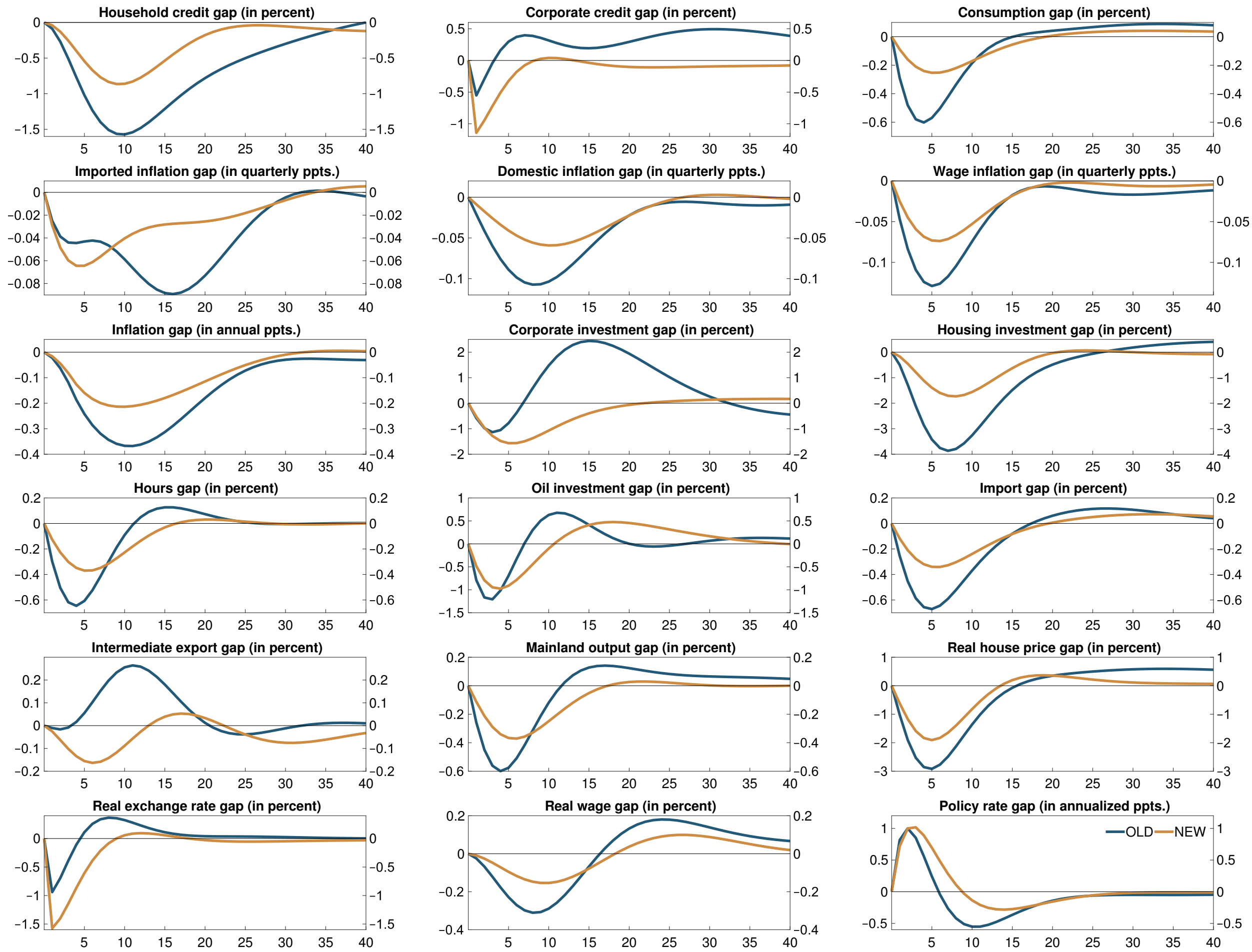

Figure 133: Impulse responses to a monetary policy shock: old vs. new model

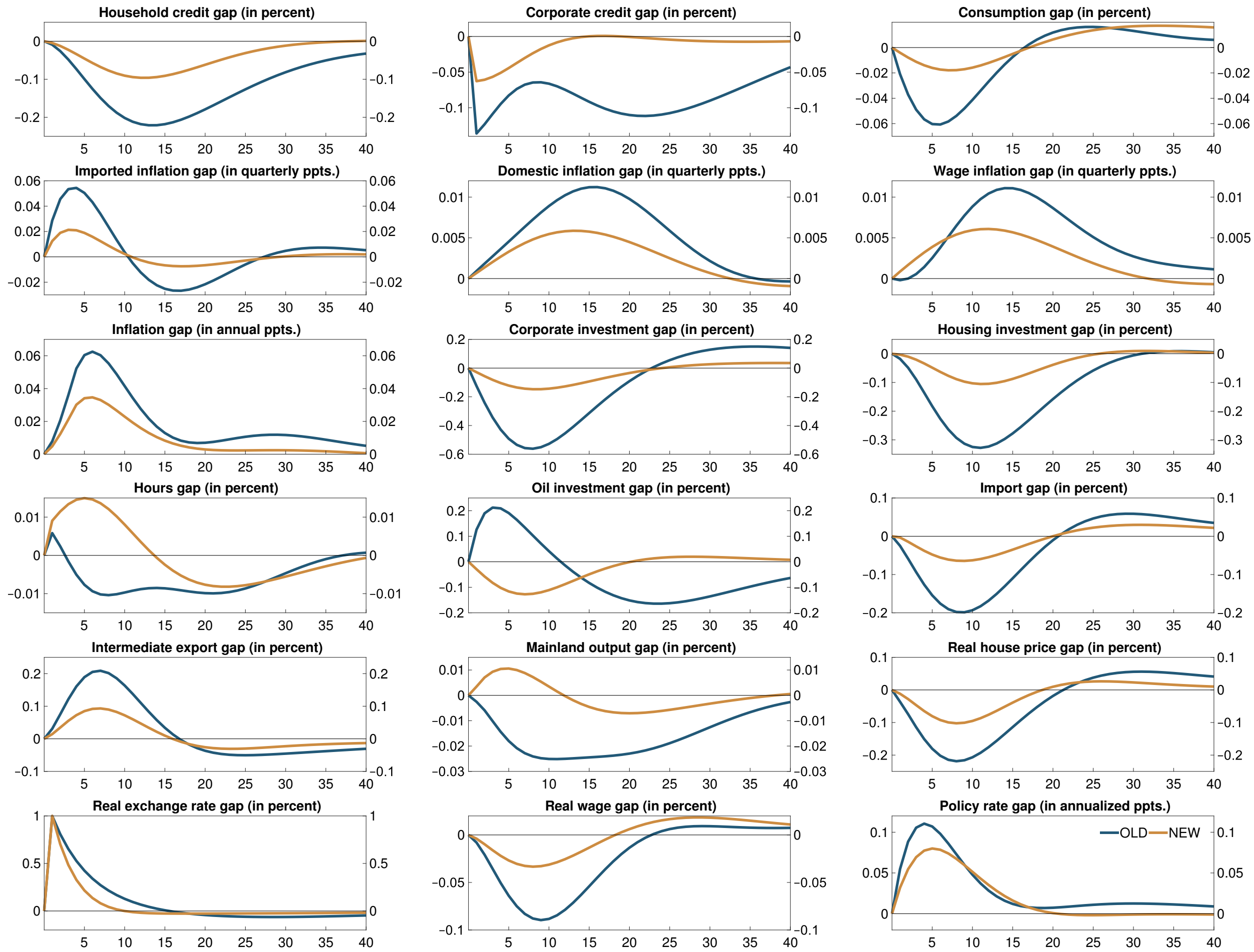

Figure 134: Impulse responses to an external risk premium shock: old vs. new model

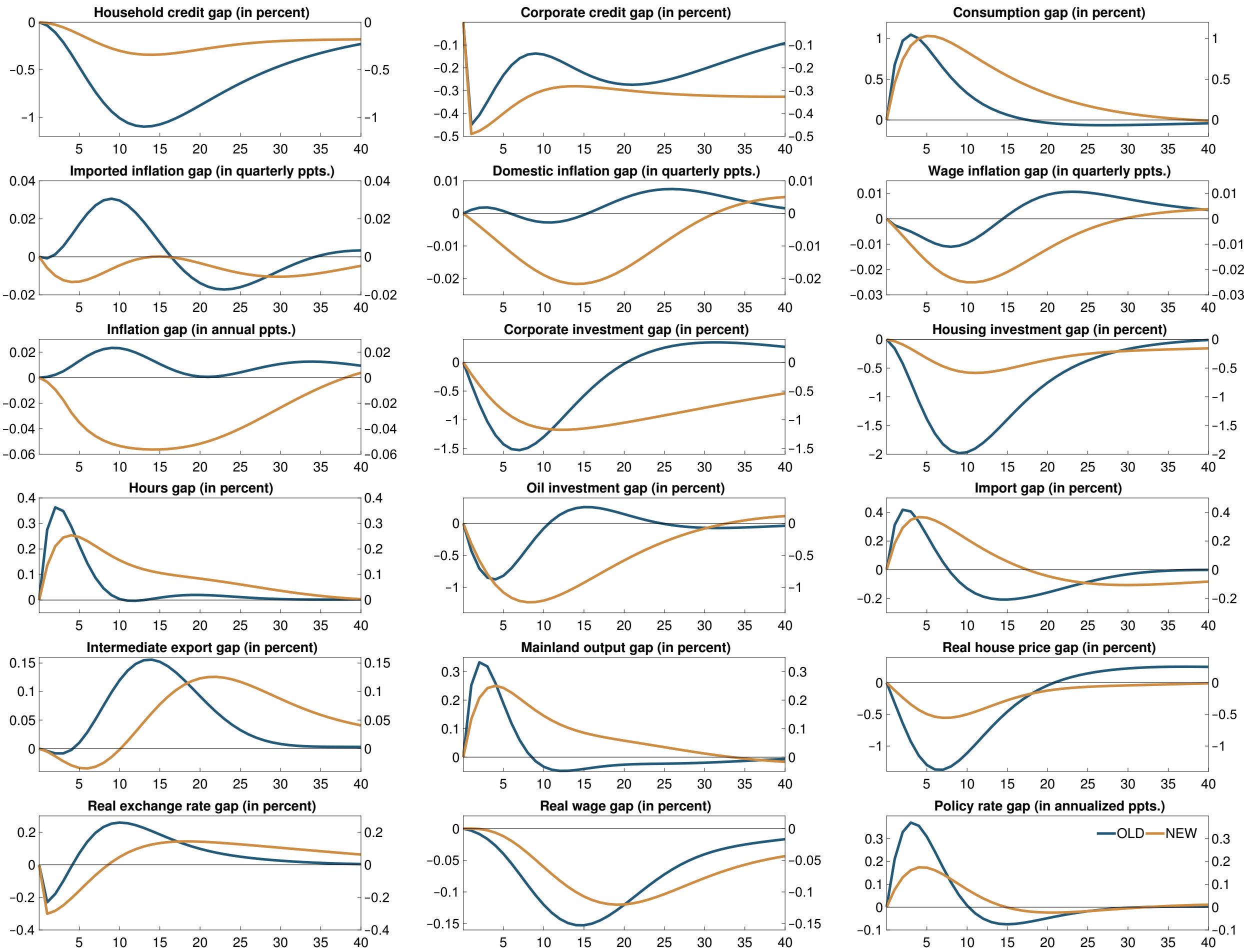

Figure 135: Impulse responses to a consumption preference shock: old vs. new model

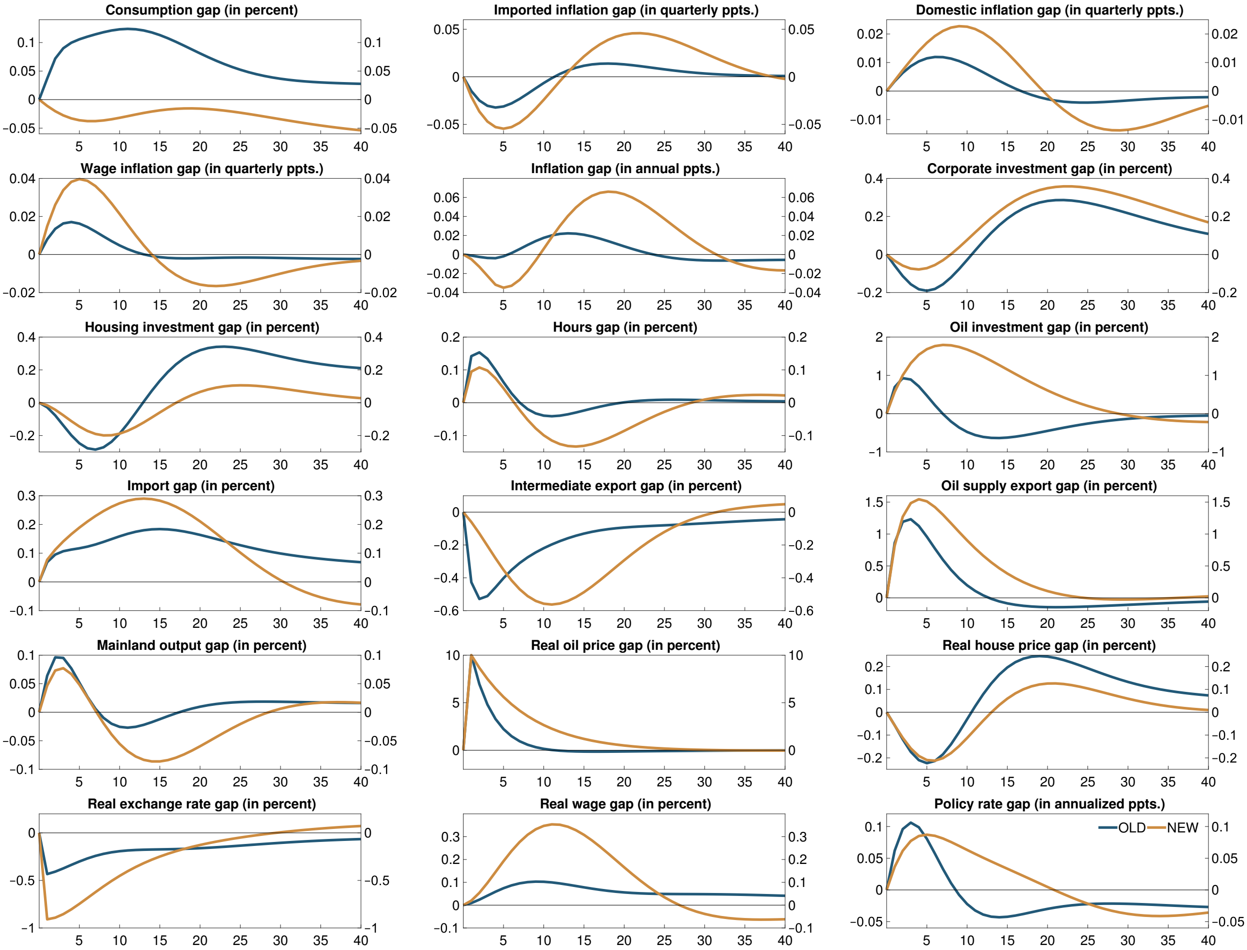

Figure 136: Impulse responses to a real oil price shock: old vs. new model

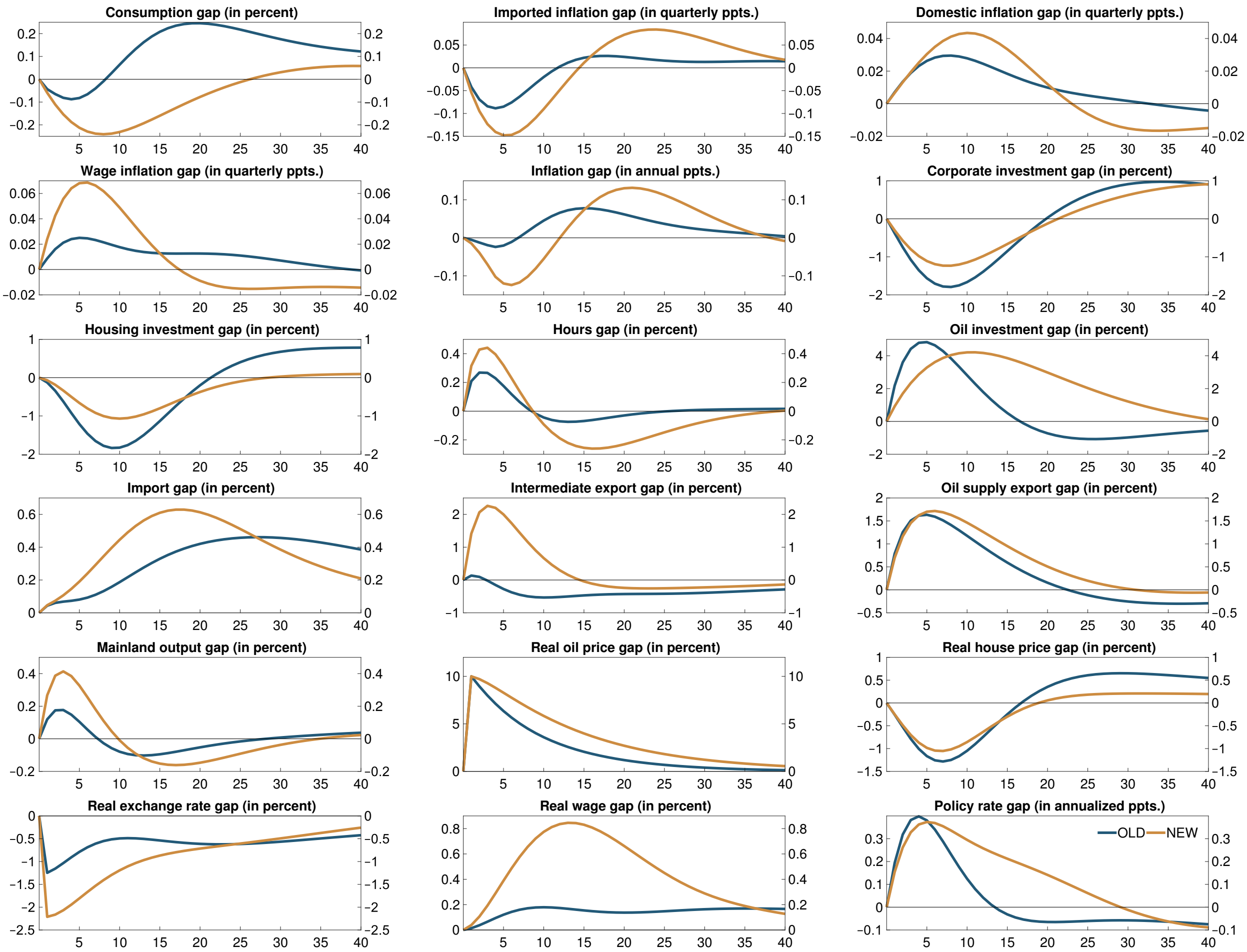

Figure 137: Impulse responses to a global demand shock: old vs. new model

Q Text names of parameters

Table 11: Dynamic parameters

Text name	Parameter
Households	
ALPHA_SA_NW	α^h
KAPPA_SA_NW	κ^h
back_sa	b^{sa}
BC_NW	b^c
BD_NW	b^d
BETA_NW	β
BH_NW	b^h
BL_NW	b^l
DELTA_H_NW	δ^H
lambda_sa	λ^{sa}
PHI_W_NW	ϕ^W
Z_D_NW	z^d
ZETA_NW	ζ
Intermediate goods sector	
ALPHA_NW	α
PHI_PM_TP	ϕ^{PM^*}
PHI_PQ_NW	ϕ^{PQ}
THETAF_TP	θ^{F*}
XI_NW	ξ
Final goods	
MU_NW	μ
Entrepreneurs	
ALPHA_E_NW	α^e
KAPPA_E_NW	κ^e
PHI_U_NW	ϕ_u
Capital producers	
DELTA_NW	δ
PHI_I1_NW	ϕ_{I1}
PHI_I2_NW	ϕ_{I2}
Housing sector	
PHI_H1_NW	ϕ_{H1}
PHI_H2_NW	ϕ_{H2}
Banking sector	
CHI_C_NW	χ_c
CHI_O_NW	χ_o
DELTAB_NW	δ^b
PHI_B_NW	ϕ^B
PHI_D_NW	ϕ^D
PHI_E_NW	ϕ^e
PHI_IH_NW	ϕ^F
PHI_S_NW	ϕ^S
THETAD_NW	θ^D
RW_BSA	ς^h
RW_BU	ς^e
Oil sector	
ALPHA_LO_NW	α_l
ALPHA_O_TP	α_{o*}

ALPHA_OIL	α_o
ALPHA_QO_NW	α_q
DELTA_O_NW	δ_O
GAMMA_O_NW	γ^O
PHI_UF_NW	ϕ^{uf}
PHI_PR_NW	ϕ^{PR}
PHI_PR_TP	ϕ^{PR^*}
PHI_RI_NW	ϕ^{RI}
RHO_GF	ρ_{G_F}
THETAR_NW	θ^R
THETAR_TP	θ^{R^*}
Z_OIL	Z_O
Z_R_NW	Z_R
Foreign sector	
ALPHA_P_TP	α^{P*}
ALPHA_Y_TOT_TP	α^{GLOB}
ALPHA_Y_TP	α^{Y*}
BETA_P_OIL	β^O
BETA_TP	β^*
KAPPA_P_OIL	κ^O
LAMBDA_Y_NTP	λ^{YNTP}
MU_TP	μ^*
OMEGA_P_TP	ω^{P*}
OMEGA_R_TP	ω^{R*}
OMEGA_Y_TP	ω^{Y*}
PHI_P_TP	ϕ^{P*}
PHI_P_TP_POIL	ϕ^{OP*}
PHI_PM_NW	ϕ^{PM}
PHI_Y_NTP_POIL	ϕ^{ONTP}
PHI_Y_NTP_YTP	ϕ^{YNTP}
PHI_Y_TP	ϕ^{Y*}
PHI_Y_TP_POIL	ϕ^{O*}
PHI_Y_TP_YNTP	ϕ^{YNTP*}
PSI_R_TP	ψ^{R*}
THETAF_NW	θ^F
Monetary policy	
LAM_DR	λ_{dr}
LAM_LR	λ_{lr}
LAM_Y	λ_y
OMEGA_P_NW	ω_P
OMEGA_P_NW1	ω_{P1}
OMEGA_PREM_NW	ω_{PREM}
OMEGA_R_NW	ω_R
OMEGA_RF_NW	ω_{RF}
OMEGA_S_NW	ω_S
OMEGA_W_NW	ω_W
OMEGA_Y_NW	ω_Y

Table 12: Shock-related parameters

Text name	Parameter
LAMBDA_B_NW	λ_B
LAMBDA_G_NW	λ_G
LAMBDA_H_NW	λ_h
LAMBDA_I_NW	λ_I
LAMBDA_IH_NW	λ_{IH}
LAMBDA_INF_TAR_NW	λ_{inf}
LAMBDA_IOIL_NW	λ_{IOIL}
LAMBDA_L_NW	λ_{z^L}
LAMBDA_MC_TP	λ_{MC*}
LAMBDA_NU_NW	λ_{ν}
LAMBDA_NU_TP	λ_{ν_*}
LAMBDA_P_OIL	λ_{PO*}
LAMBDA_PHI_ENT_NW	$\lambda_{\phi^{ent}}$
LAMBDA_PHI_SA_NW	λ_{ϕ}
LAMBDA_PREM_NW	λ_{prem}
LAMBDA_PSI_NW	λ_{ψ}
LAMBDA_RN3M_NW	λ_{RN3M}
LAMBDA_RN3M_TP	λ_{R*}
LAMBDA_THETAE_NW	λ_{θ^e}
LAMBDA_THETAH_NW	λ_{θ^H}
LAMBDA_THETAH_TP	$\lambda_{\theta^{H*}}$
LAMBDA_THETAIH_NW	$\lambda_{\theta^{IH}}$
LAMBDA_U_NW	λ_u
LAMBDA_U_TP	λ_{U*}
LAMBDA_WEDGE_NW	λ_{wedge}
LAMBDA_YO_TP	λ_{YO*}
std_E_B_NW	σ_B
std_E_G_NW	σ_G
std_E_H_NW	σ_h
std_E_I_NW	σ_I
std_E_IH_NW	σ_{IH}
std_E_INF_TAR	σ_{inf}
std_E_IOIL_NW	σ_{IOIL}
std_E_L_NW	σ_{z^L}
std_E_MC_TP	σ_{MC*}
std_E_NU_NW	σ_{ν}
std_E_NU_TP	σ_{ν_*}
std_E_P_OIL	σ_{PO*}
std_E_PHI_ENT_NW	$\sigma_{\phi^{ent}}$
std_E_PHI_SA_NW	σ_{ϕ}
std_E_PREM_NW	σ_{prem}
std_E_PSI_NW	σ_{ψ}
std_E_RN3M_NW	σ_{RN3M}
std_E_RN3M_TP	σ_{R*}
std_E_THETAE_NW	σ_{θ^e}
std_E_THETAH_NW	σ_{θ^H}
std_E_THETAH_TP	$\sigma_{\theta^{H*}}$
std_E_THETAIH_NW	$\sigma_{\theta^{IH}}$
std_E_U_NW	σ_u
std_E_U_TP	σ_{U*}
std_E_WEDGE_NW	σ_{wedge}
std_E_Y_NTP	σ_{YNTP}
std_E_YO_TP	σ_{YO*}
RHO_FFM	ρ_{ffm}

Table 13: Steady-state parameters

Text name	Parameter
DPQ_P_NW_SS	π_{ss}
DPQ_P_TP_SS	π^*_{ss}
DZH_NW_SS	π^h_{ss}
DZT_NW_SS	π^z_{ss}
G_NW_SS	G_{ss}
INF_TARG_SS	$z_{inf,ss}$
M_OIL_TP_SS	$M_{O*,ss}$
MC_TP_SS	MC^*_{ss}
MP_NW_SS	γ^b_{ss}
CCB_NW	$CCB^b_s s$
NAT_Y_TP_SS	$Y_{NAT*,ss}$
NU_NW_SS	ν_{ss}
NU_TP_SS	ν^*_{ss}
O_NW_SS	O_{ss}
P_OIL_SS	P^{O*}_{ss}
PHI_ENT_NW_SS	ϕ^{ent}_{ss}
PHI_SA_NW_SS	ϕ_t
PSI_NW_SS	ψ_{ss}
RN3M_TP_SS	R^*_{ss}
THETAE_NW_SS	θ^e_{ss}
THETAH_NW_SS	θ^H_{ss}
THETAIH_NW_SS	θ^{IH}_{ss}
Z_B_SS	$Z_{B,ss}$
Z_H_NW_SS	z^h_{ss}
Z_I_NW_SS	$z_{I,ss}$
Z_IH_NW_SS	$z_{IH,ss}$
Z_IOIL_NW_SS	$Z_{IOIL,ss}$
Z_L_NW_SS	z^L_{ss}
Z_PREM_NW_SS	$Z_{prem,ss}$
Z_U_NW_SS	z^u_{ss}
Z_X_NW_SS	$z_{x,ss}$