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An estimated DSGE model of energy, costs and inflation in the United Kingdom

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Abstract

In this paper, I estimate a dynamic stochastic general equilibrium (DSGE) model of the United Kingdom. The basic building blocks of the model are standard in the literature. The main complication is that there are three consumption goods: non-energy output, petrol and utilities; given relative prices and their overall wealth, consumers choose how much of each of these goods to consume in order to maximise their utility. Each of the consumption goods is produced according to a sector-specific production function and sticky prices in each sector imply sector-specific New Keynesian Phillips Curves. I show how this model, once estimated, could form a useful additional input within a policymaker's 'suite of models' by considering its implications for the responses of various macroeconomic variables to different economic shocks and by decomposing recent movements of energy and non-energy output and inflation into the proportions caused by each of the shocks.

Key words: Dynamic stochastic general equilibrium model, energy prices and inflation.

JEL classification: E13, E31.

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Summary

The job of monetary policy makers is to set monetary policy so as to achieve their goal of low and stable inflation. In order to carry this out, it is important to understand what drives inflation and how changes in monetary policy feed through the economy into inflation. But no single model can capture all aspects of reality. This is why many central banks have used, and continue to use, a variety of macroeconomic models to help in their understanding of inflation. The main purpose of this paper is to estimate a model of the United Kingdom that, unusually, includes an energy sector. It could in principle be used as another input within a policymaker's 'suite of models'.

The standard model of inflation suggests that it is driven by lagged and future expected inflation and movements in costs. One important cost for most producers is the cost of energy. So, inflation will be affected by movements in energy prices. In addition, to the extent that consumers use energy themselves, movements in energy prices will have a direct, and immediate, effect on consumer price inflation, which is not necessarily captured by standard models. The novelty of this paper, relative to previous work, is that the model takes seriously the effects of movements in energy and other costs on inflation. The goal is to produce a macroeconomic model that can be used to analyse quantitatively the effects on inflation of many temporary shocks, including but not limited to energy prices as well as how monetary policy can respond to such shocks. Furthermore, estimating the model enables us to evaluate how these shocks have evolved over time and the implications of this for explaining movements in output and inflation.

The basic building blocks of the model are standard. The main complication is that there are three consumption goods: non-energy output, petrol and utilities (which can be thought of as a combination of gas and electricity). Each of these consumption goods is produced using different combinations of five inputs: labour, capital, imported (non-energy) intermediates, oil and gas. The prices set by the producers of these goods are sticky. Demand for oil and gas over and above what we produce has to be met from abroad. The central bank affects aggregate demand via movements in interest rates. How this level of aggregate demand translates into demand for each of the goods is determined by consumers' preferences and relative prices. Finally, the model adds a government that 'eats up' some of the non-energy good and levies taxes as well as a specific duty on petrol.

The estimates suggest, not surprisingly, that petrol prices are highly flexible, utility prices are quite flexible, while non-energy prices, on the other hand, are very sticky. The relative stickiness of prices in the three sectors are in line with survey and other evidence for the United Kingdom. In terms of the shocks, the estimates suggest that the productivity shock is fairly persistent but the others much less so; the model is able to explain persistence in the data without having to resort to extremely persistent shocks. The estimated standard deviation of monetary policy shocks is very low, not altogether surprising given that the model was estimated over the inflation-targeting period. But, the domestic demand and investment-specific technology shocks are highly volatile over this period. Finally, the estimates suggest that the

model including energy prices is better able to explain UK macroeconomic data than an otherwise identical model that does not include energy prices.

Given these estimates, it is possible for the model's user to apply the model quantitatively to UK policy issues. The paper has shown how this could be done by examining the effects of many different shocks on inflation and by decomposing recent movements in output and inflation into those parts caused by each of the model's structural shocks. It found that the fall in gross non-energy output from 2008 Q2 to 2009 Q3 was driven by three shocks: to productivity, to world demand and to the domestic risk premium, proxying the effects of the recent financial crisis. The risk premium shock also put downwards pressure on inflation during this period while the productivity shock was putting upwards pressure on inflation. The world demand shock, by contrast, was much less important in explaining the behaviour of inflation over this period.

1 Introduction

The job of monetary policy makers is to set monetary policy – by which I typically mean interest rates, though currently many central banks are operating directly on bank reserves through quantitative easing – so as to achieve their goal of low and stable inflation. But in order to carry out this job, it is important to understand what drives inflation and how changes in monetary policy feed through the economy into inflation. This is why many central banks have used, and continue to use, a variety of macroeconomic models to help in their understanding of inflation. The main purpose of this paper is to estimate a dynamic stochastic general equilibrium (DSGE) model of the United Kingdom that could be used as another input within a policymakers 'suite of models'.

Previous authors have estimated DSGE models for the United Kingdom, eg, Di Cecio and Nelson (2007), Harrison and Oomen (2010), Kamber and Millard (2010) and Faccini *et al* (2011). The standard model of inflation – as embodied in the models estimated by all of these authors – is based around the 'New Keynesian Phillips Curve' (NKPC), which suggests that inflation is driven by lagged and future expected inflation and real marginal cost. Typically in these models, real marginal cost will be equivalent to real unit labour costs (the 'labour share'), although, as shown by Faccini *et al* and Kamber and Millard, this is not the case in models where hiring and firing costs are important and real marginal cost has to be amended accordingly.

But importantly for this paper, when labour and energy are complementary inputs to production, real marginal cost will also be affected by movements in energy prices. Hence, given NKPC theory, movements in energy prices will be important for inflation. In addition, to the extent that consumers use energy themselves, movements in energy prices will have a direct effect on consumer price inflation, which is not necessarily captured by the NKPC. This effect was clearly seen recently in the United Kingdom as the rise in oil prices from $75 a barrel in 2007 Q3 to $121 a barrel in 2008 Q2 was associated with a rise in CPI inflation from 1.8% in 2007 Q3 to 4.8% in 2008 Q3. So, the novelty of this paper, relative to those of Di Cecio and Nelson (2007), Harrison and Oomen (2010), Kamber and Millard (2010) and Faccini *et al* (2011) is that the goal is to estimate a model that takes seriously the effects of movements in all the elements within firms' costs – labour, capital, imported intermediates and energy – on inflation, and that can be used to analyse how a central bank should respond to movements in energy prices in order to achieve its inflation target.

There is a large literature that seeks to understand the effects of movements in energy prices on output and inflation.[1] Most of this literature uses a structural VAR approach in which shocks to oil prices have typically been identified as in Rotemberg and Woodford (1996). The idea is that the nominal price of oil is determined by the worldwide demand and supply of oil and, so, can be thought of as exogenous to output and inflation (and other variables) within any given economy. This implies that, to examine the effects of an exogenous oil price shock, all the researcher needs to do is to run a VAR and calculate the impulse response functions based on

[1] See Blanchard and Gali (2007) for a review of the relevant empirical literature.

the oil price being ordered first in the VAR. An alternative approach to identifying oil price shocks has been to consider specific dates on which the oil price moved in a dramatic (that is, 'exogenous and unforeseeable') way. Hamilton (1985) came up with a list of dates on which such 'oil shocks' had happened and this list was extended by Hoover and Perez (1994) who used monthly data. Most recently, Cavallo and Wu (2006) develop measures of exogenous oil-price shocks for the period 1984 to 2006 based on market commentary (specifically that found in *Oil Daily* and *Oil and Gas Journal*) on daily oil price fluctuations. They then regress output and inflation on these measures to find out how they respond to oil price shocks.

All of these empirical approaches find that oil shocks have large effects on output and inflation. But, constructing a model in which oil has large effects has proven to be difficult. Hamilton (2008), for example, shows that given the share of energy in production in the United States and the elasticity of output with respect to a change in energy use, movements in oil prices can only explain a small fraction of the falls in GDP typically seen after oil price rises. Kim and Loungani (1992) and Dhawan and Jeske (2008) show the same thing in DSGE models. Against this, Rotemberg and Woodford (1996) argue that under imperfect competition with countercyclical desired mark-ups it is possible to generate falls in output in line with the empirical results.

In this paper, I take a DSGE model and estimate it using UK data. The model itself is not original: it is that developed in Harrison *et al* (2011) to analyse the effects of the large rise in oil prices between 2003 and 2008 on UK inflation. But, the emphasis in the two papers is different. Harrison *et al* are interested in analysing the effects of energy theoretically, with a particular emphasis on the implications of *permanent* energy price shocks for economies with declining stocks of natural resources, such as the United Kingdom. In contrast, the goal of this work is to produce a macroeconomic model that can be used to analyse quantitatively the effects of many *temporary* shocks, including but not limited to energy prices, on inflation as well as how monetary policy can respond to such shocks. Furthermore, estimating the model enables us to evaluate how these shocks have evolved over time and the implications of this for explaining movements in output and inflation.

The rest of the paper is structured as follows. Section 2 lays out the model of Harrison *et al* (2011). Section 3 discusses the data and the estimation procedure and presents the estimation results. Section 4 discusses the implications of the estimates for the responses of macroeconomic variables to the shocks in the model and Section 5 shows the evolution of these shocks over time and decomposes recent movements in output and inflation among them. Section 6 concludes.

2 The model

The basic building blocks of the Harrison *et al* (2011) model are standard in the literature. The main complication is that there are three consumption goods: non-energy output, petrol and utilities (which can be thought of as a combination of gas and electricity). This approach is similar to that of Kim and Loungani (1992) and Dhawan and Jeske (2008), who allow for consumption of energy and non-energy; the current model goes further by splitting energy into petrol and utilities. The central bank operates a Taylor rule that affects aggregate demand via an IS curve. How this level of aggregate demand translates into demand for each of the goods is determined by preferences and relative prices. Wage inflation depends on total hours worked in a 'Phillips Curve' relationship. Each of the consumption goods is produced according to a sector-specific production function and sticky prices in each sector imply sector-specific New Keynesian Phillips Curves (NKPCs). The production functions themselves involve different combinations of five inputs: labour, capital, imported (non-energy) intermediates, oil and gas.[2] At the margin, demand for oil and gas has to be met by reducing our net exports of these goods (increasing our net imports). Finally, the model adds a government that 'eats up' some of the non-energy good and levies taxes as well as a specific duty on petrol. This model incorporates nominal rigidities in the goods and labour markets and real rigidities such as habit formation in consumption, investment adjustment cost and variable capital utilisation. In what follows, I just present the log-linear equilibrium conditions; a detailed derivation can be found in the technical appendix to Harrison *et al*

2.1 Households

Households consume the three final goods and supply differentiated labour to the firms. They are also assumed to own the capital stock and make decisions about capital accumulation and utilisation. This assumption, now standard in the business cycle literature, is done in order to simplify the firms' decision problem. The following set of equation determines the household's choice of consumption, capital accumulation and utilisation:

$$\hat{c}_t = \frac{\psi_{hab}(1-\sigma_c)}{1+\psi_{hab}(1-\sigma_c)}\hat{c}_{t-1} + \frac{1}{1+\psi_{hab}(1-\sigma_c)}E_t\hat{c}_{t+1} - \frac{\sigma_c}{1+\psi_{hab}(1-\sigma_c)}\left(i_t - E_t\pi_{c,t+1} - \left(\frac{1}{\beta}-1\right) + \varepsilon_{b,t}\right) \qquad \textbf{(1)}$$

$$\left(i_t - E_t\pi_{c,t+1} - \left(\frac{1}{\beta}-1\right) + \varepsilon_{b,t}\right) = \left(\frac{\varepsilon_k}{1-\delta+\chi_z} + (1+\varepsilon_k)\right)\chi_k\hat{k}_{t-1} - \left(\frac{(1+\varepsilon_k)}{1-\delta+\chi_z}+1\right)\chi_k\hat{k}_t + \frac{\chi_k}{1-\delta+\chi_z}E_t\hat{k}_{t+1} - \chi_k\varepsilon_k\hat{k}_{t-2} + \frac{\chi_z}{1-\delta+\chi_z}E_t\hat{w}_{k,t+1} + \varepsilon_{inv,t} \qquad \textbf{(2)}$$

$$\hat{w}_{k,t} = \phi_z\hat{z}_t \qquad \textbf{(3)}$$

where c is consumption, i is the nominal interest rate, π_c is the inflation rate of consumer prices, ε_b is best thought of as a risk premium shock, w_k is the rental rate for capital, ε_{inv} is an investment-specific technology shock, z is the capital utilisation rate and k is the capital stock.[3] Variables without time subscripts refer to their steady-state values and 'hatted' variables represent log deviation from trend. In terms of the parameters, ψ_{hab} represents the degree of habit formation in consumption, σ_c is the intertemporal elasticity of substitution, β is the discount rate, χ_k scales the costs of adjusting the capital stock, χ_z scales the effect of capital

[2] This represents a difference to the approach of Kim and Loungani (1992) and Dhawan and Jeske (2008) who assume that energy – petrol and utilities in the current model – is not produced but rather is directly imported.
[3] The investment-specific technology shock reduces the costs of adjusting the capital stock and so means that a given level of investment will add more to the capital stock.

utilisation on the depreciation rate, δ is the steady-state depreciation rate and ϕ_z is the inverse elasticity of the capital utilisation cost function.

Equation **(1)** is the consumption Euler equation. Consumption depends on past consumption due to external habit formation. As a result, the elasticity of consumption to the interest rate depends not only on the elasticity of substitution but also on the degree of habit formation parameter. Equation **(2)** is the capital accumulation equation in which lagged capital appears due to the assumption of capital adjustment costs.[4] Equation **(3)** determines capacity utilisation as a function of the rental rate of capital.

Aggregate consumption is composed of consumption of petrol, utilities and 'non-energy'. Consumption of 'energy' will be given by:

$$\hat{c}_{E,t} = (1-\psi_p)\hat{c}_{U,t} + \psi_p \hat{c}_{P,t} \quad \textbf{(4)}$$

and, hence, aggregate consumption will be given by:

$$\hat{c}_t = (1-\psi_e)\hat{c}_{n,t} + \psi_e \hat{c}_{e,t} \quad \textbf{(5)}$$

Relative prices will be given by:

$$\hat{p}_{U,t} = \frac{1}{\sigma_e}\hat{c}_{n,t} + \left(\frac{1}{\sigma_p} - \frac{1}{\sigma_e}\right)\hat{c}_{E,t} - \frac{1}{\sigma_p}\hat{c}_{U,t} \quad \textbf{(6)}$$

and

$$\hat{p}_{U,t} - \hat{p}_{P,t} = -\frac{1}{\sigma_p}\hat{c}_{U,t} + \frac{1}{\sigma_p}\hat{c}_{P,t} \quad \textbf{(7)}$$

Households also have the option of holding either foreign or domestic bonds but trade in foreign bonds incurs quadratic costs. This results in the UIP condition:

$$E_t \hat{s}_{t+1} - \hat{s}_t = -\left(i_t - \left(\frac{1}{\beta} - 1\right)\right) - \chi_{bf} b_{f,t} + \varepsilon_{rf,t} \quad \textbf{(8)}$$

where s is the nominal exchange rate, χ_{bf} is a parameter determining the cost of holding foreign bonds and $\varepsilon_{\mathrm{rf}}$ is a shock to world real interest rates. As a normalisation, I denote foreign bond holdings as a proportion of non-energy output and I assume, without loss of generality, that the supply of domestic government bonds is zero in all periods; that is, the government balances its budget via lump-sum taxes on consumers.

[4] Note that, following Harrison and Oomen (2010), I assume *capital* adjustment costs rather than the *investment* adjustment costs, more often used in the literature. Although this formulation is much more intuitive than the more standard formulation, it means that the model is unable to capture the hump-shaped dynamics of investment.

Each household is a monopoly supplier of differentiated labour. Thus, they set their wages as a mark-up over their marginal rate of substitution between leisure and consumption (percentage deviation denoted by *mrs*), subject to nominal wage stickiness and partial indexation of wages to inflation. Hence, wage inflation will be given by:

$$\dot{W}_t = \frac{\xi_w}{1+\beta\xi_w}\dot{W}_{t-1} + \frac{\beta}{1+\beta\xi_w}E_t\dot{W}_{t+1} - \frac{\psi_w\left(1-\beta\left(1-\psi_w\right)\right)}{\left(1+\frac{\sigma_w}{\sigma_h}\right)\left(1-\psi_w\right)\left(1+\beta\xi_w\right)}\left(\hat{w}_t - mrs_t\right) + \varepsilon_{w,t} \qquad \textbf{(9)}$$

where $\dot{W}$ is nominal wage inflation and ε_w is a wage mark-up shock. Here ψ_w is the share of household members able to reoptimise their wages and ξ_w governs the extent to which non optimised wages are indexed to past inflation. The steady-state wage mark-up is given by $\frac{\sigma_w}{\sigma_w - 1}$ and σ_h denotes the Frisch elasticity of labour supply. The equations defining the marginal rate of substitution and the real consumption wage are:

$$mrs_t = \frac{1}{\sigma_h}\hat{h}_t + \frac{1}{\sigma_c}\left(\hat{c}_t + \psi_{hab}\left(\sigma_c - 1\right)\hat{c}_{t-1}\right) \qquad \textbf{(10)}$$

$$\hat{w}_t = \dot{W}_t + \hat{w}_{t-1} - \pi_{c,t} \qquad \textbf{(11)}$$

2.2 Non energy producing firms

The representative non-energy producing firm is assumed to have the following production function:

$$\hat{q}_t = \left(1-\alpha_q\right)\hat{B}_t + \alpha_q\hat{e}_t + \varepsilon_{a,t} \qquad \textbf{(12)}$$

where q denotes output of non-energy, and ε_a represents a shock to this. B denotes a bundle of value-added, V_n, and intermediate imported goods, M_n:

$$\hat{B}_t = \left(1-\alpha_B\right)\hat{V}_{n,t} + \alpha_B\hat{M}_{n,t} \qquad \textbf{(13)}$$

and e denotes energy input in this sector, which will be given by:

$$\hat{e}_t = \hat{I}_{p,t} = \hat{I}_{u,t} \qquad \textbf{(14)}$$

where I_p is input of petrol, and I_u is input of utilities, both to the non-energy sector.

Cost minimisation implies the following demand curves for value-added, imports and energy:

$$\hat{V}_{n,t} = \hat{\mu}_t - \hat{p}_{vc,t} + \frac{1}{\sigma_q}\hat{q}_t + \frac{\sigma_q - 1}{\sigma_q}\hat{B}_t + \frac{\sigma_q - 1}{\sigma_q}\varepsilon_{a,t} \qquad \textbf{(15)}$$

$$\hat{M}_{n,t} = \hat{\mu}_t - \hat{p}_{m,t} + \frac{1}{\sigma_q}\hat{q}_t - \left(\frac{1}{\sigma_q} - 1\right)\hat{B}_t + \frac{\sigma_q - 1}{\sigma_q}\varepsilon_{a,t} \quad \textbf{(16)}$$

$$\hat{e}_t = \sigma_q \hat{\mu}_t + \hat{q}_t - \sigma_q\left(\psi_n \hat{p}_{p,t} + (1-\psi_n)\hat{p}_{U,t}\right) + (\sigma_q - 1)\varepsilon_{a,t} \quad \textbf{(17)}$$

where μ is real marginal cost and p_{vc} is the 'competitive' price of value-added (the marginal cost of producing it). Firms in the non-energy sector are also subject to nominal rigidities in their price-setting. In particular, each period they are only allowed to set their price optimally with a probability of 1-χ_p. If they cannot change their price optimally, they partially index their price to lagged inflation. The resulting NKPC is:

$$\pi_t = \frac{\beta}{1+\beta\varepsilon}E_t\pi_{t+1} + \frac{\varepsilon}{1+\beta\varepsilon}\pi_{t-1} + \frac{(1-\chi_p)(1-\beta\chi_p)}{(1+\beta\varepsilon)\chi_p}\hat{\mu}_t + \varepsilon_{\mu,t} \quad \textbf{(18)}$$

where ε is the degree of indexation and ε_μ is a price mark-up shock.

2.3 Value-added sector

'Value-added' producers use labour and capital to produce value-added, *V*:

$$\hat{V}_t = (1-\alpha_v)\hat{h}_t + \alpha_v\left(\hat{k}_{t-1} + z_t\right) \quad \textbf{(19)}$$

The term in *z* shows that the capital effectively used in production depends on the intensity of capital utilisation. Unlike Harrison *et al* (2011), I assume value-added producers need to borrow the money to finance a proportion, ψ_{wc}, of their wage bill. This can be motivated by the fact that firms typically need to borrow to finance their working capital needs: that is, the need for funds to cover the gap between production and when the firm is able to sell its output. This assumption has been used by many others, eg, Fuerst (1992) and Christiano and Eichenbaum (1992, 1995), and implies a 'cost channel' of monetary transmission.

Cost minimisation by value-added producers implies the following demand curves for capital and labour:

$$\hat{h}_t = \hat{V}_t + \sigma_V\left(\hat{p}_{vc,t} - \hat{w}_t - \psi_{wc}\left(i_t - \left(\frac{1}{\beta} - 1\right) + \varepsilon_{b,t}\right)\right) \quad \textbf{(20)}$$

$$\hat{k}_{t-1} + \hat{z}_t = \hat{V}_t + \sigma_V\left(\hat{p}_{vc,t} - \hat{w}_{k,t}\right) \quad \textbf{(21)}$$

2.4 Petrol producers

Petrol, q_p, is produced using inputs of crude oil, I_o, and value-added, V_p. I assume a simple Leontieff production function:

$$\hat{q}_{p,t} = \hat{I}_{o,t} = \hat{V}_{p,t} \quad \textbf{(22)}$$

The motivation for this choice of production function is that it is not clear how adding more and more workers to a given amount of oil could physically increase the amount of petrol that can be produced from it. Firms in this sector are also subject to nominal rigidities in their price-setting. In this case, they are able to optimally change their price in any given quarter with probability 1-χ_{pp} and ε_{pp} represents the degree of indexation. The resulting NKPC is:

$$\pi_{pb,t} = \frac{\beta}{1+\beta\varepsilon_{pp}} E_t \pi_{pb,t+1} + \frac{\varepsilon_{pp}}{1+\beta\varepsilon_{pp}} \pi_{pb,t-1} + \frac{(1-\chi_{pp})(1-\beta\chi_{pp})}{(1+\beta\varepsilon_{pp})\chi_{pp}} \hat{\mu}_{p,t} \tag{23}$$

where real marginal cost in this sector will be given by:

$$\hat{\mu}_{p,t} = \psi_{qp} \hat{p}_{vc,t} + (1-\psi_{qp}) \hat{p}_{o,t} - \hat{p}_{pb,t} \tag{24}$$

where p_o is the price of oil and p_{pb} is the basic (pre-duty) price of petrol. Finally, I can note that by definition:

$$\pi_{pb,t} = \pi_t + \hat{p}_{pb,t} - \hat{p}_{pb,t-1} \tag{25}$$

2.5 Utilities producers

Output of utilities, q_u, is produced using inputs of gas, I_g, and value-added, V_u. I assume a simple Leontieff production function:

$$\hat{q}_{u,t} = \hat{I}_{g,t} = \hat{V}_{u,t} \tag{26}$$

Again, the motivation for this choice of production function is that it is not clear how adding more and more workers to a given amount of natural gas could physically increase the amount of gas and electricity that can be produced from it. Firms in this sector are also subject to nominal rigidities in their price-setting. In this case, they are able to optimally change their price in any given quarter with probability χ_u and ε_u represents the degree of indexation. The resulting NKPC is:

$$\pi_{u,t} = \frac{\beta}{1+\beta\varepsilon_u} E_t \pi_{u,t+1} + \frac{\varepsilon_u}{1+\beta\varepsilon_u} \pi_{u,t-1} + \frac{(1-\chi_u)(1-\beta\chi_u)}{(1+\beta\varepsilon_u)\chi_u} \hat{\mu}_{u,t} \tag{27}$$

where real marginal cost in this sector will be given by:

$$\hat{\mu}_{u,t} = \psi_u \hat{p}_{vc,t} + (1-\psi_u) \hat{p}_{g,t} - \hat{p}_{u,t} \tag{28}$$

where p_g is the price of gas and p_u is the price of utilities. Finally, I can note that by definition:

$$\pi_{u,t} = \pi_t + \hat{p}_{u,t} - \hat{p}_{u,t-1} \tag{29}$$

2.6 Monetary and fiscal policy

Monetary policy is assumed to follow a Taylor rule with the central bank responding to deviations of inflation from target and value-added from flexible-price value-added:

$$i_t - \left(\frac{1}{\beta} - 1\right) = \theta_{rg}\left(i_{t-1} - \left(\frac{1}{\beta} - 1\right)\right) + \left(1-\theta_{rg}\right)\left(\theta_{pdot}\pi_{c,t} + \theta_y \hat{y}_t\right) + \varepsilon_{i,t} \quad \textbf{(30)}$$

where ε_i is a monetary policy shock. Flexible-price value-added is defined as what value-added would be in a flexible-price version of the model given the estimated values of the shocks.

The fiscal authority levies a duty on petrol. In my estimation, I assume that this is not changed over time. Given that, I obtain:

$$\hat{p}_{p,t} = (1-\psi_d)\hat{p}_{pb,t} \quad \textbf{(31)}$$

That is, since it is held constant, the petrol duty has no role other than to reduce the impact of a change in petrol producers' other costs on the final price of petrol paid by consumers. Since, I assume, as said earlier, that the government balances its budget using lump-sum taxes on consumers (denoted by *T*), we can write the government's budget constraint as $G_t = \psi_d P_{p,t} q_{p,t} + T_t$. Unanticipated changes in government spending will form part of the 'domestic demand' shock that I discuss below.

2.7 Foreign sector

I assume that the United Kingdom is a small open economy. Hence, world prices are exogenous. Oil and gas prices adjust immediately to their world prices:[5]

$$\hat{p}_{o,t} = \varepsilon_{p_o} - \hat{s}_t \quad \textbf{(32)}$$

$$\hat{p}_{g,t} = \varepsilon_{p_g} - \hat{s}_t \quad \textbf{(33)}$$

where ε_{p_o} is a shock to world oil prices and ε_{p_g} is a shock to world gas prices.

UK import prices, on the other hand, take time to adjust to purchasing power parity. This results in the NKPC for import prices:

$$\pi_{m,t} = \frac{\iota_{pm}}{1+\beta\iota_{pm}}\pi_{m,t-1} + \frac{\beta}{1+\beta\iota_{pm}}E_t\pi_{m,t+1} + \frac{\left(1-\xi_{pm}\right)\left(1-\beta\xi_{pm}\right)}{\left(1+\beta\iota_{pm}\right)\xi_{pm}}\left(\varepsilon_{p_{mf}} - \hat{s}_t - \hat{p}_{m,t}\right) \quad \textbf{(34)}$$

where ε_{p_m} is a shock to the world price of our imports.
Finally, I assume the following demand function for our exports of non-energy goods:

[5] For simplicity, I ignore issues about different varieties of crude oil as well as refining costs.

$$\hat{x}_{n,t} = \psi_z \hat{x}_{n,t-1} + (1-\psi_z)(\varepsilon_{y_f} - \eta_x \hat{s}_t) \quad \textbf{(35)}$$

where ε_{y_f} is a world demand shock.

2.8 Market clearing

I close the model with the following market-clearing conditions:

$$\hat{p}_{c,t} + \hat{c}_t = \frac{c_n}{p_c c}\hat{c}_{n,t} + \frac{p_u c_u}{p_c c}(\hat{p}_{U,t} + \hat{c}_{U,t}) + \left(1 - \frac{c_n}{p_c c} - \frac{p_u c_u}{p_c c}\right)(\hat{p}_{P,t} + \hat{c}_{P,t}) \quad \textbf{(36)}$$

$$V_t = \frac{V_n}{V}\hat{V}_{n,t} + \frac{V_u}{V}\hat{V}_{u,t} + \left(1 - \frac{V_n}{V} - \frac{V_u}{V}\right)\hat{V}_{p,t} \quad \textbf{(37)}$$

$$\hat{q}_{P,t} = \frac{c_P}{q_P}\hat{c}_{P,t} + \left(1 - \frac{c_P}{q_P}\right)\hat{I}_{P,t} \quad \textbf{(38)}$$

$$\hat{q}_{U,t} = \frac{c_U}{q_U}\hat{c}_{U,t} + \left(1 - \frac{c_U}{q_U}\right)\hat{I}_{U,t} \quad \textbf{(39)}$$

$$\hat{I}_{O,t} = -\frac{X_o}{I_o}\hat{X}_{O,t} \quad \textbf{(40)}$$

$$\hat{I}_{G,t} = -\frac{X_g}{I_g}\hat{X}_{G,t} \quad \textbf{(41)}$$

$$\hat{q}_t = \frac{c_n}{q}\hat{c}_{n,t} + \frac{k}{q}\hat{k}_t - \frac{(1-\delta)k}{q}\hat{k}_{t-1} + \frac{\chi_z k}{q}\hat{z}_t + \frac{x_n}{q}\hat{x}_{n,t} + \frac{c_g}{q}\varepsilon_{g,t} \quad \textbf{(42)}$$

$$b_{f,t} = \frac{1}{\beta}b_{f,t-1} + \frac{x_n}{q}\hat{x}_{n,t} + \frac{X_g}{q}(\hat{p}_{g,t} + \hat{X}_{g,t}) + \frac{X_o}{q}(\hat{p}_{o,t} + \hat{X}_{o,t}) - \frac{M_n}{q}(\hat{p}_{m,t} + \hat{M}_{n,t}) \quad \textbf{(43)}$$

where ε_g is a shock to the exogenous components of domestic demand shock. This can be thought of as combining shocks to government spending, stockbuilding and the part of investment that cannot be explained via the cost of capital.

2.9 Shock processes

As is common in the literature, I suppose that the shocks follow AR(1) processes:

$$\varepsilon_{a,t} = \rho_a \varepsilon_{a,t-1} + \eta_{a,t} \quad \textbf{(44)}$$

$$\varepsilon_{b,t} = \rho_b \varepsilon_{b,t-1} + \eta_{b,t} \quad \textbf{(45)}$$

$$\varepsilon_{g,t} = \rho_g \varepsilon_{g,t-1} + \eta_{g,t} \quad \textbf{(46)}$$

$$\varepsilon_{i,t} = \rho_i \varepsilon_{i,t-1} + \eta_{I,t} \quad \textbf{(47)}$$

$$\varepsilon_{\mu,t} = \rho_\mu \varepsilon_{\mu,t-1} + \eta_{\mu,t} \quad \textbf{(48)}$$

$$\varepsilon_{inv,t} = \rho_{inv} \varepsilon_{inv,t-1} + \eta_{inv,t} \quad \textbf{(49)}$$

$$\varepsilon_{w,t} = \rho_w \varepsilon_{w,t-1} + \eta_{w,t} \quad \textbf{(50)}$$

$$\varepsilon_{y_f,t} = \rho_{y_f} \varepsilon_{y_f,t-1} + \eta_{y_f,t} \quad \textbf{(51)}$$

$$\varepsilon_{p_{mf},t} = \rho_{p_{mf}} \varepsilon_{p_{mf},t-1} + \eta_{p_{mf},t} \quad \textbf{(52)}$$

$$\varepsilon_{p_o,t} = \rho_{p_o} \varepsilon_{p_o,t-1} + \eta_{p_o,t} \quad \textbf{(53)}$$

$$\varepsilon_{p_g,t} = \rho_{p_g} \varepsilon_{p_g,t-1} + \eta_{p_g,t} \quad \textbf{(54)}$$
$$\varepsilon_{rf,t} = \rho_{rf} \varepsilon_{rf,t-1} + \eta_{rf,t} \quad \textbf{(55)}$$

where the η's are all assumed to be iid normal processes, whose standard deviations are to be estimated.

3 Estimation

3.1 Data

The model was estimated using Bayesian techniques on data for the period 1996 Q2 (the earliest quarter for which data on wholesale gas prices were available) to 2009 Q3. As there are ten shocks in the BBWE model, ten data series were used in the estimation: five domestic and five 'world'. In terms of domestic data, I used data on final output of the non-energy producing sector, consumption, the consumption deflator, investment, total hours worked in the private sector, real wages and the Bank Rate. Consumption was defined as the sum of the ONS chained volume measures of final consumption expenditure by households (*ABJR*) and non-profit institutions (*HAYO*). The consumption deflator was calculated by dividing the sum of the ONS measures of final consumption expenditure at current market prices by households (*ABJQ*) and non-profit institutions (*HAYE*) by the volume measure. Investment was defined as 'business investment' (NPEL). How the series for final output of the non-energy producing sector was constructed is discussed at length in Harrison *et al* (2011). Data on total hours worked in the private sector were taken from the Bank of England Quarterly Model (BEQM) and is described in Harrison *et al* (2005). The real wage was calculated by dividing private-sector wages and salaries including self-employment income (again as described in Harrison *et al* (2005)) by total hours worked in the private sector and then again by the consumption deflator. Finally, the ONS publish a series for the 'London clearing banks: Base rate' as an annual rate (Code: AMIH) and this was converted to a quarterly rate. Prior to the estimation, all data were detrended using the Hodrick-Prescott filter with the smoothing parameter, λ, set to 1,600.

For world data I used series for UK-weighted world trade, world export prices and world interest rates taken from BEQM described in Harrison *et al* (2005). I used the dollar oil price, available on a daily basis from Datastream (Code: OILBRNP_P) converted to its quarterly average. Finally, I calculated a world wholesale gas price by multiplying the wholesale gas price in sterling (available on a daily basis from Bloomberg: Code: NBPGDAHDBBSW) by the sterling exchange rate index, published daily by the Bank of England. Following Harrison and Oomen (2010), these data were used to estimate the foreign shock processes separately and the results were hard-coded into the model that was estimated. The estimation results were:[6]

$$\varepsilon_{y_f,t} = 0.9061\varepsilon_{y_f,t-1} + \eta_{y_f,t},\ \sigma_{y_f} = 0.0142 \quad \textbf{(56)}$$
$$\varepsilon_{p_{mf},t} = 0.8991\varepsilon_{p_{mf},t-1} + \eta_{p_{mf},t},\ \sigma_{p_{mf}} = 0.0075 \quad \textbf{(57)}$$

[6] These equations – with the exception of the equation for world gas prices – were estimated over the period 1977 Q1 to 2009 Q3. The equation for world gas prices was estimated over the period 1996 Q2 – the earliest date for which we have data on wholesale gas prices – to 2009 Q3.

$$\varepsilon_{p_o,t} = 0.7283\varepsilon_{p_o,t-1} + \eta_{p_o,t},\ \sigma_{p_o} = 0.1410 \quad \textbf{(58)}$$
$$\varepsilon_{p_g,t} = 0.5940\varepsilon_{p_g,t-1} + \eta_{p_g,t},\ \sigma_{p_g} = 0.2544 \quad \textbf{(59)}$$
$$\varepsilon_{r_f,t} = 0.8738\varepsilon_{r_f,t-1} + \eta_{r_f,t},\ \sigma_{r_f} = 0.0012 \quad \textbf{(60)}$$

One thing we can note here is that the shocks to world oil and gas prices have high volatility and low persistence relative to the other foreign shocks.

3.2 Priors

I followed Harrison and Oomen (2010) and split my parameters into two groups: those that were most important in determining the steady state of the model and, hence, average ratios, and those that determine the dynamics of the model. Parameters in the first group were set so as to match the steady-state values used in Harrison *et al* (2011). When I came to estimate the model, I held these parameters fixed. The values I used for this first group of parameters, and the relevant steady-state ratios I fixed, are shown in Table A.

Table A: First group parameter values

Parameter	Value	Description	Motivation
β	0.9925	Discount factor	Assumption
χ_{bf}	0.001	Cost of adjusting portfolio of foreign bonds	Normalisation
δ	0.013	Depreciation rate	Assumption
χ_z	$=1/\beta-(1-\delta)$	Scales the effect of capital utilisation on the depreciation rate	Ensures capital utilisation equals 1 in steady state
σ_w	3.8906	Elasticity of demand for differentiated labour	Implies a wage mark-up of 1.35 (that is, 35%) in steady state
σ_e	0.4	Elasticity of substitution between non-energy and energy in consumption	Assumption
σ_p	0.1	Elasticity of substitution between petrol and utilities in energy consumption	Assumption
σ_v	0.5	Elasticity of substitution between labour and capital in value-added production	Assumption
σ_q	0.15	Elasticity of substitution between energy and everything else in non-energy production	Assumption
η_x	1.5	Elasticity of demand for exports	Harrison *et al* (2011)
ψ_e	0.0526	Share of energy in consumption	Implies $\frac{p_u c_u}{p_c c} = 0.0215$
ψ_p	0.5913	Share of petrol in energy consumption	Implies $\frac{p_p c_p}{p_c c} = 0.03$
α_q	0.0528	Cost share of energy in non-energy output	Implies $\frac{p_o i_o + p_g i_g}{q + p_u c_u + p_p (c_p + X_p)} = 0.016$
α_B	0.3154	Cost share of imports in 'bundle'	Implies $\frac{p_m m_n}{q + p_u c_u + p_p (c_p + X_p)} = 0.25$

Table A (continued): First group parameter values

Parameter	Value	Description	Motivation
α_v	0.1701	Cost share of capital in value-added	Implies $\frac{wh}{p_v V} = 0.75$
ψ_n	0.3096	Cost share of petrol in energy output	Implies $\frac{p_p i_p}{p_u i_u} = 1.82$
ψ_{qp}	0.1844	Cost share of value-added in petrol output	Implies $\frac{p_p i_p}{p_u i_u} = 1.82$
ψ_u	0.4834	Cost share of value-added in utilities output	Implies $\frac{p_p i_p}{p_u i_u} = 1.82$
ψ_d	0.617	Share of duty in petrol prices	Implies $\frac{d_p(1+\tau_p)}{p_p} = 0.617$
$\frac{c_n}{p_c c}$	0.9474	Share of non-energy consumption in total consumption	To match data in Harrison *et al* (2011)
$\frac{p_u c_u}{p_c c}$	0.0215	Share of utility consumption in total consumption	To match data in Harrison *et al* (2011)
$\frac{V_n}{V}$	0.9815	Share of value-added used as input in non-energy goods	To match data in Harrison *et al* (2011)
$\frac{V_u}{V}$	0.0145	Share of value-added used as input in utilities	To match data in Harrison *et al* (2011)
$\frac{c_p}{q_p}$	0.4204	Share of petrol output going to consumption	To match data in Harrison *et al* (2011)
$\frac{c_u}{q_u}$	0.4054	Share of utilities output going to consumption	To match data in Harrison *et al* (2011)
$\frac{X_o}{I_o}$	0.4551	Ratio of oil exports to oil inputs	To match data in Harrison *et al* (2011)
$\frac{X_g}{I_g}$	-0.0792	Ratio of gas exports to gas inputs	To match data in Harrison *et al* (2011)
$\frac{c_n}{q}$	0.5802	Share of private consumption in non-energy output	To match data in Harrison *et al* (2011)
$\frac{k}{q}$	4.7202	Ratio of capital to non-energy output	To match data in Harrison *et al* (2011)
$\frac{c_g}{q}$	0.1032	Share of government consumption in non-energy output	To match data in Harrison *et al* (2011)
$\frac{x_n}{q}$	0.2552	Share of exports in non-energy output	To match data in Harrison *et al* (2011)
$\frac{M_n}{q}$	0.2581	Ratio of imports of non-energy goods to output of non-energy goods	To match data in Harrison *et al* (2011)
$\frac{X_o}{q}$	0.0035	Ratio of oil exports to output of non-energy goods	To match data in Harrison *et al* (2011)
$\frac{X_g}{q}$	-0.0007	Ratio of gas exports to output of non-energy goods	To match data in Harrison *et al* (2011)

For the second group of parameters, I generally took my priors from Harrison and Oomen (2010). In particular, I set the priors for the inverse of risk aversion in consumption, σ_c, the scale parameter for the costs of adjusting the capital stock, χ_k, the elasticity of capital utilisation costs, ϕ_z, and the elasticity of labour supply σ_h, exactly in line with Harrison and Oomen. My prior for the coefficient on inflation in the Taylor rule is normal with a mean of 1.5 (as in the original Taylor paper) and a standard deviation of 0.25. For the remaining parameters I used beta distributions – since, by definition, they have to lie between 0 and 1 – with relatively loose priors. In all cases, I set my prior means to 0.5 and my prior standard deviations to 0.2. My priors are shown in Table B. In terms of the parameters governing the shock processes, I use beta distributions for the autocorrelation coefficients with means of 0.5 and standard deviations of 0.2, and I use inverse gamma distributions for the standard deviations with means of 1% and two degrees of freedom.

Table B: Priors for second group parameters

Parameter	Description	Prior distribution	Prior mean	Prior standard deviation
σ_c	Intertemporal elasticity of substitution	Normal	0.66	0.198
ψ_{hab}	Degree of habit persistence in consumption	Beta	0.5	0.2
ε_k	Degree of persistence in investment adjustment costs	Beta	0.5	0.2
χ_k	Scale of capital adjustment costs	Normal	201	60.3
ϕ_z	Inverse elasticity of capital utilisation costs	Normal	0.56	0.168
ψ_{wc}	Share of wage bill paid financed by borrowing	Beta	0.5	0.2
σ_h	Frisch elasticity of labour supply	Normal	0.43	0.107
ψ_w	Probability of being able to change wages	Beta	0.5	0.2
ξ_w	Degree of wage indexation	Beta	0.5	0.2
χ_p	Probability of not being able to change price: non-energy sector	Beta	0.5	0.2
χ_u	Probability of not being able to change price: utilities	Beta	0.5	0.2
χ_{pp}	Probability of not being able to change price: petrol	Beta	0.5	0.2
ε_p	Degree of indexation: non-energy sector	Beta	0.5	0.2
ε_u	Degree of indexation: utilities sector	Beta	0.5	0.2
ε_{pp}	Degree of indexation: petrol sector	Beta	0.5	0.2
ψ_x	Degree of persistence in export demand	Beta	0.5	0.2
ψ_{pm}	Probability of not being able to change price: importers	Beta	0.5	0.2
ε_{pm}	Degree of indexation: importers	Beta	0.5	0.2
θ_{pdot}	Taylor rule coefficient on inflation	Normal	1.5	0.25
θ_y	Taylor rule coefficient on output	Normal	0.125	0.05
θ_{rg}	Degree of interest rate smoothing in Taylor rule	Beta	0.5	0.2

3.3 Estimation results

As is now standard in the literature, I first estimated the mode of the posterior distribution by maximising the log posterior function, which combines the priors with the likelihood given by the data, and then used the Metropolis-Hastings algorithm (as implemented in *Dynare*) to obtain the full posterior distribution. I used a sample of 250,000 draws (dropping the first 50,000 draws), obtaining an acceptance rate of 0.31. To test the stability of the sample, I used the Brooks and Gelman (1998) diagnostic (as implemented by *Dynare*), which compares within and between moments of multiple chains. Table C shows the posterior mode and means for the model parameters together with a 90% confidence interval.

Table C: Estimation results

Parameter	Description	Posterior mode	Posterior mean	Confidence interval	
σ_c	Intertemporal elasticity of substitution	0.7103	0.6256	0.4777	0.7775
ψ_{hab}	Degree of habit persistence in consumption	0.6019	0.5876	0.4204	0.7564
ε_k	Degree of persistence in investment adjustment costs	0.1887	0.1871	0.0793	0.2920
χ_k	Scale of capital adjustment costs	106.05	116.52	64.47	172.96
ϕ_z	Inverse elasticity of capital utilisation costs	0.4554	0.4591	0.3207	0.5980
ψ_{wc}	Share of wage bill paid financed by borrowing	0.5548	0.4974	0.2551	0.7067
σ_h	Frisch elasticity of labour supply	0.3547	0.3423	0.2724	0.4172
ψ_w	Probability of being able to change wages	0.4630	0.4719	0.3487	0.5972
ξ_w	Degree of wage indexation	0.1708	0.1882	0.0389	0.3212
χ_p	Probability of not being able to change price: non-energy sector	0.8904	0.8968	0.8297	0.9668
χ_u	Probability of not being able to change price: utilities	0.5618	0.5760	0.4478	0.7047
χ_{pp}	Probability of not being able to change price: petrol	0.2192	0.2371	0.0948	0.3853
ε_p	Degree of indexation: non-energy sector	0.2832	0.1491	0.0307	0.2581
ε_u	Degree of indexation: utilities sector	0.2769	0.2073	0.0829	0.3359
ε_{pp}	Degree of indexation: petrol sector	0.5021	0.4622	0.2479	0.7901
ψ_x	Degree of persistence in export demand	0.4175	0.4152	0.3150	0.5234
ψ_{pm}	Probability of not being able to change price: importers	0.4283	0.4169	0.2817	0.5654
ε_{pm}	Degree of indexation: importers	0.8937	0.8296	0.7141	0.9481
θ_{pdot}	Taylor rule coefficient on inflation	1.2190	1.1951	0.9904	1.4646
θ_y	Taylor rule coefficient on output	0.1528	0.1494	0.1196	0.1813
θ_{rg}	Degree of interest rate smoothing in Taylor rule	0.7800	0.7640	0.6952	0.8318

In terms of the parameter values themselves, the posterior mean estimate for the inverse coefficient of relative risk aversion, σ_c, is slightly lower than its prior mean, though it is not well identified by the data. The posterior mean estimate for ε_k is much lower than its prior mean, suggesting little persistence in investment. The inverse Frisch elasticity of labour supply is lower than its prior mean and is well identified. The degree of habits in consumption is not well identified and, at 0.59, is a little lower than previous estimates on UK data.[7] I find that about 50% of the wage bill has to be financed using working capital, though again this parameter is not well identified. There appears to be little persistence in export demand.

In terms of nominal rigidities, the posterior mean estimates suggest, not surprisingly, that petrol prices are flexible, being changed roughly every four months on average. Utility prices are also quite flexible being changed roughly every seven months on average. Non-energy prices, on the other hand, are very sticky, being changed roughly every 29 months on average, respectively. The relative stickiness of prices in the three sectors are in line with survey and other evidence for the United Kingdom.[8] But the absolute degree of price stickiness in the non-energy sector

[7] See, eg, Banerjee and Batini (2003).
[8] See Greenslade and Parker (2010) and Bunn and Ellis (2009).

seems much too high, although this result has often been found in estimated DSGE models.[9] Indexation in all sectors is quite low suggesting little inflation persistence. The posterior estimates suggest that import prices are relatively flexible, changing on average every five months, and the degree of indexation of import prices is high. Surprisingly, wages are estimated to be fairly flexible, changing roughly every six months on average. Wage changes are hardly indexed to lagged wage inflation, as might be expected given the lack of formal indexation of wage bargains in the United Kingdom at present.

Turning to the shocks, Table D shows the estimated posterior mode and means for the autocorrelation coefficients and standard errors of the domestic shocks, together with a 90% confidence interval. The posterior estimates suggest that the productivity shock is fairly persistent but the other shocks much less so; the model is able to explain persistence in the data without having to resort to extremely persistent shocks. The mean posterior estimate for the standard deviation of monetary policy shocks is only 15 basis points. This is not altogether surprising given that the model was estimated over the inflation-targeting period. But, the domestic demand and investment-specific technology shocks are highly volatile over this period with posterior mean estimates for their standard deviations of 9.2% and 6.1%, respectively.

Table D: Estimation results for the domestic shock processes

	Posterior mode	Posterior mean	Confidence interval	
Autocorrelation coefficients				
Productivity, ε_a	0.8906	0.8747	0.8176	0.9311
Risk premium, ε_b	0.7217	0.6656	0.5760	0.7544
Domestic demand, ε_g	0.7306	0.6621	0.5235	0.8263
Monetary policy, ε_i	0.3381	0.3174	0.1888	0.4458
Investment-specific technology, ε_{inv}	0.4269	0.4323	0.3025	0.6055
Wage mark-up, ε_w	0.2569	0.2247	0.0924	0.3407
Price mark-up, ε_μ	0.2615	0.2398	0.0842	0.3935
Standard deviations				
Productivity, ε_a	0.0120	0.0123	0.0103	0.0142
Risk premium, ε_b	0.0032	0.0041	0.0030	0.0052
Domestic demand, ε_g	0.0901	0.0923	0.0777	0.1068
Monetary policy, ε_i	0.0015	0.0015	0.0013	0.0018
Investment-specific technology, ε_{inv}	0.0551	0.0612	0.0320	0.0952
Wage mark-up, ε_w	0.0093	0.0098	0.0079	0.0118
Mark-up, ε_μ	0.0025	0.0028	0.0023	0.0034

Tables E and F show the importance of each of the shocks in terms of how much each explains the variance in the endogenous variables. The productivity shock is clearly the most important in explaining consumption, accounting for almost two thirds of the variation in consumption. The investment-specific technology shock contributes little to the variation in all variable except for investment, where it explains 83% of the variance. The bulk of the variation in GDP, total hours and gross output is explained by a combination of the productivity, domestic demand, monetary policy and risk premium shocks, which together account for 79%, 77% and 81% of

[9] See Smets and Wouters (2003) and Gali *et al* (2001) for the euro area and Di Cecio and Nelson (2007), Harrison and Oomen (2010) and Kamber and Millard (2010) for the United Kingdom.

their variance, respectively. Turning to nominal variables, 64% of the variation in price inflation is explained by the price mark-up shock, with the productivity shock accounting for about 18%. Similarly, 80% of the variation in wage inflation is explained by the wage mark-up shock. And, so, a combination of the mark-up and productivity shocks explain 83% of variation in the real wage. 80% of the variation in the nominal interest rate is explained by the productivity, monetary policy and price mark-up shocks. Perhaps surprisingly, the foreign shocks account for little of the variation in UK data with the exception of the real exchange rate, 33% of whose variation is explained by them. Another 30% of the variation in the real exchange rate is explained by the productivity shock.

Table E: Variance decompositions – domestic shocks

	Productivity	Monetary policy	Domestic demand	Investment-specific technology	Wage mark-up	Price mark-up	Risk premium
Consumption	62.7%	6.8%	3.3%	0.2%	1.2%	3.0%	10.6%
Investment	2.1%	3.8%	1.7%	83.3%	0.5%	2.7%	5.1%
GDP	20.5%	13.8%	22.5%	4.7%	4.4%	5.5%	21.8%
Gross output	38.3%	9.3%	20.2%	4.0%	0.3%	4.8%	13.5%
Total hours	21.4%	12.7%	21.8%	4.5%	8.0%	4.2%	21.0%
Real wage	11.0%	5.2%	1.3%	0.2%	57.5%	14.2%	4.3%
Real exchange rate	29.7%	11.2%	1.4%	0.2%	1.4%	6.1%	17.5%
Nominal interest rate	35.4%	26.6%	2.5%	0.4%	0.3%	17.8%	8.6%
Annual inflation rate	17.8%	2.0%	0.3%	0.0%	5.7%	63.7%	0.9%
Annual wage inflation rate	1.4%	5.8%	1.4%	0.2%	79.7%	3.6%	5.7%

Table F: Variance decompositions – foreign shocks

	Oil price	Foreign demand	Foreign export price	Foreign interest rate	Gas price
Consumption	0.3%	4.8%	2.8%	3.6%	0.7%
Investment	0.0%	0.4%	0.1%	0.1%	0.0%
GDP	0.1%	2.5%	0.2%	3.8%	0.2%
Gross output	0.1%	6.7%	1.8%	0.8%	0.2%
Total hours	0.1%	2.3%	0.2%	3.5%	0.2%
Real wage	0.4%	4.0%	0.6%	0.6%	0.7%
Real exchange rate	0.1%	10.8%	1.3%	20.3%	0.2%
Nominal interest rate	0.9%	0.7%	1.3%	4.0%	1.6%
Annual inflation rate	2.8%	0.5%	1.0%	2.2%	3.2%
Annual wage inflation rate	0.0%	0.9%	0.1%	1.0%	0.1%

3.4 Effects of including/excluding energy

This section discusses how the inclusion of energy price effects – the main contribution of this model over, say, the Smets and Wouters (2007) model – affects the estimated coefficients of the model and whether, overall, it forms a better description of UK macroeconomic data than the simpler model. In order to do this, I consider an otherwise identical model in which consumption consists of only one good, which is produced using labour, capital and imports only. I drop the world oil and gas prices from my set of observed variables in the estimation and shocks to world oil and gas prices from my set of shocks in the model. I leave my fixed parameters and priors unchanged. The results are shown in the 4th column of Table G and the 3rd column of Table H.

Table G: Parameter estimates for model with and without energy

Parameter	Description	Baseline	Ex-energy
σ_c	Intertemporal elasticity of substitution	0.6256	0.6481
ψ_{hab}	Degree of habit persistence in consumption	0.5876	0.5310
ε_k	Degree of persistence in investment adjustment costs	0.1871	0.3698
χ_k	Scale of capital adjustment costs	116.52	219.03
ϕ_z	Inverse elasticity of capital utilisation costs	0.4591	0.5560
ψ_{wc}	Share of wage bill paid financed by borrowing	0.4974	0.5629
σ_h	Frisch elasticity of labour supply	0.3423	0.3943
ψ_w	Probability of being able to change wages	0.4719	0.4672
ε_w	Degree of wage indexation	0.1882	0.4864
χ_p	Probability of not being able to change price: non-energy sector	0.8968	0.5344
χ_u	Probability of not being able to change price: utilities	0.5760	-
χ_{pp}	Probability of not being able to change price: petrol	0.2371	-
ε_p	Degree of indexation: non-energy sector	0.1491	0.3149
ε_u	Degree of indexation: utilities sector	0.2073	-
ε_{pp}	Degree of indexation: petrol sector	0.4622	-
ψ_x	Degree of persistence in export demand	0.4152	0.4274
ψ_{pm}	Probability of not being able to change price: importers	0.4169	0.4489
ε_{pm}	Degree of indexation: importers	0.8296	0.4788
θ_{pdot}	Taylor rule coefficient on inflation	1.1951	1.3542
θ_y	Taylor rule coefficient on output	0.1494	0.1413
θ_{rg}	Degree of interest rate smoothing in Taylor rule	0.7640	0.3018

Table H: Shock process parameters for the model with and without energy

Autocorrelation coefficients	Baseline	Ex-energy
Productivity, ε_a	0.8747	0.5252
Risk premium, ε_b	0.6656	0.4652
Domestic demand, ε_g	0.6621	0.4810
Monetary policy, ε_i	0.3174	0.5148
Investment-specific technology, ε_{inv}	0.4323	0.3414
Wage mark-up, ε_w	0.2247	0.5641
Price mark-up, ε_μ	0.2398	0.5600
Standard deviations		
Productivity, ε_a	0.0123	0.0157
Risk premium, ε_b	0.0041	0.0074
Domestic demand, ε_g	0.0923	0.0920
Monetary policy, ε_i	0.0015	0.0035
Investment-specific technology, ε_{inv}	0.0612	0.1382
Wage mark-up, ε_w	0.0098	0.0076
Price mark-up, ε_μ	0.0028	0.0071

As can be seen, some of the parameter estimates look quite different. In particular, the model with no explicit energy effects estimates capital adjustment costs to be much larger, wage and price indexation to be much higher and suggests that prices are quite flexible. This result probably reflects 'averaging' of the degrees of stickiness estimated for the individual sectors in the model with explicit energy effects. Given the lack of energy price shocks, the model without energy requires more volatility in the other shocks to explain the data. Finally, we can note that the model with energy price effects included explains the data much better than the model that does not include them. In particular, the estimated log data density for the benchmark model is 1818 whereas for the model excluding energy effects it is only 1623.

4 Impulse response functions

This section presents some impulse response functions for the estimated model. In particular, the results in this section are brought to bear on two questions: to what extent does the inclusion of energy effects alter the estimated responses of variables to shocks in the model, and, more specifically, how do variables respond to world oil and gas price shocks. The variables considered are value-added output, aggregate consumption, inflation, the base rate, the real wage and the exchange rate.[10]

[10] Throughout this section 'output' refers to 'value-added' output (that is, GDP) and not to the gross output of any sector or the economy as a whole.

4.1 How does energy affect the responses of variables to shocks?

Chart 1 shows the responses of output, aggregate consumption, inflation, the base rate, the exchange rate and the real wage to a one standard deviation monetary policy shock. In each case, the chart shows the responses implied by the estimated model together with the responses implied by the estimated model that excluded energy. In the benchmark estimated model, the shock represents an exogenous increase in the base rate of 51 basis points; in the version of the model estimated without energy effects, it represents a shock to interest rates of 84 basis points.

Taking the results of the benchmark model first, we can note that the shock has quite a large effect on output, which falls by about 0.45%, while inflation falls by only about 0.03 percentage points on impact. Consumption also falls. The maximum response of real variables to the shock occurs immediately. Output and consumption then return to base with the shock having a minimal effect on either of them after about one year. Inflation continues to fall for three quarters after the initial shock, reaching a minimum -0.10 percentage points below base, before returning back to base. The effect is basically zero after about two years. Interest rates take about a year to return to base. The exchange rate follows the path of the interest rate – as a result of UIP – with the initial impact of the shock being an appreciation of 0.6%. The shock has a significant effect on real wages in the benchmark model as nominal wages fall quickly relative to the price level – given the estimated degrees of wage and price stickiness. These responses are in line with the empirical results of, eg, Di Cecio and Nelson (2007), Kamber and Millard (2010) and Christiano *et al* (2005), except that the responses of output and consumption are not ‘hump-shaped’. This results from the assumption of ‘capital adjustment costs’ in the current paper rather than ‘investment adjustment costs’. Christiano *et al* (2005) makes clear that it is investment adjustment costs that are key to generating hump-shaped responses in real variables to a monetary policy shock. So, replacing these with capital adjustment costs, which Smets and Wouters (2007) argue would not generate a hump-shaped response of investment to shocks, is likely to result in a lack of hump-shaped responses in all real variables. The response of real wages is large and hump-shaped as a result of the high degree of wage flexibility estimated in the current model, particularly relative to the price of non-energy goods.

We can note that, with the exception of inflation, real wages and interest rates, the responses of variables are similar to their responses in the estimated version of the model without energy. The inflation response is much stronger in the model without energy effects given that prices were estimated to be much more flexible in this model. For the same reason, the real wage response is much smaller in the model that excluded energy effects.

Chart 1: Effects of a monetary policy shock

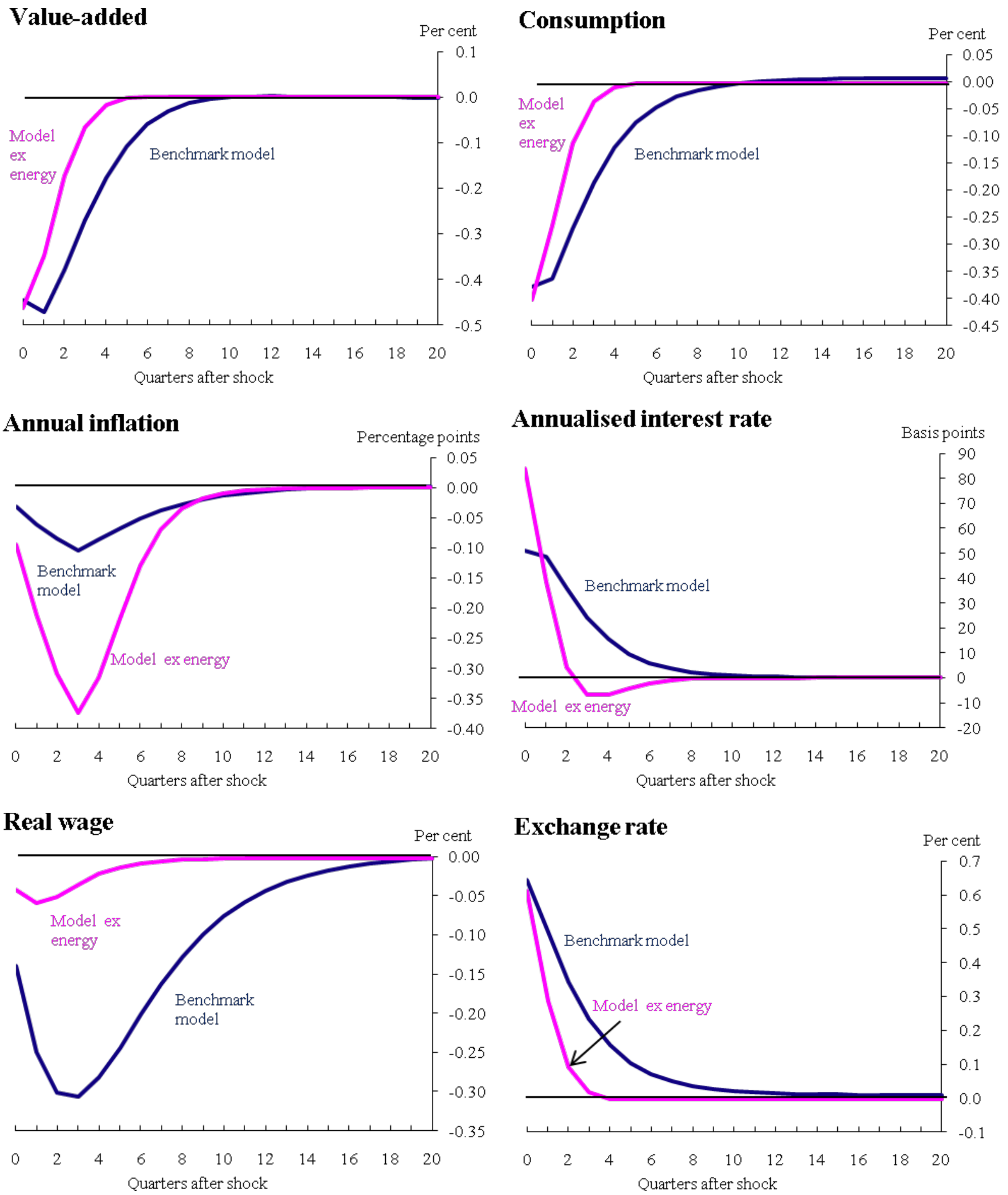


Chart 2: Effects of a productivity shock

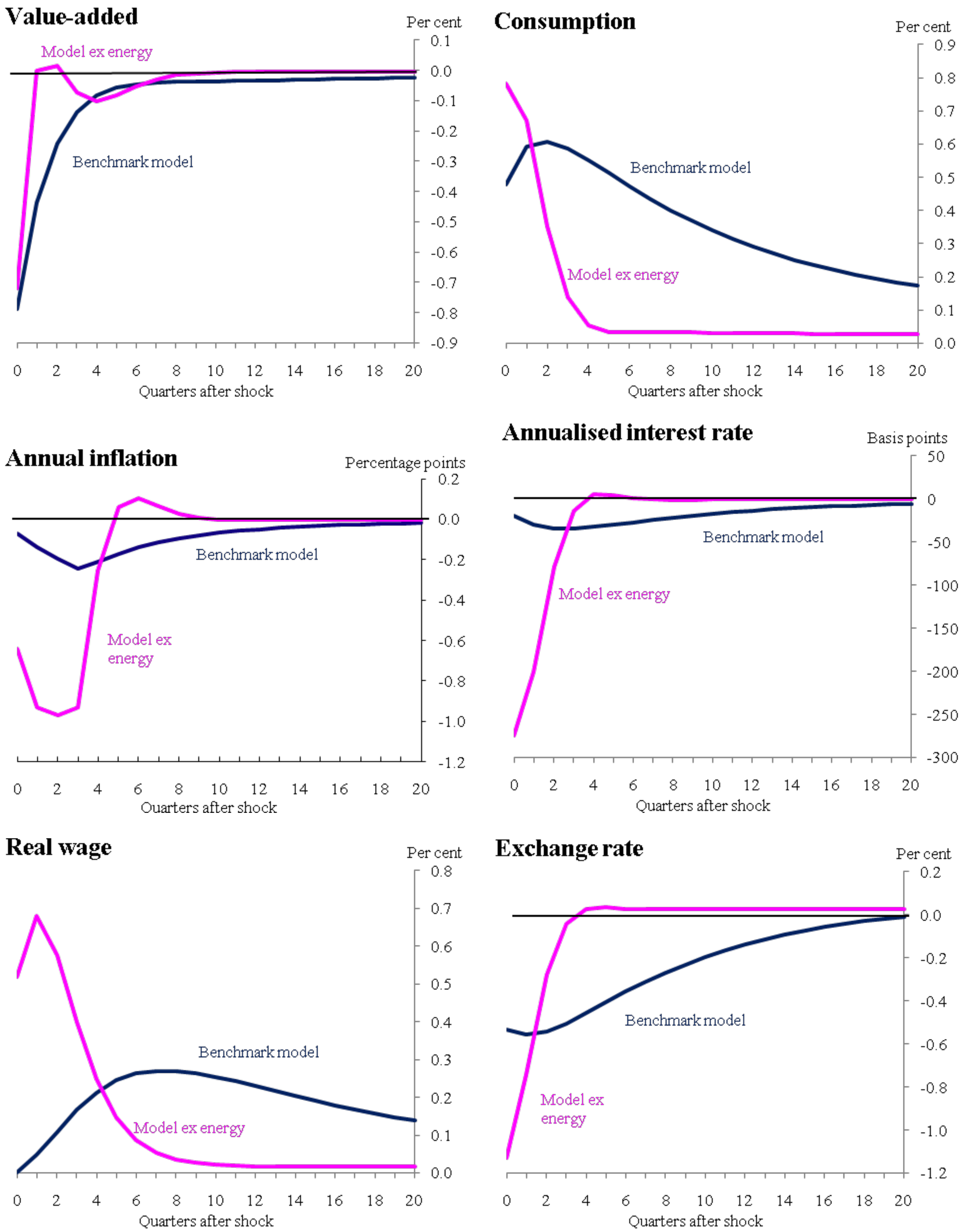


Chart 2 shows the responses of the same variables to a positive productivity shock for the benchmark model and for the version of the model without energy. Perhaps surprisingly, value-added output falls. This is because the productivity shock affects gross output (of the non-energy good) given value-added input. With sticky prices, demand for gross output will not respond much to the increase in productivity, so producers will cut down on inputs – including value-added. Consumption rises as the shock makes households wealthier and habit persistence is large enough to ensure a hump-shaped response. Inflation and interest rates fall and the exchange rate depreciates as UK goods are now cheaper to produce *vis-à-vis* foreign goods. We can note that the inclusion of energy within the model has a large impact on the responses; in particular, value-added oscillates for the first couple of years after the shock before returning to base and the effect of the shock on inflation (and, as a result, interest rates) is much stronger. Again these results come about because prices are estimated to be quite flexible in the version of the model that ignores energy prices.

Chart 3: Effects of a domestic risk premium (financial) shock

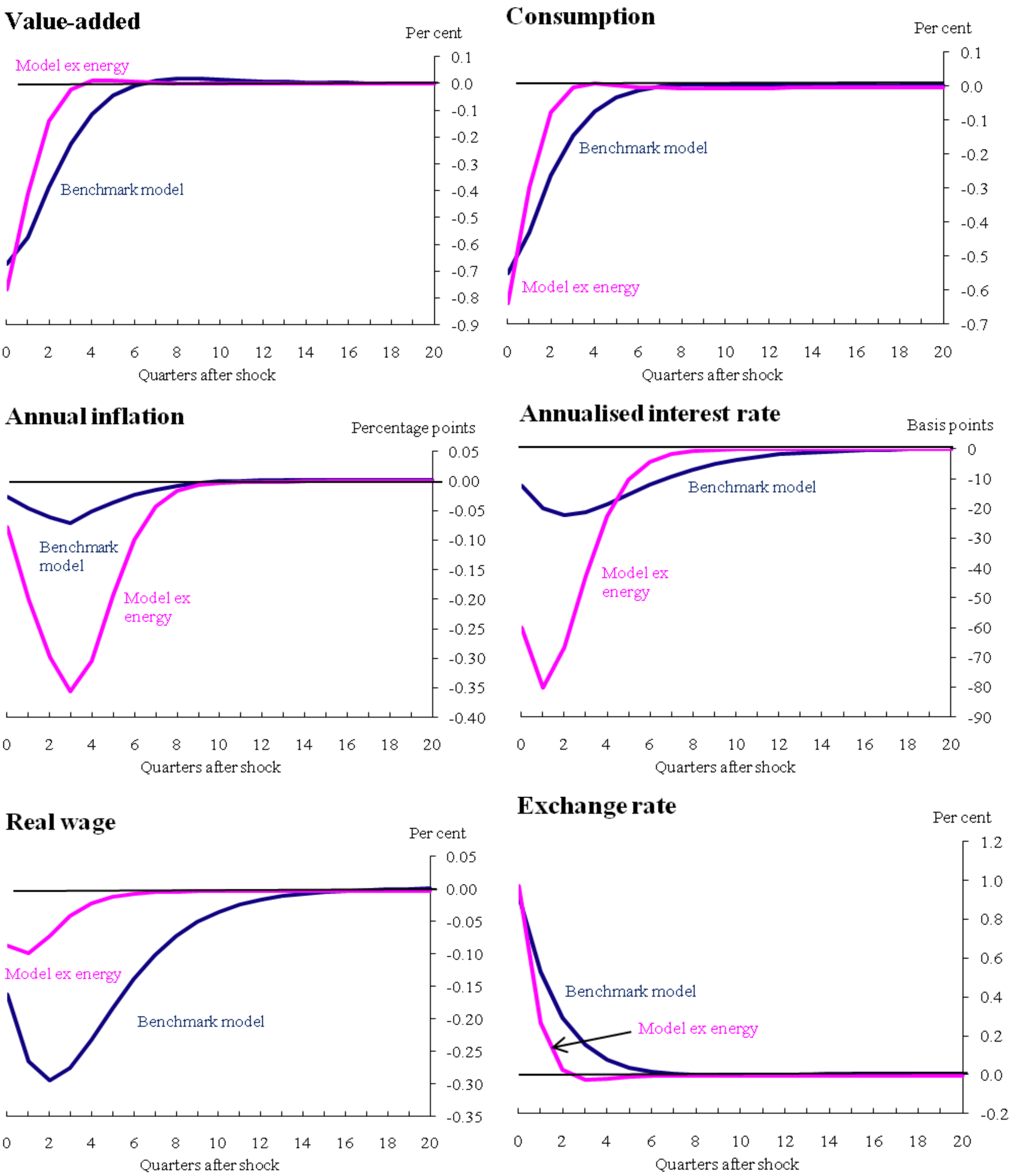


Chart 3 shows the responses of value-added output, aggregate consumption, investment, inflation, the base rate, the exchange rate, the real wage, employment and wage inflation to a positive domestic risk premium shock (ie, a shock that raises the interest rate faced by consumers relative to the policy rate). This is an important shock to consider since we would expect it to pick up the recent financial crisis. As expected, an increase in risk premia caused by, say, a credit tightening, would lead to falls in consumption, output and price inflation. However, the exchange rate appreciates as demand falls in the United Kingdom relative to abroad; the effect on the exchange rate of changes in the relative risk of UK versus foreign assets would, in this model, come through movements in the foreign exchange risk premium shock. In this case, the responses of output, consumption and the exchange rate are quantitatively similar to their responses in the estimated version of the model without energy. Real wages respond less in the model with no explicit energy effects since they are estimated to be stickier. Inflation, on the contrary responds by more – since prices are estimated to be more flexible – and the interest rate responds more given the central bank's Taylor rule.

Chart 4 shows the effects of a one standard deviation (about 9%) domestic demand shock. Such a shock leads to an increase in output of about 0.85% but a fall in consumption of about 0.15%, as the increase in output is much smaller than the increase in the exogenous components of domestic demand. The increase in demand leads to a rise in inflation and interest rates. The real wage rises on account of the increased demand for labour, though the magnitude of this rise again depends on which version of the model is used. Finally, the increase in domestic demand relative to foreign leads to an appreciation of the exchange rate.

Finally in this subsection, Charts 5 and 6 show the effects of a world demand and a world export price shock, respectively. A world demand shock leads to an increase in output, real wages and, eventually, consumption. The increase in demand also pushes up on inflation and interest rates rise in response but the effect on both these variables is small. The rise in relative demand for the home economy's exports leads to an appreciation of the exchange rate. Now, a shock to world demand might be expected to lead to rises in world commodity prices, such as oil and gas, with a dampening effect on domestic output. However, this channel is not present in this model since world oil and gas prices are assumed to be exogenous and are unaffected by world demand.

A shock to world export prices leads to a rise in domestic import prices, which, in turn, feeds into domestic inflation. Domestic consumption falls as final output becomes more expensive. The response of value-added is interesting. A rise in import prices leads to a reduction in gross output and, other things equal, lowers the demand for value-added. But in the model with explicit energy effects, the fall in the relative price of energy will lead to an increase in demand for energy – both for production and consumption – and, in turn, an increase in the demand for value-added in energy production, outweighing the effect coming from the fall in demand for value-added in the production of non-energy goods. We can note, however, that in both cases the effect on value-added is small. Finally, the exchange rate appreciates in response to the increased demand for the home economy's exports.

Chart 4: Effects of a domestic demand shock

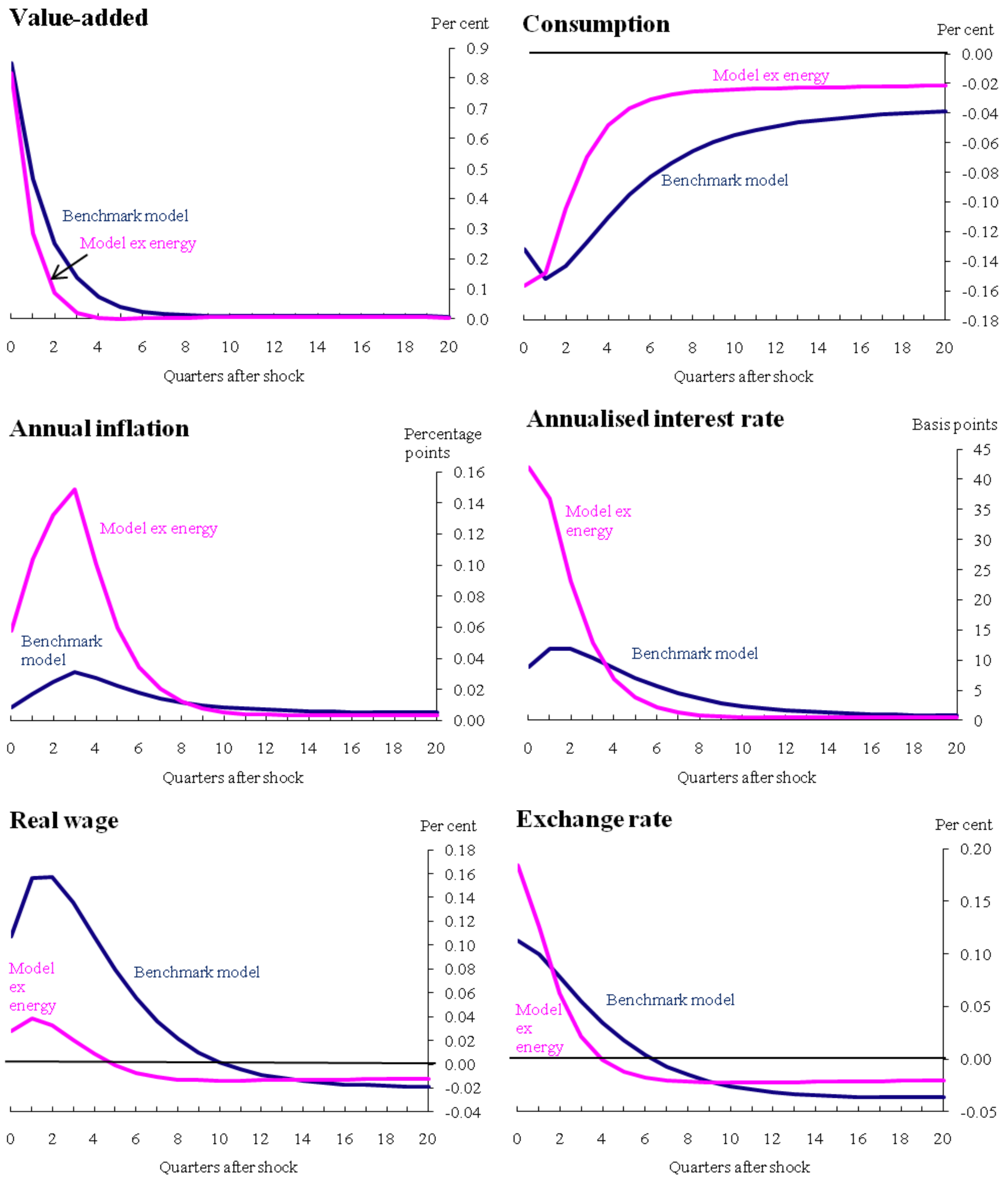


Chart 5: Effects of a world demand shock

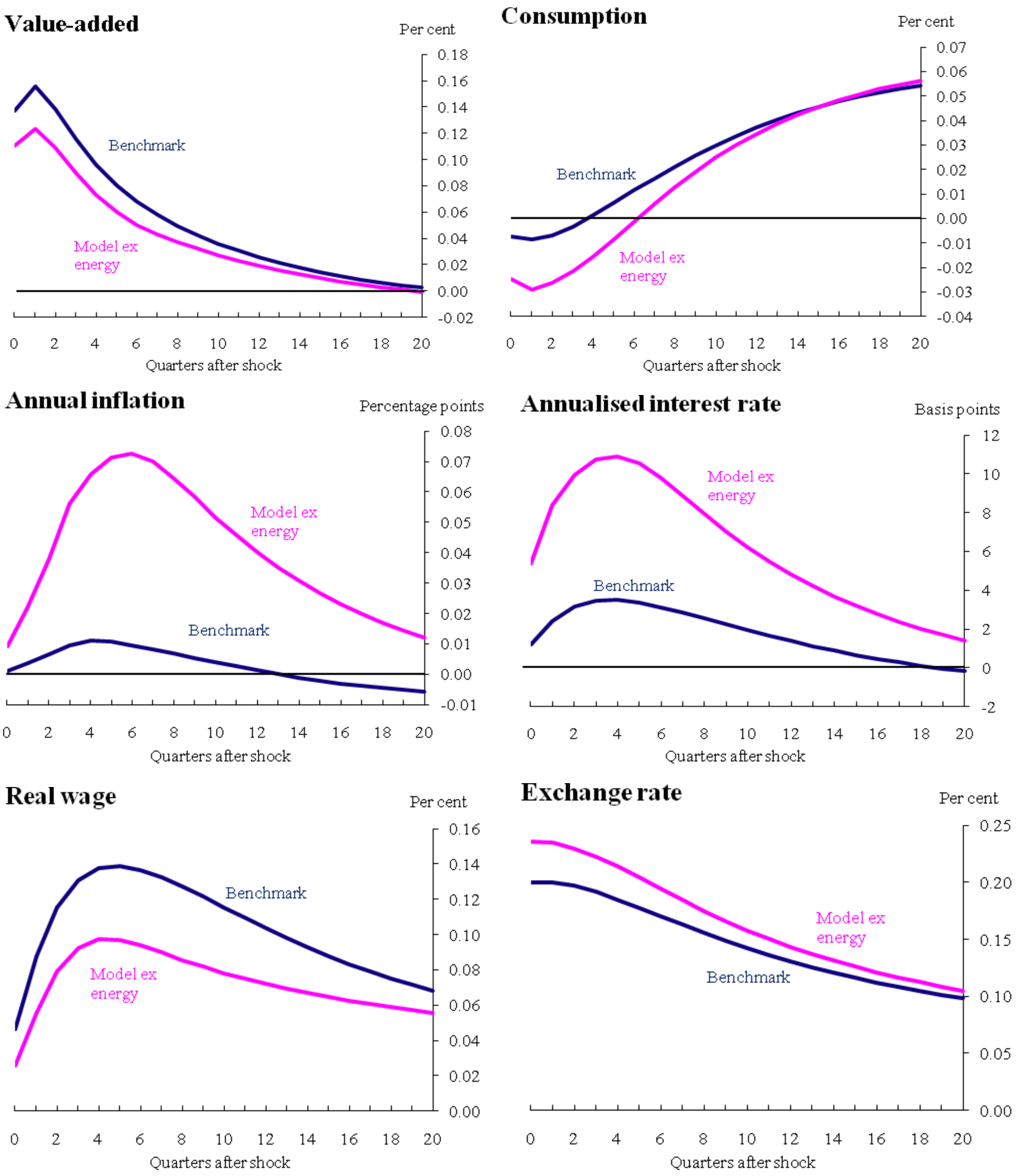
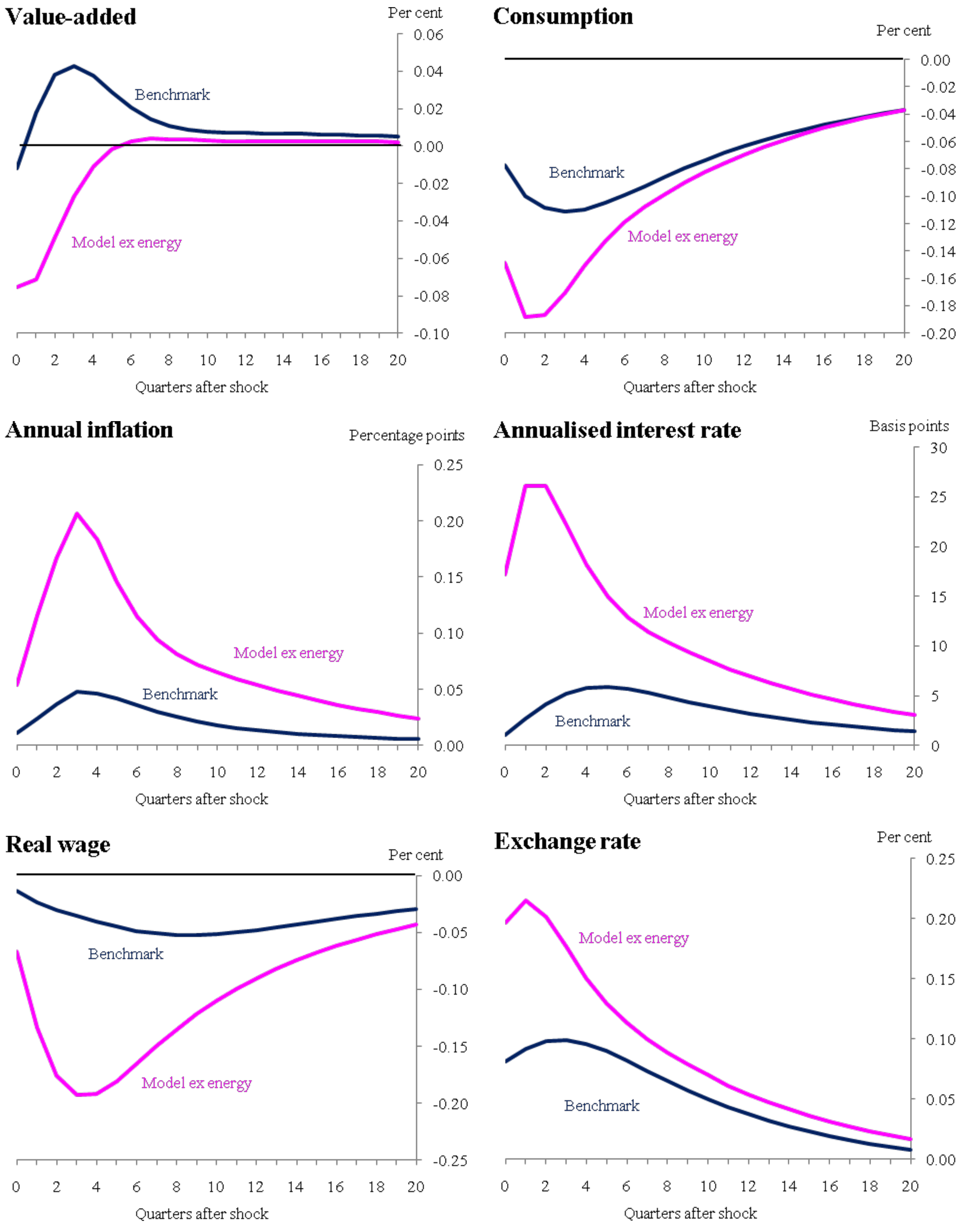


Chart 6: Effects of a world export prices shock



4.2 *The effects of a rise in energy prices*

The key difference between this model and more standard macroeconomic models is the presence of a supply chain linking movements in world oil and gas prices, to movements in petrol and utilities prices, to movements in the overall level of consumer prices. Given that, it is instructive to consider the effects of shocks to the world prices of oil and gas.

Chart 7: Effects of a world oil price shock

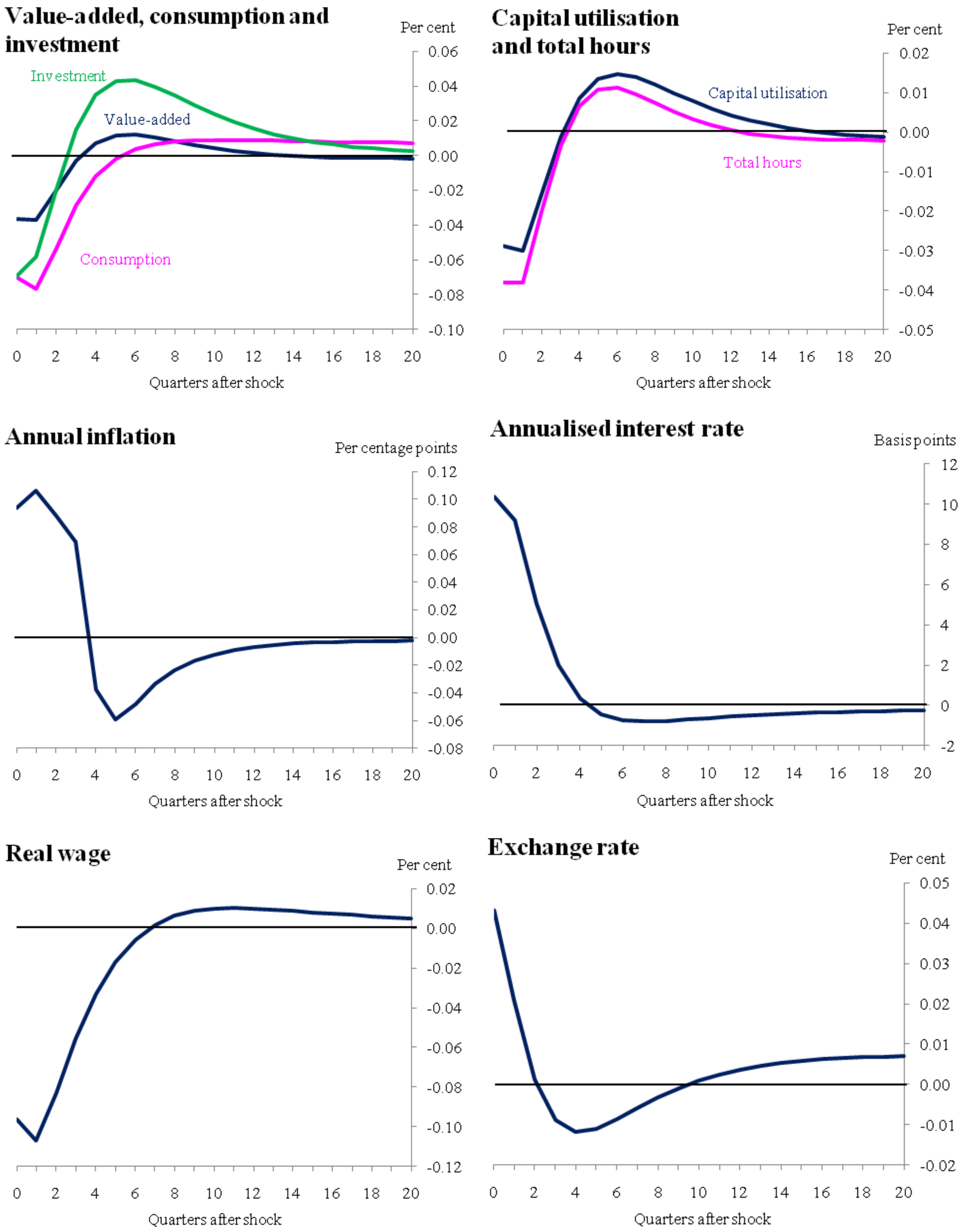
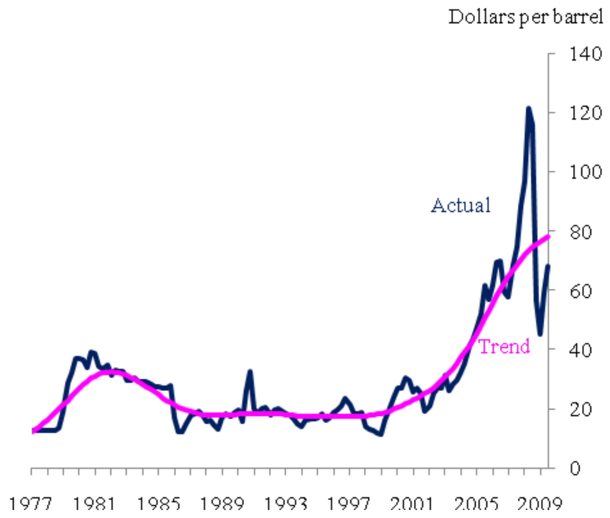


Chart 7 shows the responses of output, aggregate consumption, investment, inflation, the base rate, the exchange rate, the real wage, employment and wage inflation to a temporary exogenous increase in the world price of oil of 14% (a one standard deviation shock). The effects of such a shock on real variables are small.[11] Output has fallen by just under 0.04% after one quarter, consumption by roughly 0.08% and investment by roughly 0.06%. Inflation is 0.11 percentage points higher after one quarter but then falls back quickly, being close to its steady-state rate after two years and beyond. Workers take a hit in their real consumption wage in the year and a half following the shock; that is, there is little evidence of real wage resistance.

Why are the effects of an oil shock estimated to be so low? The answer is the result of the relatively low autocorrelation of this shock (estimated to be 0.73). Given the persistence of movements in oil prices, this seems like a surprising result. The answer to the puzzle can be seen in Chart 8. The chart shows that the large rises in the oil price in recent years have been interpreted as trend increases by the model; it is only the additional movements in the oil price that are interpreted as shocks.[12]

Chart 8: World oil price, actual and trend

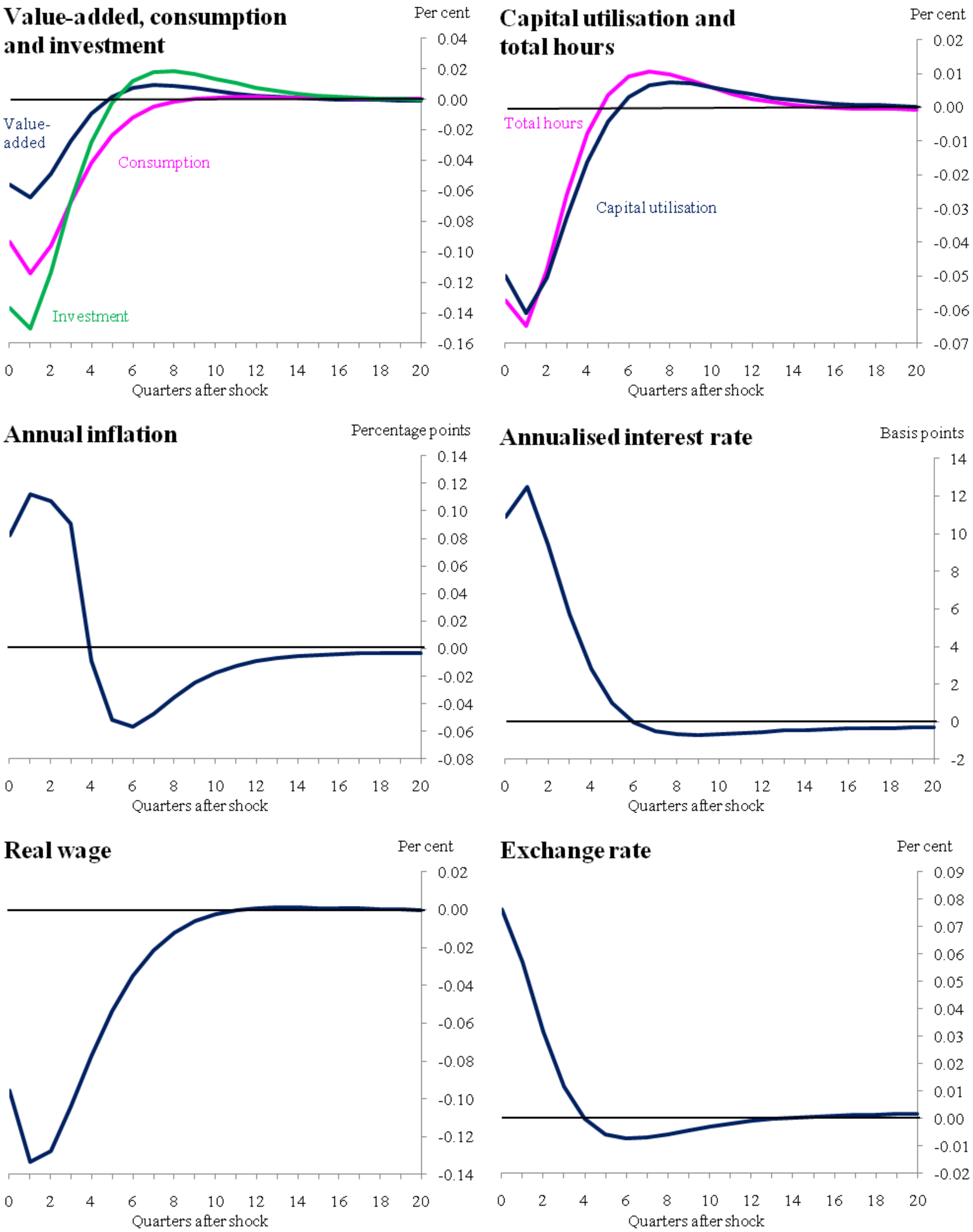


This model can also be used to analyse the effects of shocks to world gas prices. Chart 9 shows the responses of output, aggregate consumption, investment, inflation, the base rate, the exchange rate, the real wage, employment and wage inflation to a temporary exogenous increase in the world price of gas of 25% (a one standard deviation shock). The effects of this shock are similar to those of an oil price shock. The effects on real variables are, again small and, again, this is because the shock has low persistence (estimated to be 0.59). Output has fallen by 0.06% after one quarter, consumption by 0.11% and investment by 0.15%. Inflation is 0.11 percentage points higher after two quarters but then falls back quickly. Again, workers take a hit in their real consumption wage in the two years following the shock.

[11] Although this might seem surprising, it is, as I said earlier, a fairly common result within the DSGE literature on oil (eg, Dhawan and Jeske (2008) and Rotemberg and Woodford (1996)) and it also matches the recent experience of large oil price movements with little obvious effect on output.

[12] It would be instructive to consider the effects of permanent movements in energy prices within this model. But, in order to do this properly, it is necessary to take a stand on the degree of self-sufficiency of oil and gas production in the long run, as is done in Harrison *et al* (2008), but which is really beyond the scope of this paper. The interested reader is referred to their paper for further elaboration on these issues.

Chart 9: Effect of a world gas price shock



5 Using the model to decompose movements in output and inflation

A major motivation for estimating this model is that it is important for monetary policy makers to understand what drives output and inflation in different periods. Given that the estimation produces time series for the shocks, it is possible to decompose movements in output and inflation into those fractions caused by each of the shocks. Doing this enables us to ascertain what shocks have been the main drivers of these variables.

Chart 10: Domestic shocks

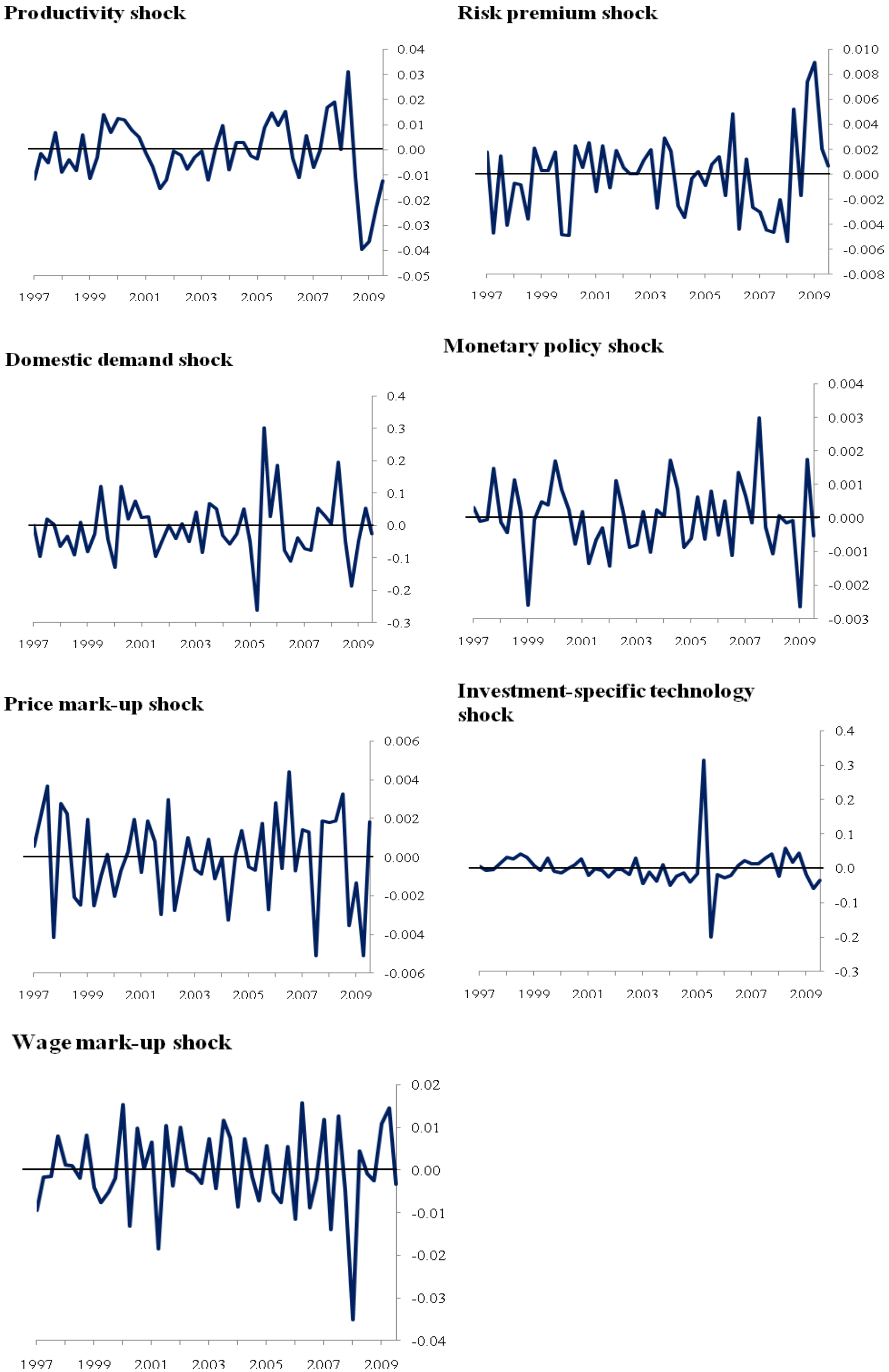
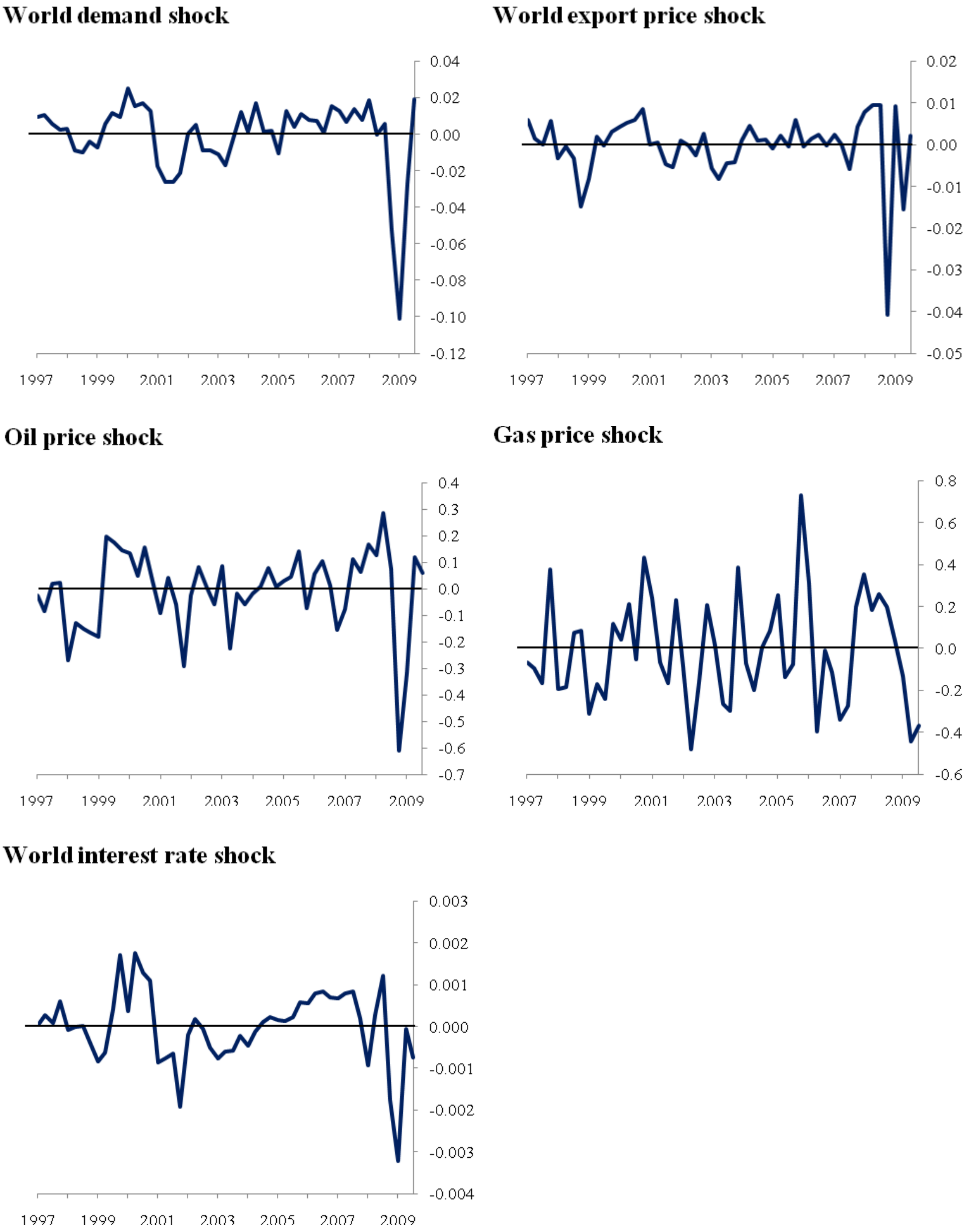


Chart 10 shows the estimated time series for the domestic shocks within the model and Chart 11 shows the time series for the world shocks. As implied by the estimation results, we can see that the shocks to domestic demand, investment-specific technology and world oil and gas prices have been highly volatile over this period whereas monetary policy shocks have been small.

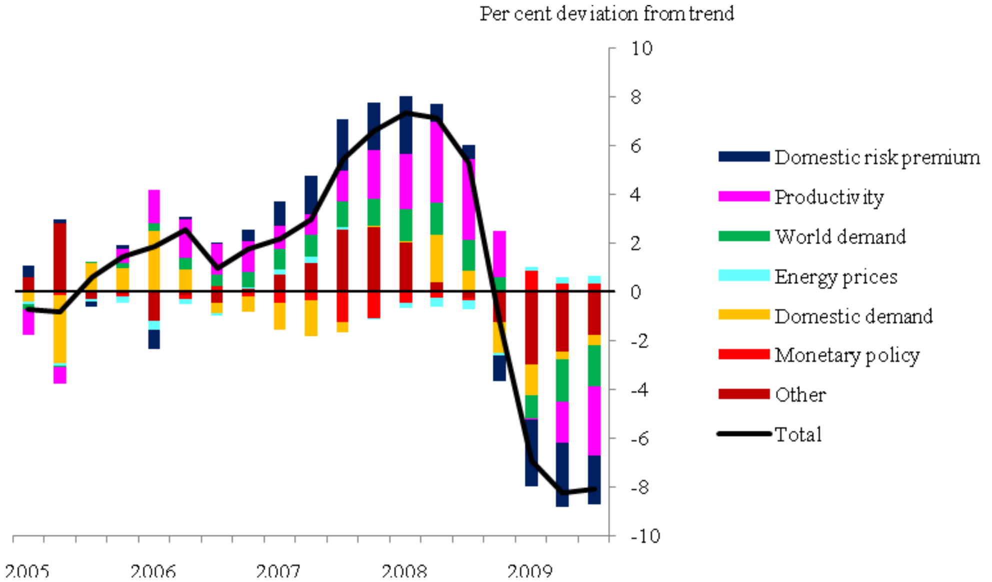
Chart 11: Foreign shocks



Concentrating on the recent past, we can see that the economy has been affected by large negative shocks to productivity and domestic and world demand and a large positive shock to the domestic risk premium. This positive shock to the domestic risk premium is what the model will have picked up as the financial crisis of 2007-09. The increase in risk premium occasioned by the financial crisis would act to reduce demand in the model creating a recession, as was seen in the United Kingdom from 2008 Q2 to 2009 Q3. The world demand shock reflects what happened to world trade around the end of 2008 and the beginning of 2009. The negative productivity shock is harder to explain; it is likely to reflect, at least partly, the negative impact of the financial crisis on the ability of firms to raise working capital.

To investigate further which shocks have been driving the UK economy over this sample period, Chart 12 shows a decomposition of movements in gross non-energy output between 2005 Q1 and 2009 Q3 into the portions caused by each of the shocks. We can see that, as expected, the recent slowdown in gross non-energy output has been driven by the negative productivity shock, the domestic risk premium shock and world demand.[13] What may come as a little surprising is that energy prices are not major drivers of movements in non-energy output, despite being an input into production of that good and despite having moved substantially over this period. Again, this can be explained by the fact that the bulk of the movement in oil and gas prices was treated as a 'trend increase; the remaining movements are quite volatile and, as a result, non-energy producers seem to smooth through movements in this component of costs. Monetary policy shocks were mildly supporting output in 2009 since interest rates were cut by more than would have been suggested by the Taylor rule in the model. Of course, the 'systematic' response of monetary policy would have been supporting output in 2009 as would have the additional monetary stimulus coming from quantitative easing.

Chart 12: Shock decomposition for gross non-energy output



[13] Recall, a negative productivity shock would result in a rise in value-added output but a fall in gross output.

Of course, we might expect movements in energy prices to be key determinants of movements in energy (ie, petrol and utilities) output. This is illustrated in Chart 13. As can be seen, the high energy prices of 2008 substantially pulled down on energy output. By the end of the sample, low energy prices were pushing up on energy output. In addition, low productivity of non-energy inputs in the non-energy sector were pushing up on the demand for energy as non-energy producers substituted towards energy. Against this, low world demand and the risk premium shock (proxying the effects of the financial crisis) were pulling energy output down.

Chart 13: Shock decomposition for gross energy output

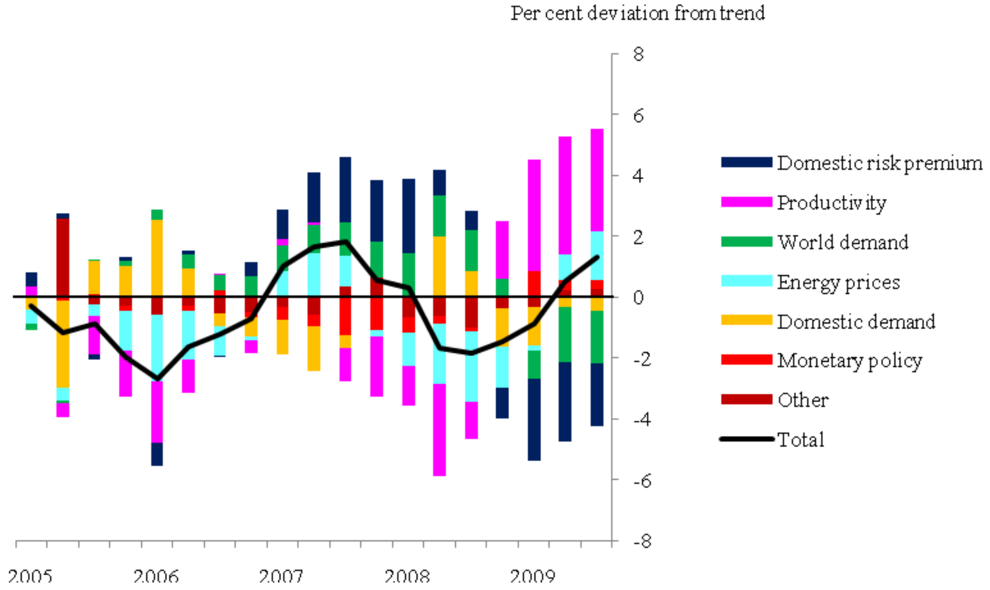
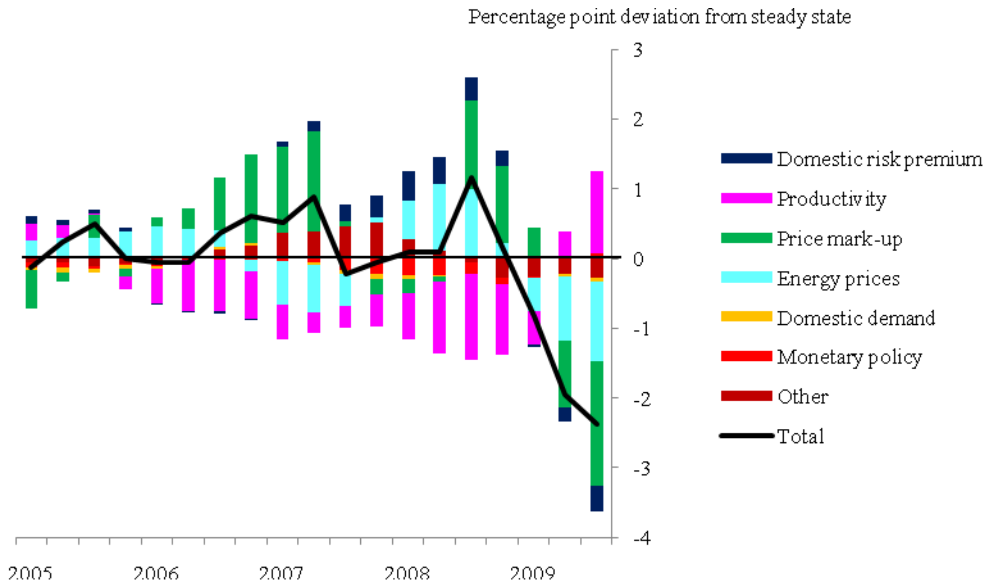


Chart 14: Shock decomposition for the CPI inflation rate



Turning to inflation, Chart 14 suggests that the price mark-up shock was pushing down substantially on inflation in 2009 with the financial shock and energy prices also contributing. Against this, the negative productivity shock was acting to push inflation up. Energy prices seem to have a much larger effect on inflation than they do output. The high oil prices in early

2008 and gas prices throughout 2008 were pushing up on inflation in 2008. As oil and gas prices fell in 2009, they again acted to push down on inflation.

6 Conclusions

This paper has estimated a DSGE model of the United Kingdom developed originally by Harrison *et al* (2011). The basic building blocks of the model are standard in the literature. The main complication is that there are three consumption goods: non-energy output, petrol and utilities; given relative prices and their overall wealth, consumers choose how much of each of these goods to consume in order to maximise their utility. Each of the consumption goods is produced according to a sector-specific production function and sticky prices in each sector imply sector-specific New Keynesian Phillips Curves. This model, once estimated, forms a useful additional input within a policymaker's 'suite of models'.

Estimating the parameters of this model using Bayesian techniques enables the user to apply the model quantitatively to UK policy issues. The paper has shown how this could be done by examining the effects of many different shocks on inflation and by decomposing recent movements in output and inflation into those parts caused by each of the structural shocks. It found that the fall in gross non-energy output from 2008 Q2 to 2009 Q3 was driven by three shocks: to productivity, to world demand and to the domestic risk premium. The risk premium shock also put downwards pressure on inflation during this period while the productivity shock was putting upwards pressure on inflation. The world demand shock was much less important in explaining the behaviour of inflation over this period.

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