Global Shocks in the US Economy: Effects on Output and Real Exchange Rate

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ABSTRACT

This paper studies the effects of global shocks, relative to domestic shocks (productivity, mark-up, and demand shocks), in accounting for US business cycle fluctuations. We do this by developing and estimating a two-sector open economy dynamic stochastic general equilibrium model that features several real frictions and structural shocks. The central finding from the estimated model is that global shocks are the main driver of movements in many US macroeconomic aggregates. Particularly, we find that they explain around 40% of the variations in our main variables of interest—output and real exchange rate. This important quantitative contribution is achieved by using indirect inference estimation techniques to test the model. We identify exogenous world demand, oil price shocks, preference for exported energy-intensive goods, and the price of imported energy-intensive goods as the global shocks most prominent in causing the largest variations in economic outcomes. By contrast, foreign interest rates and preference for aggregate exported goods are found to be bystanders.

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1. Introduction

How important are global shocks for economic fluctuations? Which kind of global shocks can most account for observed business cycles? How big are the impacts of domestic shocks, as captured by productivity, mark-up, and demand shocks, as sources of variation in real economic activities, once we allow for global shocks? For any country, obtaining answers to these questions is fundamental to designing and implementing relevant macroeconomic and regulatory policies. The focus of our analysis in this paper is the US. In particular, we examine to what extent US output and real exchange rate are driven by global shocks, and to what extent they are caused by domestic shocks. As the world's largest economic power, most existing theoretical and empirical studies tend to treat the US as the source of external shocks for other countries (e.g., Belke et al., 2019; Canova, 2005; Justiniano and Preston, 2010; Kazi et al., 2013; Kim, 2001; Schmitt-Grohé, 1998). Yet, history shows us that the US itself is not immune to disturbances originating from abroad (e.g., the Arab-Israeli war of the early 1970s and the East Asian crisis of 1997-98). Our goal in this paper is to contribute to this line of discourse by using an estimated two-sector open economy dynamic stochastic general equilibrium (DSGE) model to structurally account for the size of the effects of global shocks on the US economy.

Our paper has two main contributions. First, our theoretical analysis builds on a two-sector open economy DSGE model first presented in Meenagh et al. (2015). In order to establish whether the US economy experiences energy business cycles, these authors advanced a novel two-sector model of the US with varying intensities of oil demand in production that also incorporates a high number of real frictions and shocks. Besides, the model allows for two types (energy-intensive and non-energy intensive) of final goods and a commodity (crude oil) to be traded on the world markets. From a modelling perspective, this was a notable contribution to the DSGE literature because previous work on this topic had generally been based on one-sector one-good autarky model except for oil imports (e.g., Dhawan and Jeske, 2008; Kim and Loungani, 1992).[1] Our paper extends their model in two distinct ways: (i) we let households have access to both home and foreign bonds, and (ii) we include ten more structural shocks in the version that we use in this paper.[2]

The paper's second contribution is that the model is tested and estimated by the method of indirect inference on unfiltered data.[3] In testing, we apply the indirect inference procedure to a set of initial parameters put forward as true for our model, and ask: could these coefficients, within this model framework, be the true model generating the data? Of course, only one true model with one set of

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[1] An important exception to this modelling approach can be found in the contribution by Bodenstein et al. (2011).

[2] Meenagh et al.'s (2015) model allows for only US government bonds and embodies twelve shocks. We have extended their model appropriately to allow us to investigate the effects of global shocks on US output and real exchange rate relative to domestic shocks (which we categorised as either productivity, mark-up, or demand shocks).

[3] Our empirical analysis uses unfiltered data because, in reality, macroeconomic data is non-stationary. For a discussion of the plausibly misleading cyclical behaviours that accompany the use of filtered data, see, for example, Christiano and Fitzgerald (2003) and Hamilton (2016).

coefficients is feasible. Nevertheless, we may have chosen coefficients that are not precisely right numerically so that the same model with other coefficient values could be correct. Only when we have evaluated the model with all coefficient values that are credible within the model theory will we have adequately tested it. Hence, in estimation, we further utilise our indirect inference procedure to seek alternative coefficient sets that could do better in duplicating US macroeconomy features. The primary reason why we favour the use of indirect inference is that it involves a powerful test of the model on the data. On this basis, we are able to say categorically that the model fits the data. As our empirical approach is less popular, we elaborate on it further in Section 3. In addition, the use of unfiltered data allows us to add non-stationary shocks. So, beyond the theoretical refinements of Meenagh et al. (2015), we have also improved empirically on their work. As a result, our model can more appropriately mimic the dynamic properties of the US and the rest of the world data over the period under study.

To preview our results, employing a two-equation VARX(1) of output and real exchange rate, we find that the model is not rejected and is able to reproduce the features of the US data jointly, passing the Wald test with a *p*-value of 0.063. The central result that we document is the pivotal role of global shocks on US economic fluctuations. According to the estimated model, global shocks explain nearly 40% of the variances of US output and real exchange rate, as well as the variations in consumption, labour hours, and foreign bonds. Furthermore, global shocks account for well over 50% of the variabilities in the remaining macroeconomic aggregates: investment, imports, exports, wages, interest rate, and oil use. Unbundling global shocks, the results of the structural variance decomposition indicate that exogenous world demand and oil price shocks are the most important driving variables; these are followed by the preference for exported energy-intensive goods and the price of imported energy-intensive goods. Of the six global shocks modelled, the only two with negligible contributions to the US business cycle behaviour are the preference for aggregate exported goods and foreign interest rates. Using historical decomposition, we also show that global shocks were dominant in causing changes to US output and real exchange rate. Then, in an application motivated by the continuing debate in the existing literature about the importance of oil price shocks, we use the estimated model to predict the frequency of occurrence of output expansions and contractions in the presence (absence) of oil crisis for the US economy.

Our modelling strategy is derived broadly in the tradition of early international real business cycle (IRBC) literature (e.g., Ahmed et al., 1993; Backus et al., 1992, 1995; Baxter and Crucini, 1995; Dellas, 1986; Stockman and Tesar, 1995). The main departures of our paper from that literature are two. First, we have adopted the assumption of incomplete asset markets to limit the degree of risk-sharing across countries implied by the structure of models in the early IRBC literature. In this regard, our model is in the fashion of the new open economy macroeconomics (NOEM) literature (e.g., Adolfson et al., 2007; Justiniano and Preston, 2010). Second, the foundational element of the production structure in our model is in the spirit of Kim and Loungani (1992), who extended Kydland and Prescott's (1982) model to allow a role for energy price shocks. Building on their approach, an added feature of our model is that we disaggregate the US economy into energy-intensive and non-energy intensive sectors, with both producing goods that are tradeable internationally. Consequently, we are able to study the business cycle implications of global and domestic shocks for US aggregate and disaggregate macroeconomic data.

The rest of the paper proceeds as follows. Section 2 describes our two-sector open economy DSGE model. Section 3 discusses the unfiltered data and the estimation methodology. Section 4 contains our findings. The final section concludes with a summary of the paper's findings, policy implications, and suggestions for future research.

2. Model

In this section, we outline the model framework adopted in our analysis of the effects of global shocks on output and real exchange rate. The model structure (based on Meenagh et al. (2015)) combines several features of the models developed in Kim and Loungani (1992) and Backus et al. (1995). Similar to those papers, for example, we retain the intertemporal utility-maximizing behaviour of households and the perfectly competitive profit-maximizing nature of firms. Particularly, we allow production to involve energy demand, as in Kim and Loungani (1992). Additionally, we closely follow the model of Backus et al. (1995) and Bodenstein et al. (2011) along a two-country substructure to build a two-sector open economy DSGE model. Thus, there are two economic blocks in the model setup. We take the US to represent the home economy, and the rest of the world (ROW) to constitute the foreign economy. Our discussion focuses on key economic decisions of the US, which we assume to consist of four agents: firms, households, a government and traders. The foreign economy (taken to be exogenous) is assumed to have equal numbers of counterpart agents that are making equivalent choices. Following the now standard practice in the DSGE literature, we have also added an array of real rigidities, such as consumption habit formation, capital adjustment costs and variable capital utilisation rate, that are emphasised in many benchmark models (Christiano et al., 2005; Smets and Wouters, 2007). For brevity, we present the specific functional forms on technologies and preferences, together with the decision problems faced by firms, households, and traders. We also show that the behaviour of the government is fully Ricardian. For full log-linearized model listing, the reader is referred to Section A of the Online Appendix. In what follows, $i \in \{H, F\}$ (H designates the home economy and F the foreign economy) and $j \in \{E, N\}$ (E signifies energy-intensive sector and N the non-energy intensive sector) will be utilised when we need to distinguish between economies and sectors, respectively.

2.1. Firms

The total output of the US economy in period t, Y_t, is given as the sum of the gross outputs of the energy-intensive, $Y_{E,t}$, and the non-energy intensive, $Y_{N,t}$, sectors:

$$Y_t = Y_{E,t} + Y_{N,t} \qquad (1)$$

where, in each sector, there exists a continuum of identical, profit-maximising firms occupying the interval $[0,1]$. The US sectoral outputs, $Y_{j,t}$, are produced using the constant elasticity of substitution (CES) technology that employs three factors:

$$Y_{j,t} = A_{j,t} L_{j,t}^{1-\alpha_j} \left[\theta_j \left(U_{j,t} K_{j,t-1}\right)^{-\nu_j} + \left(1-\theta_j\right)\left(Q_{j,t} O_{j,t}\right)^{-\nu_j}\right]^{-\frac{\alpha_j}{\nu_j}} \tag{2}$$

where $\alpha_j, \theta_j \in (0,1)$ and $\nu_j \in (0,\infty)$ are technology parameters that capture output elasticity of labour hours $(1-\alpha_j)$, weight of capital services in production, and elasticity of substitution in production, respectively. $L_{j,t}$, $U_{j,t}K_{j,t-1}$, and $O_{j,t}$ represent labour hours, capital services (with $U_{j,t}$ denoting variable capital utilisation rate and $K_{j,t-1}$ the quantity of physical capital at the end of period $t-1$), and oil use, respectively; $A_{j,t}$ is sector-specific productivity shock and, motivated by Nordhaus (1980), $Q_{j,t}$ is sector-specific oil efficiency shock—this type of shock captures the effect of exogenous stochastic factors that may additionally affect the intensity with which energy is used.

The period *t* profits of firms in each sector can be summarised by: $\Pi_{j,t} = P_{j,t}Y_{j,t} - \left(W_t + \xi_{j,t}\right)L_{j,t} - \left(R_{j,t} + \vartheta_{j,t}\right)U_{j,t}K_{j,t-1} - P_{O,t}O_{j,t}$, where $P_{j,t}$, W_t, $R_{j,t}$, and $P_{O,t}$ are, respectively, the relative prices of sectoral goods, real wage rate, real rental rate of sectoral capital services, and the exogenous real world price of oil. $\xi_{j,t}$ is exogenous wage bill shifter and $\vartheta_{j,t}$ is exogenous capital cost shifter. Note that aggregate demand for oil in the economy is taken to be the sum of the sectoral oil demands: $O_t = O_{E,t} + O_{N,t}$.

2.2. Households

The US is assumed to be populated by a continuum of identical, infinitely lived households occupying the interval $[0,1]$. Their lifetime utility function is described by:

$$E_t \sum_{t=0}^{\infty} \beta^t \, \tau_t \left[\frac{\left(C_t - \iota C_{t-1}\right)^{1-\sigma}}{1-\sigma} - \zeta_t \frac{\left(L_t\right)^{1+\omega}}{1+\omega}\right] \tag{3}$$

where $\beta, \iota \in (0,1)$, and $\sigma, \omega \geq 0$ are preference parameters that denote the discount factor, consumption habit formation, elasticity of substitution in consumption, and the inverse of Frisch elasticity of labour supply, respectively. C_t is consumption, $L_t = L_{E,t} + L_{N,t}$ is total labour hours, τ_t is the intertemporal preference shock, and ζ_t is the labour supply shock.

Households add to their stocks of sectoral physical capital by investing in corresponding capital goods, $I_{j,t}$. The law of motion for physical capital stock in sector j can thus be written as:

$$K_{j,t} = \left(1 - \delta\left(U_{j,t}\right)\right) K_{j,t-1} + Z_{j,t} I_{j,t} - AC_{j,t}^{K} \tag{4}$$

with $\delta(U_{j,t}) = \delta_{j,0} + \delta_{j,1}(U_{j,t})^{\delta_{j,2}}/\delta_{j,2}$ and $AC_{j,t}^{K} = \psi_j(K_{j,t}/K_{j,t-1} - 1)^2 K_{j,t-1}/2$ denoting the time-varying depreciation rates and the capital adjustment costs, respectively (Basu and Kimball, 1997; Dhawan and Jeske, 2008), where $\delta_{j,0}, \psi_j \geq 0$, $\delta_{j,1} > 0$, and $\delta_{j,2} > 1$. $Z_{j,t}$ is sector-specific investment technology shock. From this, total investment is: $I_t = I_{E,t} + I_{N,t}$. Households rent these capital stocks to firms in the two sectors. They also hold US (foreign) bonds denoted by B_{t-1} ($B_{F,t-1}$), earning gross returns R_{t-1} ($R_{F,t-1}$), and receive profits, $\Pi_t = \Pi_{j,t} + \Pi_{T,t}$, from firms and traders.

On the assumption that the income of households covers their expenses, their flow budget constraint in real terms is:

$$\begin{aligned} W_t L_t + R_{t-1}B_{t-1} + R_{F,t-1}B_{F,t-1}/P_t + R_{E,t}U_{E,t}K_{E,t-1} + R_{N,t}U_{N,t}K_{N,t-1} + \Pi_t \\ \geq C_t + I_t + T_t + B_t + B_{F,t}/P_t + AC_{F,t}^{B}/P_t \end{aligned} \tag{5}$$

where P_t is the consumer price index (CPI) in the US (or the real exchange rate, with $P_{F,t}$, the consumer price index in the foreign economy, being the *numeraire*), T_t is a lump-sum transfer, and following Schmitt-Grohé and Uribe (2003), we specify adjustment costs for procuring additional foreign bonds to be quadratic $AC_{F,t}^{B} = \psi_F(B_{F,t} - B_F)^2/2$ (with $\psi_F \geq 0$, the adjustment cost parameter, and B_F, the steady state level of foreign bonds).

2.3. US government

The exogenous government spending takes up a fraction of domestic absorption; this is achieved by borrowing from the households and levying taxes on them. Thus, the government balances its budget in each period *t*:

$$G_t = T_t + B_t - R_{t-1}B_{t-1} \tag{6}$$

Implicit in the above budget constraint is that government debt does not change over time: $B_{t-1} = B_t$.

2.4. Traders

Following the approach of Backus et al. (1995), we now assume that goods produced in the two sectors of the US economy are imperfect substitutes for similar goods originating from the counterpart sectors in the foreign economy. The innovation of our model is that we have two goods from each country rather than one. On this basis, consumption, investment, and government spending in both economies are assumed to be composites of four goods. For the US, the respective definitions are:

$$C_t = \Phi_C\left(C_{i,t}^j\right) \tag{7}$$

$$I_t = \Phi_I\left(I_{i,t}^j\right) \tag{8}$$

and

$$G_t = \Phi_G\left(G_{i,t}^j\right) \tag{9}$$

where the aggregator functions Φ_C, Φ_I, and Φ_G (and all the ones defined hereafter) are assumed to be increasing and homogeneous-of-degree-one in their arguments. This aggregation approach is due to Armington (1969); see Feenstra et al. (2018) for a recent exposition.

Meanwhile, to retain our focus on the effects of global shocks on aggregate economic activities, we use total expenditures by US households and government. Formally, this is given as:

$$D_t = C_t + I_t + G_t \tag{10}$$

where D_t is domestic absorption (and can now be interpreted as a composite of the four final goods in this world economy). Hence, we can write that:

$$D_t = \Phi_D\left(D_{H,t}, M_t\right) \tag{11}$$

with $\Phi_D(.) = (\kappa^{1/\phi}(D_{H,t})^{(\phi-1)/\phi} + (1-\kappa)^{1/\phi}\varpi_t(M_t)^{(\phi-1)/\phi})^{\phi/(\phi-1)}$. $D_{H,t}$ is domestic absorption of goods produced in the US, M_t is total imports, and ϖ_t is exogenous preference for aggregate imports; $\phi > 0$ is the elasticity of substitution between home and foreign goods, and $\kappa \in (0, 1)$ is the home bias parameter.

As shown by Backus et al. (1995), the aggregator function (Φ_D) is sufficient for use if one is modelling two countries with two goods as they did. We, however, need further disaggregation since we have a model of two countries and four goods. We achieve this by defining US domestic absorption and aggregate imports of goods as functions of energy-intensive and non-energy intensive goods:

$$D_t = \Gamma_D\left(D_{j,t}\right) \tag{12}$$

and

$$M_t = \Gamma_M\left(M_{j,t}\right) \tag{13}$$

with $\Gamma_D(.) = (\lambda^{1/\mu}\gamma_t(D_{E,t})^{(\mu-1)/\mu} + (1-\lambda)^{1/\mu}(D_{N,t})^{(\mu-1)/\mu})^{\mu/(\mu-1)}$ and $\Gamma_M(.) = (\chi^{1/\varrho}\varphi_t(M_{E,t})^{(\varrho-1)/\varrho} + (1-\chi)^{1/\varrho}(M_{N,t})^{(\varrho-1)/\varrho})^{\varrho/(\varrho-1)}$. $D_{j,t}$ and $M_{j,t}$ are, respectively, the total demand of US households and government of sector j goods produced in home and foreign economies; $\mu, \varrho > 0$ are the elasticity of substitution parameters across the sectoral goods, and $\lambda, \chi \in (0, 1)$ are the bias parameters for the energy-intensive goods. Lastly, γ_t and φ_t denote the respective exogenous preferences for energy-intensive goods produced in home and foreign economies.

The profits of traders are composed of three parts: $\Pi_{T,t} = \Pi_{\Phi_D,t} + \Pi_{\Gamma_D,t} + \Pi_{\Gamma_M,t}$, with $\Pi_{\Phi_D,t} = P_tD_t - P_{H,t}D_{H,t} - M_t$, $\Pi_{\Gamma_D,t} = P_tD_t - P_{E,t}D_{E,t} - P_{N,t}D_{N,t}$, and $\Pi_{\Gamma_M,t} = M_t - P^F_{E,t}M_{E,t} - P^F_{N,t}M_{N,t}$. We define US CPI (real exchange rate) as $P_t = (\lambda(\gamma_t)^{\mu}(P_{E,t})^{1-\mu} + (1-\lambda)(P_{N,t})^{1-\mu})^{1/(1-\mu)}$. The other price that showed up in the solved (log-linearized) model is the exogenous world price of imported energy-intensive goods, $P^F_{E,t}$. $P_{H,t}$ and $P^F_{N,t}$, which are, respectively, the price index of composite goods produced in the home economy and the exogenous world price of non-energy intensive goods, do not enter into the equations used for model simulation.[4]

While all the agents (firms, households, the government, and traders) in the foreign economy are making decisions symmetric to those presented above for the US economy, the two equilibrium conditions that will suffice to complete the characterisation of trade transactions concern aggregate imports and imports of energy-intensive goods by traders in the foreign economy. In what follows, all variables and parameters, though written for the foreign economy, have identical meanings to their home economy equivalents, such that we only elaborate on key ones. To begin with, we assume that the exogenous total foreign absorption, $D_{F,t}$, can analogously be written as: $D_{F,t} = C_{F,t} + I_{F,t} + G_{F,t}$. Noting first that $D_{F,t}$ is a composite of foreign and US goods, we can write that: $D_{F,t} = \Phi_{D_F}(D_{W,t}, M_{F,t}) = \Phi_{D_F}(D_{W,t}, X_t)$, where $D_{W,t}$ is the foreign absorption of goods produced in the ROW, and $M_{F,t} = X_t$ is either total imports (from the standpoint of foreign traders) or total exports (from the viewpoint of US traders). We can then write that: $\Phi_{D_F}(.) = ((\kappa_F)^{1/\phi_F}(D_{W,t})^{(\phi_F-1)/\phi_F} + (1-\kappa_F)^{1/\phi_F}\varpi_{F,t}(X_t)^{(\phi_F-1)/\phi_F})^{\phi_F/(\phi_F-1)}$, using the latter anatomization.

Moreover, our discussion so far dictates that $D_{F,t}$ is likewise a composite of four types of goods. Hence, we cast an expression for US exports as:

$$X_t = \Gamma_X(X_{j,t}) \tag{14}$$

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[4] In an empirical paper on the associations between world shocks, world prices, and business cycles in 138 countries covering the period 1960-2015, Fernández et al. (2017) documented that it is important to specify multiple world prices rather than a single one in order to elicit the true effects of global shocks on the domestic output of a country. Our modelling strategy is thus consistent with their empirical proposition and finding.

where $\Gamma_X(.) = ((\chi_F)^{1/\varrho_F}\varphi_{F,t}(X_{E,t})^{(\varrho_F-1)/\varrho_F} + (1-\chi_F)^{1/\varrho_F}(X_{N,t})^{(\varrho_F-1)/\varrho_F})^{\varrho_F/(\varrho_F-1)}$.

2.5. Aggregation, exogenous processes, and competitive equilibrium

The market clears for energy-intensive goods:

$$Y_{E,t} = D_{E,t} + X_{E,t} - M_{E,t} \tag{15}$$

where, by Walras' Law, the market also clears for non-energy intensive goods. The aggregate resource constraint in the home economy is satisfied by:

$$Y_t = C_t + I_t + G_t + X_t - M_t - P_{O,t}O_t \tag{16}$$

Furthermore, the dynamics of the current account implies that the market for foreign bonds is cleared by:

$$B_{F,t} = R_{F,t-1}B_{F,t-1} + P_tX_t - M_t - P_{O,t}O_t \tag{17}$$

Turning now to the exogenous shocks in our model, we note that there are twenty-two of them. A number of these shocks can be directly observed in the data (government spending, world demand, foreign interest rate, oil price, and the price of imported energy-intensive goods); see Section 3.2 below for further discussion. The remaining shocks are wedges in the model's equilibrium equations (e.g., intertemporal preference, labour supply, and sectoral productivity shocks);[5] these ones are derived as residuals (the difference between data and model).[6] As our data are unfiltered, we carry out tests of stationarity for all shocks (see Section B of the Online Appendix). Based on the tests' results, we treat one half of the shocks as stationary (or trend-stationary) and the remaining one half as non-stationary. We model the former group of shocks as *AR*(1) processes in levels:

$$\varepsilon_{s_1,t} = \rho_{s_1}\varepsilon_{s_1,t-1} + \eta_{s_1,t} \tag{18}$$

for $s_1 = \{\tau_t, \zeta_t, R_{F,t}, Z_{j,t}, \vartheta_{j,t}, Q_{j,t}, \varpi_t, \varpi_{F,t}\}$. Whereas the non-stationary shocks are estimated using *AR*(1) processes in first differences:

$$\Delta\varepsilon_{s_2,t} = \rho_{s_2}\Delta\varepsilon_{s_2,t-1} + \eta_{s_2,t} \tag{19}$$

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[5] The equilibrium equations of the model are log-linearized around the model's deterministic steady state and solved in Dynare.

[6] Details on the procedures for constructing the model residuals are given in Section B of the Online Appendix.

for $s_2 = \{\xi_{j,t}, P_{O,t}, A_{j,t}, G_t, \gamma_t, P_{E,t}^F, \varphi_t, \varphi_{F,t}, D_{F,t}\}$. In equations (18) and (19), the innovations $\eta_{s_1,t}$ and $\eta_{s_2,t}$ are mutually independent, serially uncorrelated, and normally distributed with mean zero and variances $\sigma_{s_1}^2$ and $\sigma_{s_2}^2$, respectively.

Finally, an equilibrium is a set of endogenous stochastic processes for quantities and prices $\{C_t, L_t, L_{j,t}, B_{F,t}, I_t, I_{j,t}, U_{j,t}, K_{j,t}, Y_t, Y_{j,t}, O_t, O_{j,t}, D_t, D_{E,t}, M_t, M_{E,t}, X_t, X_{E,t}, P_t, P_{j,t}, W_t, R_t, R_{j,t}\}_{t=0}^{\infty}$, such that given the initial conditions for consumption (C_{t-1}), bonds ($B_{t-1}, B_{F,t-1}$), capital ($K_{j,t-1}$), and the realisations of a set of exogenous stochastic processes driving the model $\{\tau_t, \zeta_t, R_{F,t}, Z_{j,t}, \vartheta_{j,t}, Q_{j,t}, \varpi_t, \varpi_{F,t}, \xi_{j,t}, P_{O,t}, A_{j,t}, G_t, \gamma_t, P_{E,t}^F, \varphi_t, \varphi_{F,t}, D_{F,t}\}_{t=0}^{\infty}$, firms maximise their profits given the prices, households maximise their utility given the prices, traders maximise their profits given the prices, the government's budget constraint is met, and all markets clear.

3. Estimation

3.1. Data

The model is estimated on US annual data over the 1949-2013 period. The constructed dataset includes 29 observations, falling within four categories: (i) the aggregate and sectoral measures on output, investment, labour hours, oil use, and prices of goods, (ii) the time series for consumption, wages, interest rate, and foreign bonds, (iii) the aggregate and energy-intensive sector measures of exports, imports, and domestic absorption, and (iv) the sectoral measures on capital stock and capital utilisation rate. Details on the data sources and construction of the variables are described in Section C of the Online Appendix. Fig. 1 depicts US unfiltered data.

3.2. Indirect inference

Indirect inference techniques from Le et al. (2011) are employed in estimating our model. Meenagh et al. (2012) extend this methodology to non-stationary data, which is more suited to our purpose. Furthermore, Le et al. (2016) provide a detailed account of their application to DSGE models. Adopting the canonical US model of Smets and Wouters (2007) as the 'true' one, these authors establish, via Monte Carlo experiments, that indirect inference methodology achieves low bias and larger power in small samples compared to the other main frequentist estimation technique, classical Maximum Likelihood. As a frequentist method, it also does not rely on priors, which in macroeconomics remain controversial, because for some coefficients we may not have a strong understanding of what the priors should be. To make progress in building up support for modelling approaches, we require a method that tests the model against the data, without appeal to priors. The advantage of using indirect inference is that it provides a highly powerful test of our model against the data. In the rest of this section, we give a brief description of the intuition behind the method of indirect inference and its estimation procedures.

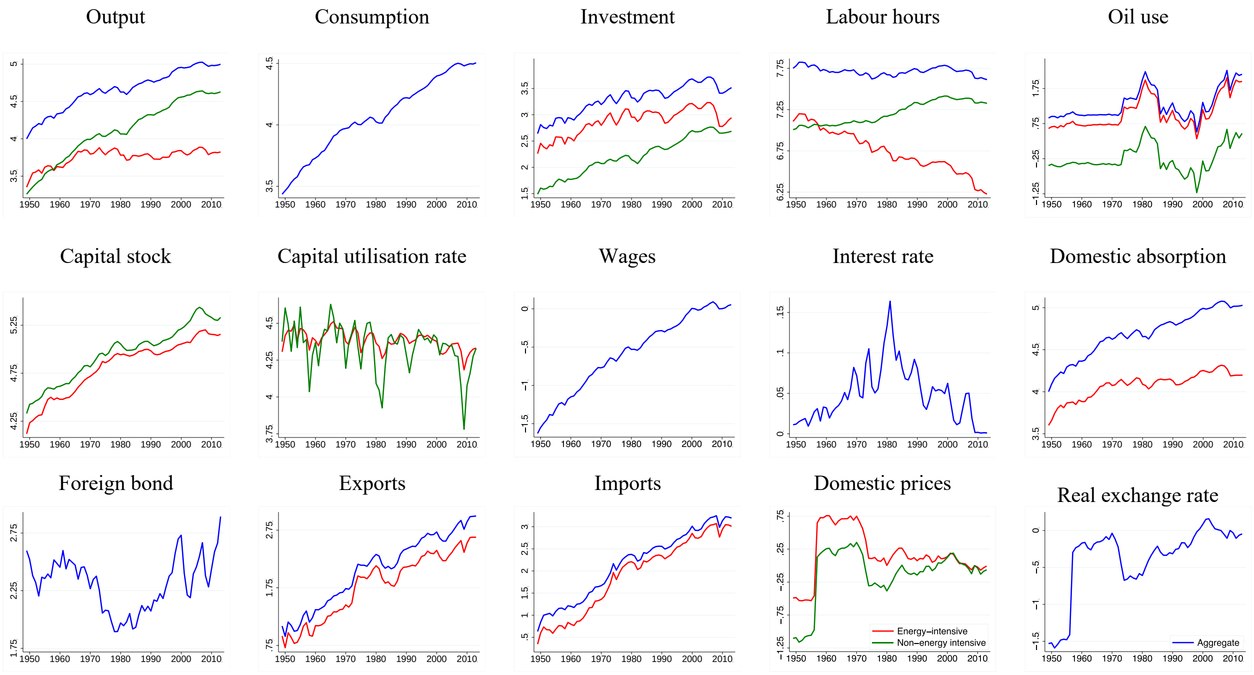

Fig. 1. US unfiltered data used for estimation (1949-2013)

The notion of indirect inference is built on choosing parameter sets θ_0 to minimise the distance between coefficients generated from simulated data and those obtained from actual data. The simulated data are computed by bootstrap simulations of our DSGE model. The description of the data properties is done by means of an auxiliary model. In practice, our choice of the auxiliary model for testing by indirect inference draws on the fact that the solution to a log-linearised DSGE model can be represented as a restricted vector autoregressive moving average (VARMA) model either in levels, if the shocks are stationary, or in first differences, if the shocks are permanent, and that this can be approximated by a VAR. Moreover, rational expectations are generated as the solution to the model, based on the VAR (e.g., Del Negro and Schorfheide, 2004, 2006; Canova, 2007; Dave and DeJong, 2007; Del Negro et al., 2007). With unfiltered data, the auxiliary model is taken to be a vector error correction model (VECM). For a structural model like ours, this can be written as a VARX(1) for the macroeconomic variables of interest:

$$\widetilde{w}_t = [I - \mathcal{F}]\widetilde{w}_{t-1} + \Upsilon \bar{x}_{t-1} + \pi t + v_t \tag{20}$$

where $\bar{x}_{t-1}$ are stochastic trends, πt are deterministic trends, and v_t are VECM innovations. The derivation of the above representation of the auxiliary model is contained in Section D of the Online Appendix.

The implementation of indirect inference estimation involves three steps.[7] First, the residuals and innovations of the structural DSGE model in Section 2 are computed based on actual data and model parameters θ_0. As stated earlier in Section 2.5, five exogenous variables are observed in the actual data, while the remaining structural shocks are to be backed out directly as errors using the model equations and actual data. Fig. 2 shows the single equation residuals (based on estimated parameters; see Section 4 for details); Fig. 3 displays the accompanying estimated innovations that are employed to shock the model. Second, simulated data are generated from the DSGE model; this is done by bootstrapping its estimated innovations to obtain $S = 1000$ independent samples. Third and finally, our auxiliary model is estimated for all data samples (actual and simulated). When applied to the simulated data, the variance-covariance matrix Ω of the distribution implied for the model's coefficient vectors a_s $(s = 1, \ldots, S)$ is obtained. The resulting Wald statistic WS is given by:

$$WS = \left(a_T - \overline{a_S(\theta_0)}\right)'\Omega(\theta_0)^{-1}\left(a_T - \overline{a_S(\theta_0)}\right) \tag{21}$$

where a_T is the estimated vector of coefficients from actual US data, $\overline{a_S(\theta_0)}$ is the mean of the estimated vector of coefficients from model-based data, and $\Omega(\theta_0)^{-1}$ is the inverse of the estimated variance-covariance matrix. The task before us when using indirect inference techniques is that of judging the proximity of the restricted reduced-form VARX(1) approximation derived from the model to the unrestricted counterparts calculated from the data (i.e., $\left(a_T - \overline{a_S(\theta_0)}\right)$). The inference is based on the above Wald statistic, which tests the model in total against the data. Here, we have chosen a test threshold of 5% so that VARX(1) coefficients of actual data with a Wald percentile above 95% will mark rejection. We also present this information using transformed Mahalanobis distance and p-value ($= 1 - \text{Wald percentile}/100$).

We note that the estimation by indirect inference is carried out by using a powerful search algorithm based on simulated annealing in which a search takes place over a wide range around the initial values, with an optimising search accompanied by random jumps around the suggested parameter space. We use calibrated values as the initial points for the search algorithm; the aim of the search is to find optimal coefficient sets that will make the model not to be rejected by the data. In the Online Appendix, Section E provides additional discussion on simulated annealing and Section F reports the initial values used to initiate the search procedure.

In our empirical analysis, meanwhile, we are concerned with whether the model can fit the main macroeconomic variables of interest. For our purpose, this is a combination of output and the real exchange rate; we select to estimate a VARX(1) on them with time trends and several shocks with unit

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[7] A more elaborate description of these three steps used in calculating the Wald statistic is provided in Section B of the Online Appendix.

roots. By doing this, we are utilising what Le et al. (2011) labelled a ‘directed’ Wald evaluation approach. Besides, we have chosen to cap the number of macroeconomic variables at 2 and the VAR order at 1 because of the power of indirect inference testing procedure, which needs to be high to achieve discrimination between models; but not so high that only almost exactly accurate models can pass. Indirect inference is a test of whether the parameters can be matched jointly, taking also into account the dynamics of all non-stationary shocks, rather than just those of output and the real exchange rate individually. As the number of variables and the VAR order are raised, so is the power of the test. Past work has found by Monte Carlo experiment that a VAR(1) with two variables typically gives the right level of power for testing macro models (Le et al., 2016; Meenagh et al., 2019).

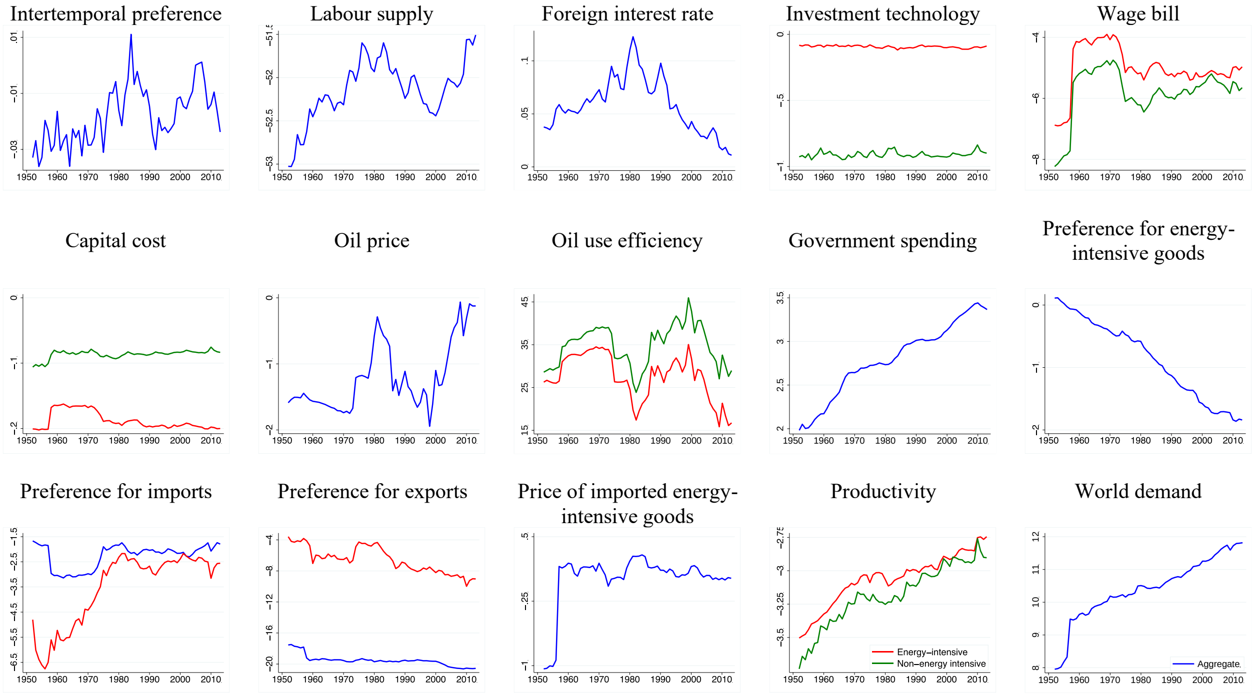

Fig. 2. Residuals

4. Findings

4.1. Estimation results

Indirect inference estimates of the structural parameters and the corresponding Wald test results are reported in Table 1. Frisch elasticity of labour supply, ω, is 6.03, which indicates that labour hours react more to changes in the real wage. The elasticity of substitution in consumption, σ, of 1.24 found here implies that households are more willing to spread consumption across time in response to a change in real interest rate. The estimated elasticity of substitution between capital services and oil use in both sectors (ν_E and ν_N) are similar: 0.29 in the energy-intensive sector and 0.27 in the non-energy intensive sector. These values mean that there are high elasticities of substitution between the two factors in both sectors. Output elasticities of labour hours are sizable in the two sectors, with $1-\alpha_E = 0.75$ and $1-\alpha_N = 0.63$. The estimated value of consumption habit formation parameter, ι, is 0.3, which is lower compared to estimates in existing literature (e.g., Merola, 2015; Smets and Wouters, 2007). This may be due to data frequency (annual vs. quarterly), as it suggests that households are likely to adjust more to shocks over the course of a year relative to a quarter.

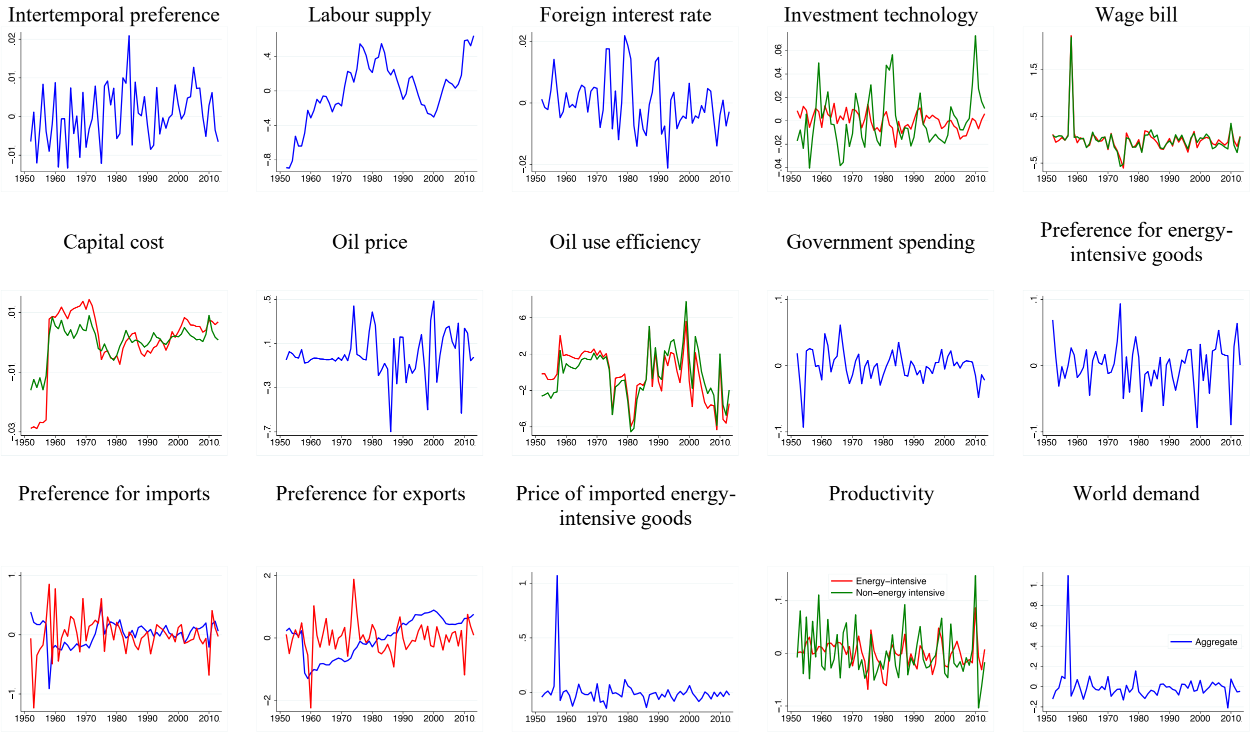

Fig. 3. Innovations

Further, the estimates of the marginal costs of capital utilisation in the energy-intensive and non-energy intensive sectors, $\delta_{j,1}u_j^{\delta_{j,2}}$ (denoted by δ_j), are 3% and 6%, respectively. These estimates indicate that return to investment in the non-energy intensive sector is higher than in the energy-intensive sector. The estimate of the elasticity of capital utilisation rate is lower in the energy-intensive sector ($\delta_{E,2} = 1.90$) than in the non-energy intensive sector ($\delta_{N,2} = 4.72$). Adjustment cost parameters for sectoral stocks of physical capital and foreign bonds are all estimated to be close to zero. We find that the elasticity of substitution between absorption of home-produced goods in the US and the imports of foreign goods is larger ($\phi = 0.97$), being more than double that between foreign economy's absorption of its own goods and US exports ($\phi_F = 0.43$). The elasticities of substitution between the components (energy-intensive and non-energy intensive goods) of each of total imports and total exports are, however, much smaller ($\varrho = 0.07$ and $\varrho_F = 0.04$). The model estimates of the elasticity of substitution between the absorption of energy-intensive and non-energy intensive goods in the US, μ, is 0.44. The bias parameter for energy-intensive goods in the US is estimated to be low ($\lambda = 0.26$).

Table 1: Indirect inference estimates of structural parameters

	Notation	Value
Firms		
Elasticity of substitution between K_E and O_E	ν_E	0.29
Elasticity of substitution between K_N and O_N	ν_N	0.27
Elasticity of output to labour hours plus 1 in the energy-intensive sector	α_E	0.25
Elasticity of output to labour hours plus 1 in the non-energy intensive sector	α_N	0.37
Weight of capital services in the energy-intensive sector	θ_E	0.997
Weight of capital services in the non-energy intensive sector	θ_N	0.993
Households		
Frisch elasticity of labour supply	ω	6.03
Elasticity of substitution in consumption	σ	1.24
Habit formation in consumption	ι	0.3
Marginal cost of capital utilisation in the energy-intensive sector	δ_E	0.03
Marginal cost of capital utilisation in the non-energy intensive sector	δ_N	0.06
Elasticity of capital utilisation rate in the energy-intensive sector	$\delta_{E,2}$	1.9
Elasticity of capital utilisation rate in the non-energy intensive sector	$\delta_{N,2}$	4.72
Adjustment cost parameter for capital in the energy-intensive sector	ψ_E	0.0001
Adjustment cost parameter for capital in the non-energy intensive sector	ψ_N	0.0007
Adjustment cost parameter for foreign bonds	ψ_F	0.0001
Traders		
Elasticity of substitution between D_H and M	ϕ	0.97
Elasticity of substitution between D_F and X	ϕ_F	0.43
Elasticity of substitution between M_E and M_N	ϱ	0.07
Elasticity of substitution between X_E and X_N	ϱ_F	0.04
Elasticity of substitution between D_E and D_N	μ	0.44
Bias parameter for energy-intensive goods	λ	0.26
Test statistics		
Wald statistic (*Y, P*)		12.905
Transformed Mahalanobis distance (*Y, P*)		1.444
p-value (*Y, P*)		0.063

Meanwhile, the weight of capital services in both sectors (θ_j) are not directly estimated, but are instead implicitly obtained by using the expression:

$$\theta_j = \frac{1}{1 + \frac{\left(o_j/k_j\right)^{1+\nu_j}}{1/\beta - \left(1 - \delta u_j\right)}} \tag{22}$$

where o_j/k_j is the respective sector's historical oil-capital ratio ($o_E/k_E = 0.011$ and $o_N/k_N = 0.014$) obtained from US post-war data, β is set equal to 0.96 to match the annual real interest rate of 4% over the sample period, and δu_j is the steady state depreciation function of capital in the two sectors ($\delta u_E = 0.09$ and $\delta u_N = 0.06$). We fix the values of the rest of the parameters in our model; see Section F of the Online Appendix.

Using these estimated values, the last three rows of Table 1 summarise the results which demonstrate whether or not the model is able to reproduce the features of the data jointly. We find that the model adequately fits the joint distribution of the data with a Wald statistic of 12.905. The transformed Mahalanobis distance of 1.444 provides support for this conclusion, because a value that is less than 1.645 is usually considered to confirm that the model is not rejected. Finally, the p-value of 0.063 confirms that the model passes the Wald test comfortably at the 95% confidence level. Table 2 reveals that many of the shocks are estimated to be mildly persistent, except for the autocorrelation coefficients of the first-differenced shocks that are treated as non-stationary. Besides, it is estimated that the sectoral oil use efficiency shocks are the most volatile, while intertemporal preference shock is the least volatile.

4.2. Variance decomposition

The primary question that we ask of the estimated model is: how crucial are global shocks in accounting for the US business cycle fluctuations? To answer this question, we first cluster the shocks following Smets and Wouters (2007), except that we follow the NOEM literature in assigning foreign interest rate to the global shocks' block (e.g., Kose 2002; Justiniano and Preston 2010; Matheson 2010). We categorise the shocks into four groups: (i) productivity shocks, (ii) mark-up shocks, (iii) demand shocks, and (iv) global shocks. Productivity shocks consist of the two sectoral productivity and the two sectoral oil use efficiency shocks. We include the exogenous wage bill and the exogenous capital cost shifters from both sectors in the mark-up shocks. The global shocks are represented by the exogenous world demand, exogenous foreign interest rate, exogenous world oil price, exogenous world price of imported energy-intensive goods, and preferences for aggregate exported goods and exported energy-intensive goods. All the remaining exogenous variables are combined into demand shocks.

Using these classifications, we report variance decomposition for aggregate macroeconomic variables in our model in Table 3. Clearly, global shocks have been the most influential determinants of movements in the US aggregate macroeconomic variables under study. For instance, we find that global shocks play a dominant role in the determination of six variables, accounting for well over 50% of their variances. More particularly, they explain 64% of the variance of investment, with productivity (10%), mark-up (10%) and demand (16%) shocks contributing the rest. In a similar vein, global shocks determine 65% of the variation in exports, 72% in imports, 58% in wages, 60% in interest rate, and 63% in oil use. As shown in the cases of these latter variables, productivity, mark-up, and demand shocks continue to play second fiddle to global shocks.

Table 2: Indirect inference estimates of shock processes

	Autocorrelation		Standard deviation	
	Notation	Value	Notation	Value
Domestic shocks				
Productivity shocks:				
Productivity in the energy-intensive sector	ρ_{a_E}	-0.004	σ_{a_E}	0.026
Productivity in the non-energy intensive sector	ρ_{a_N}	-0.006	σ_{a_N}	0.047
Oil use efficiency in the energy-intensive sector	ρ_{q_E}	0.66	σ_{q_E}	2.78
Oil use efficiency in the non-energy intensive sector	ρ_{q_N}	0.568	σ_{q_N}	2.76
Mark-up shocks:				
Wage bill shifter in the energy-intensive sector	ρ_{ξ_E}	0.03	σ_{ξ_E}	0.323
Wage bill shifter in the non-energy intensive sector	ρ_{ξ_N}	0.04	σ_{ξ_N}	0.324
Capital cost shifter in the energy-intensive sector	ρ_{ϑ_E}	0.094	σ_{ϑ_E}	0.01
Capital cost shifter in the non-energy intensive sector	ρ_{ϑ_N}	0.036	σ_{ϑ_N}	0.006
Demand shocks:				
Intertemporal preference	ρ_{τ}	0.645	σ_{τ}	0.007
Labour supply	ρ_{ζ}	-0.01	σ_{ζ}	0.358
Investment technology in the energy-intensive sector	ρ_{z_E}	0.341	σ_{z_E}	0.008
Investment technology in the non-energy intensive sector	ρ_{z_N}	-0.003	σ_{z_N}	0.023
Government spending	ρ_{g}	0.506	σ_{g}	0.023
Preference for energy-intensive goods	ρ_{γ}	0.246	σ_{γ}	0.035
Preference for imported energy-intensive goods	ρ_{φ}	0.045	σ_{φ}	0.309
Preference for aggregate imported goods	ρ_{ϖ}	0.679	σ_{ϖ}	0.204
Global shocks				
World demand	ρ_{d_F}	0.005	σ_{d_F}	0.156
Oil price	ρ_{p_O}	-0.006	σ_{p_O}	0.209
Foreign interest rate	ρ_{r_F}	0.96	σ_{r_F}	0.009
Preference for exported energy-intensive goods	ρ_{φ_F}	-0.062	σ_{φ_F}	0.553
Preference for aggregate exported goods	ρ_{ϖ_F}	0.067	σ_{ϖ_F}	0.623
Price of imported energy-intensive goods	$\rho_{p_E^F}$	0.037	$\sigma_{p_E^F}$	0.147

We find that global shocks are the most important sources of changes in the remaining variables. They explain 38% of output variability, with productivity, mark-up, and demand shocks adding 18%, 18%, and 26%, respectively. Further, the variances of consumption (36%), labour hours (36%), the real exchange rate (42%), domestic absorption (39%), and foreign bonds (37%) are largely determined by global shocks, while the other groups of shocks supply the rest of the explanations. The findings here are consistent with McCarthy and Dhareshwar (1992) and Meenagh et al. (2010) on the importance of external shocks. Additionally, we confirm that global shocks are equally as important in explaining sectoral macroeconomic variables; see Section G of the Online Appendix.

Table 3: Variance decomposition for the aggregate variables

	Domestic shocks			
	Productivity shocks	Mark-up shocks	Demand shocks	Global shocks
Output	17.92	17.56	26.34	38.19
Consumption	18.61	18.18	26.78	36.43
Investment	9.83	10.19	15.56	64.41
Exports	12.24	9.21	13.34	65.22
Imports	11.12	4.49	12.20	72.19
Labour hours	18.14	18.19	27.20	36.47
Price (real exchange rate)	25.49	13.82	18.92	41.77
Wages	8.71	22.17	10.85	58.27
Interest rate	18.05	3.53	18.03	60.40
Oil use	27.87	3.74	5.27	63.12
Domestic absorption	17.45	17.36	26.06	39.12
Foreign bonds	22.78	15.33	25.37	36.53

Note: Productivity shocks: productivity in the energy-intensive sector, productivity in the non-energy intensive sector, oil use efficiency in the energy-intensive sector, and oil use efficiency in the non-energy intensive sector; mark-up shocks: wage bill shifter in the energy-intensive sector, wage bill shifter in the non-energy intensive sector, capital cost shifter in the energy-intensive sector, and capital cost shifter in the non-energy intensive sector; demand shocks: intertemporal preference, labour supply, investment technology in the energy-intensive sector, investment technology in the non-energy intensive sector, government spending, preference for energy-intensive goods, preference for imported energy-intensive goods, and preference for aggregate imported goods; global shocks: world demand, preference for aggregate exported goods, preference for exported energy-intensive goods, foreign interest rate, oil price, and price of imported energy-intensive goods.

4.3. Shock decomposition

Next, we look at the historical contributions of the groups of shocks in our model to output and real exchange rate. This is done to further establish which shocks are the main determinants of business cycle fluctuations over the sample period. Figs. 4 and 5 show the shock decompositions for output and real exchange rate, respectively. In the diagrams, we illustrate the relative, per year, importance of each shock cluster in a stacked bar chart, and also include, as a line plot, the predicted actual (i.e., the model-based stochastic trends) of our variables of interest. According to our model, global shocks were the significant drivers of output in the US in the decades immediately following World War II until the close of the 20th Century. Nevertheless, productivity shocks were also crucial in stimulating output over this period. After the year 2000, productivity shocks dominated US output fluctuations, with the main additional contributions coming from global and demand shocks. Generally, the cohorts of global and productivity shocks played more prominent roles in output changes than those of mark-up and demand shocks over the sample period. It is also of interest that productivity and global shocks tend to work contrary to mark-up and demand shocks over the majority of the period under study.

The influence of global shocks may have been more extensive than the results indicate, had it not been for the offsetting effects that some of their components at times exerted on one another. For instance, in the periods marked by oil crises (e.g., 1973-1974 and 1978-1981), the adverse effects worked to depress the economy's output, but these effects were soaked up by the positive shocks to world demand and preference for US products. As a result, the total impact on output was still positive in most instances. However, when the negative forces of rising oil/commodity prices outweigh the realised positive effects from the other global shocks, or when most of the shocks have reinforcing (whether positive or negative) contributions, we observe what the model predicts for 1952-1954 or 2007-2013, for example.

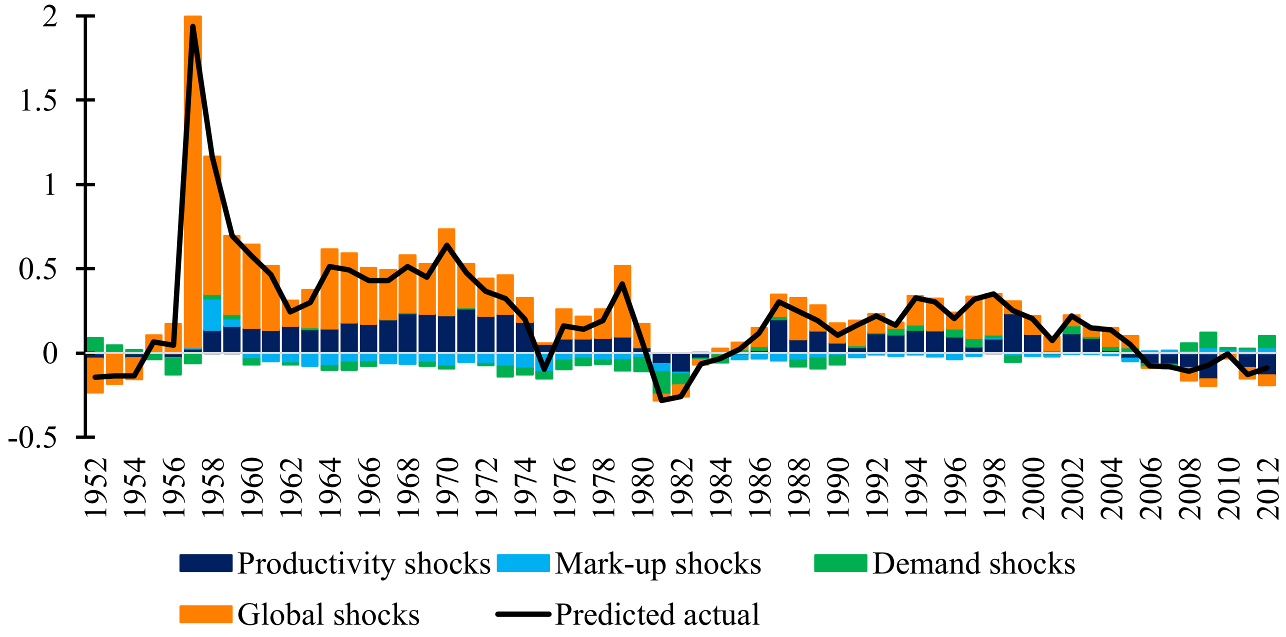

Fig. 4. Shock decomposition (output)

Note: Productivity shocks: productivity in the energy-intensive sector, productivity in the non-energy intensive sector, oil use efficiency in the energy-intensive sector, and oil use efficiency in the non-energy intensive sector; mark-up shocks: wage bill shifter in the energy-intensive sector, wage bill shifter in the non-energy intensive sector, capital cost shifter in the energy-intensive sector, and capital cost shifter in the non-energy intensive sector; demand shocks: intertemporal preference, labour supply, investment technology in the energy-intensive sector, investment technology in the non-energy intensive sector, government spending, preference for energy-intensive goods, preference for imported energy-intensive goods, and preference for aggregate imported goods; global shocks: world demand, preference for aggregate exported goods, preference for exported energy-intensive goods, foreign interest rate, oil price, and price of imported energy-intensive goods.

Turning to the shock decomposition for real exchange rate, we see some similarities in the ability of global shocks to have meaningful impacts at the beginning of the sample, just as in the case of output. This is more apparent in the results of the 1950s, such that one can conjecture that the model's interpretation of the major influence of global shocks on the American economy is highly concentrated at the beginning of our sample. Their contributions, however, appear to peter out towards the end, especially in the case of the real exchange rate. Here, the predominant factors leading US competitiveness against ROW are productivity shocks, which appear to have had sole responsibility for most of the variations in real exchange rate since the early 1980s.

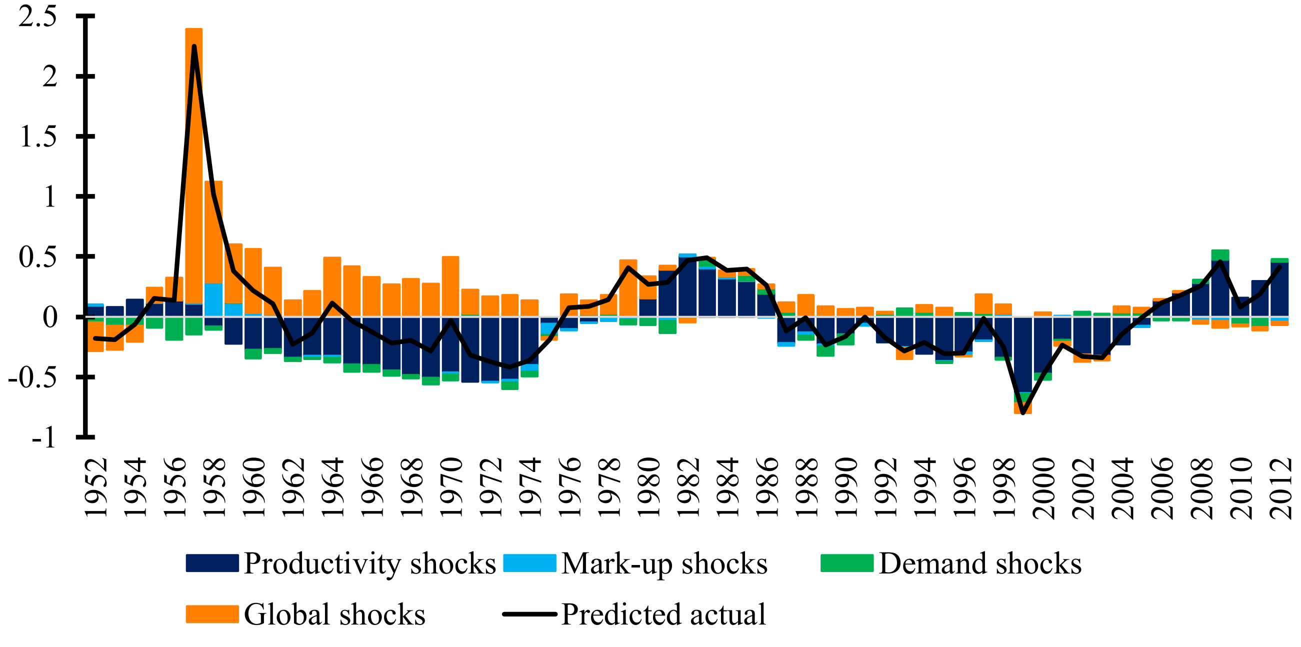

Fig. 5. Shock decomposition (real exchange rate)

Note: Productivity shocks: productivity in the energy-intensive sector, productivity in the non-energy intensive sector, oil use efficiency in the energy-intensive sector, and oil use efficiency in the non-energy intensive sector; mark-up shocks: wage bill shifter in the energy-intensive sector, wage bill shifter in the non-energy intensive sector, capital cost shifter in the energy-intensive sector, and capital cost shifter in the non-energy intensive sector; demand shocks: intertemporal preference, labour supply, investment technology in the energy-intensive sector, investment technology in the non-energy intensive sector, government spending, preference for energy-intensive goods, preference for imported energy-intensive goods, and preference for aggregate imported goods; global shocks: world demand, preference for aggregate exported goods, preference for exported energy-intensive goods, foreign interest rate, oil price, and price of imported energy-intensive goods.

4.4. Additional results and robustness

So far, we have seen that global shocks are fundamental to explaining movements in key US macroeconomic variables. Now, we show the significance of its components by measuring their individual shares in the total variance contributed by the composite global shocks to the aggregate macroeconomic variables in our model. Fig. 6 shows the results. For example, it is demonstrated that exogenous world demand is responsible for over 30% of the effects of global shocks (38.19%; see Table 3) on output variance. The remaining 70% is largely contributed by oil price, preference for exported energy-intensive goods, and the price of imported energy-intensive goods. In all cases, exogenous world demand captures the lion share of the contributions by global shocks. Also, we find that oil price shocks are slightly more significant than the preference for exported energy-intensive goods and the price of imported energy-intensive goods. Meanwhile, in the variations of output and all the other macroeconomic variables (except exports), preference for aggregate exported goods plays a very subdued role. Lastly, the effect of foreign real interest rates on US macroeconomic variables are largely non-existent, which is consistent with strong domestic monetary policy (Iacoviello and Navarro 2019).

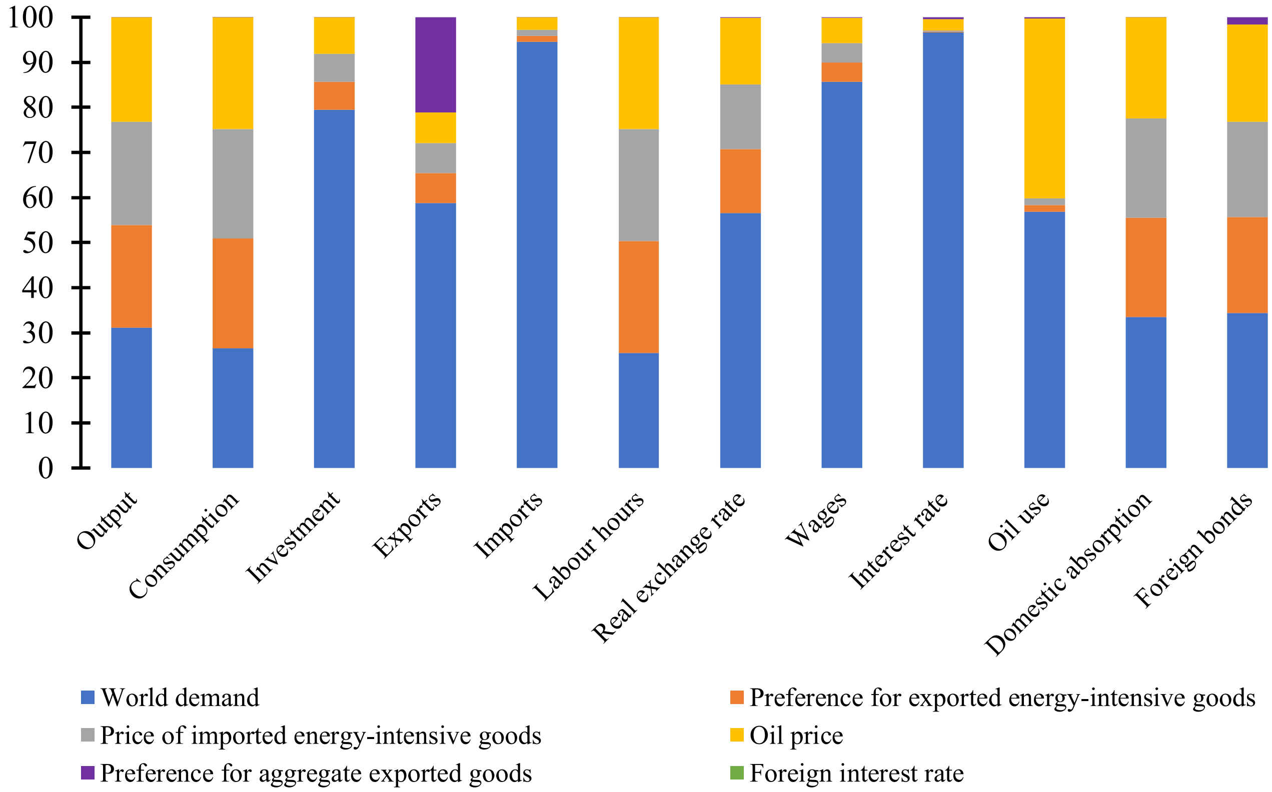

Fig. 6. Unbundling global shocks

Further, there remains a great debate in the literature about whether or not oil price shocks matter for business cycles in the US. While the focus of our paper has been broader than this aspect of global shocks, we find it useful to exploit the structure of our model to confront the issue. Thus, we consider the question: What does our model say about the role of oil price shocks in explaining US output fluctuations? Our approach here is to demonstrate the ability of the bootstrap simulated model samples to predict output expansions and contractions in the actual data, given oil price shocks.[8] Our assessment of the simulated data focuses on two facts: (i) the frequency of occurrence (in 1000 years) of expansions and contractions in tandem with oil price changes, and (ii) the percentage of events (per 1000 years) involving movements in oil price. As shown in Table 4, oil price decreases (increases) account for around 17% (16%) of the occurrence of output expansions (contractions) in the full sample. Additionally, the experiment reveals

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[8] To do this, we define an expansion (contraction) as two or three consecutive quarters of output above (below) the trend growth rate; these are then summed up to obtain an annual frequency. More specifically, expansions refer to episodes of annual growth rates of GDP above 3.5%, which is the average growth rate of US GDP over the study period. We take contractions as episodes with negative changes in output. Besides, for both expansions and contractions, we take as one episode every successive occurrence and seek an understanding of these excessive US business cycle fluctuations. In this experiment, we adopt the dating of US business cycles provided by the National Bureau of Economic Research (NBER) and the dating of oil crises documented in Hamilton (2013). Thus, for each sample period, $N = 62$, we simulate the model 1000 times. Consequently, the statistics reported relates to generated pseudo data for 62,000 years using Monte Carlo techniques. We then employ it to calculate oil price-output relationships over the sample period and compare these model predictions to actual data.

that there will be no output contractions (expansions) and no oil price increases (decreases) every 2 years. Further, in approximately every 5 years, on average, there is an oil price rise (fall) that does not affect output fluctuation. We split the sample period into two periods (pre-1980 and post-1980) and find that the results remain consistent across time. A lesson to take from this is that, although oil prices sometimes matter for output changes, there are still many instances when the booms and busts are either merely systemic or due to other factors (see, e.g., Blanchard and Gali, 2007; Davidson et al., 2010).

Table 4: An illustration of the model's predictions of expansions and contractions

	1950-2013	1950-1981	1982-2013
Expansions			
Frequency of no expansions and no oil price decreases	1.8	1.78	1.82
Frequency of expansions and no oil price decreases	4.82	5	4.72
Frequency of no expansions but oil price decreases	5.62	5.5	5.7
Frequency of expansions and oil price decreases	17.09	18.14	16.15
Contractions			
Frequency of no contractions and no oil price increases	1.79	1.77	1.81
Frequency of contractions and no oil price increases	4.89	5.07	4.76
Frequency of no contractions but oil price increases	5.72	5.6	5.77
Frequency of contractions and oil price increases	16.23	17.17	15.59

Note: An expansion (contraction) is defined as two or three consecutive quarters of output above (below) the trend growth summing to one year for annual frequency. For both expansion and contraction, we take as one episode every successive occurrence.

Lastly, the estimated structural parameter values reported in Table 1 imply that our model is not rejected at the 5% level of significance based on the Wald test. One may, however, want to test the sensitivity of the theoretical model to pass this empirical test given different parameter values, and the implication of such, for the baseline result. To do this, we focused on the Frisch elasticity of labour supply, ω, which we held constant while we re-estimated the model. In particular, our aim was to see what lower value, if any, of ω compared to the estimated coefficient of 6.03 would yield a fit between our model and data. The results of fixing ω at 1, 2, …, 5 are shown in Table 5, which reveals that the model is not rejected only when the value of ω is as high as 5.[9] On this basis, it appears that our empirical contribution is suggesting that previous lower estimates of the Frisch elasticity of labour supply do not match the data behaviour, at least within our model framework.

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[9] We note that 5 is the value that we employ to initiate the search algorithm for ω in the original estimation. The estimates obtained for all the remaining parameters for the different fixed values of ω are documented in Section H of the Online Appendix.

In any case, we recalculated the variance decompositions of shocks for the aggregate macro-variables using the estimates from setting ω to 5, 4, and 3;[10] these are reported in Section H of the Online Appendix. As shown, our baseline finding that global shocks are important for driving US business cycles remains largely unaltered. However, the reported variance decompositions indicate that the estimated values of model parameters may also play a key role with regards to which groups of shocks are important. This is particularly obvious in the reported variance decompositions, when $\omega = 5$, for which mark-up shocks played a dominant role. Although, the model did not fit the data when we set ω equal to 4 or 3, we observe that global shocks take a preeminent position, just as in our baseline finding.

Table 5: Indirect inference test results for lower values of the Frisch elasticity of labour supply

	Frisch elasticity of labour supply, ω, fixed at:				
Test statistics:	1	2	3	4	5
Wald statistic (*Y, P*)	45.197	50.641	46.537	16.218	13.981
Transformed Mahalanobis distance (*Y, P*)	6.238	5.802	5.340	2.149	1.564
p-value (*Y, P*)	0.000	0.000	0.000	0.028	0.057

5. Conclusions

This paper has: (i) investigated the role of global shocks (relative to productivity, mark-up, and demand shocks) in the determination of US business cycle fluctuations, and (ii) identified which of the global shocks are most prominent in causing variations in US macroeconomic aggregates. For this purpose, we constructed a two-sector open economy DSGE model which features a large number of real frictions and several structural shocks. We estimated the model by the method of indirect inference on unfiltered data and were therefore able to admit non-stationary shocks. This empirical procedure showed that the model successfully matched the reality seen in US data. The central finding was that global shocks account for nearly 40% of the variances of output and the real exchange rate in the US economy between 1949 and 2013. Exogenous world demand, oil price shocks, preference for exported energy-intensive goods, and the price of imported energy-intensive goods were the global shocks responsible for causing these variations. In contrast, preference for aggregate exported goods was largely a bystander. Moreover, the estimated model appears to cast productivity shocks in a supporting role. Generally, the results underscored the supremacy of global and productivity shocks over mark-up and demand shocks in determining US business cycles.

We assert that these findings have salient policy implications both for the US and ROW, especially in this age of remarkable international economic integration. For the US, supposing that the policy makers have concerns about output fluctuations and the economy's competitiveness vis-à-vis ROW, uncovering

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[10] We opt to report the variance decompositions for these values because the fit of the model worsens with lower values of ω.

ways to raise exports, tighten domestic absorption, and increase productivity should be high on their agenda. Considering also the significant role played by the components of global shocks individually, it is crucial to design targeted government policy responses. Turning to exogenous world demand, the global shock identified by our model as having the most impact, the US policy makers would need to implement policies that can adjust the composition of imports and exports appropriately, without creating additional external debt burdens. Expanding world economic integration implies that synced cross-national macroeconomic events will increasingly become the norm. So, the question to be contemplated by ROW is: If global shocks can exert such significant quantitative effects on an economic superpower such as the US, which country is safe? It appears that greater trade liberalization and lower defensive postures (e.g., trade wars) must also be on the menu in this highly connected global village market. Moving forward, therefore, the rising importance of the BRIC countries, especially China, on the world stage will need to be taken into account.

To finish the paper, we note that our analysis has centred on comparing the model-data properties of output and real exchange rate for a developed country (US). One may therefore want to engage the proposed model as a possible data generating mechanism for similar (or different) macroeconomic variables in other types of economies (e.g., a developing country) in other regions of the world. (Of course, any such extensions could include financial and/or nominal frictions if the researcher so desires.) Such an endeavour could lead to purpose-built, country-specific policy statements. Finally, we have used a two-country model of the US and ROW for our study. Future work could extend this to a three-country world economy, including another major economic block (e.g., Euro Area). We would then be able to examine whether there are differences in the business cycle responses of the US and the Euro Area to various global shocks; the results of which would have far-reaching policy implications.

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Online Appendix for “Global Shocks in the US Economy: Effects on Output and Real Exchange Rate”

ABSTRACT

This is the Online Appendix for “Global Shocks in the US Economy: Effects on Output and Real Exchange Rate”. It reports supplementary material referred to in the paper. Section A provides full log-linearized model listing. Section B provides additional information on calculating the Wald statistic, shows the equations used to recover the model residuals, and presents the stationarity tests for the exogenous variables. Section C describes the variables and data sources. Section D gives further details on the auxiliary model used for model estimation by indirect inference methodology. Section E discusses further the simulated annealing algorithm employed to search for the optimal parameters that push the model closer to the data. Section F documents the calibrated values used to initiate the estimation process and the fixed values for the parameters whose values remain unchanged throughout our analysis. Section G provides the variance decomposition for the sectoral variables. Section H reports additional estimates and variance decompositions.

A. Model listing

This section lists the log-linear equilibrium conditions from the perspective of agents (firms, households, the government, and traders) in the home economy. Each equation has been expressed for one of the twenty-nine endogenous variables in the model, with $j \in \{E, N\}$ (E signifies energy-intensive sector and N the non-energy intensive sector).

$$c_t = \frac{1}{1+\iota} E_t c_{t+1} + \frac{\iota}{1+\iota} c_{t-1} + \frac{1-\iota}{\sigma(1+\iota)} (\tau_t - E_t \tau_{t+1} - \beta r r_t) \tag{A1}$$

$$w_t = \omega l_t + \zeta_t + \frac{\sigma}{1-\iota}(c_t - \iota c_{t-1}) \tag{A2}$$

$$r_t = r_{F,t} + p_t - E_t p_{t+1} - \psi_F bb_{F,t} \tag{A3}$$

$$\begin{aligned} k_{j,t} = {} & \frac{\sigma/(1-\iota)}{\psi_j(1+\beta)}(c_t - \iota c_{t-1}) - \frac{\sigma/(1-\iota)}{\psi_j(1+\beta)}(E_t c_{t+1} - \iota c_t) \\ & + \frac{1}{\psi_j(1+\beta)}\left(E_t \tau_{t+1} - \tau_t - E_t z_{j,t+1} + z_{j,t}\right) + \frac{\beta \delta_{j,1} u_j^{\delta_{j,2}}(\delta_{j,2}-1)}{\psi_j(1+\beta)} E_t u_{j,t+1} \\ & + \frac{1}{1+\beta}\left(\beta E_t k_{j,t+1} + k_{j,t-1}\right) \end{aligned} \tag{A4}$$

$$l_{j,t} = p_{j,t} + y_{j,t} - \frac{w}{1+w} w_t - \frac{1}{1+w} \xi_{j,t} \tag{A5}$$

$$\begin{aligned} u_{j,t} = {} & \left(\frac{\delta_{j,2} - 1}{1 + \frac{1}{\delta_{j,1} u_j^{\delta_{j,2}}}} + \nu_j + 1 - \frac{\nu_j}{1 + \frac{1-\theta_j}{\theta_j} \left(\frac{o_j}{k_j} \right)^{-\nu_j}} \right)^{-1} \left\{ p_{j,t} + y_{j,t} + \frac{1}{1 + \frac{1}{\delta_{j,1} u_j^{\delta_{j,2}}}} z_{j,t} \right. \\ & + \left(\frac{\nu_j}{1 + \frac{1-\theta_j}{\theta_j} \left(\frac{o_j}{k_j} \right)^{-\nu_j}} - \nu_j - 1 \right) k_{j,t-1} - \left(\frac{1}{1 + \delta_{j,1} u_j^{\delta_{j,2}}} \right) \vartheta_{j,t} \\ & \left. + \left(\frac{\nu_j}{1 + \frac{\theta_j}{1-\theta_j} \left(\frac{o_j}{k_j} \right)^{\nu_j}} \right) \left(q_{j,t} + o_{j,t} \right) \right\} \end{aligned} \tag{A6}$$

$$\begin{aligned} o_{j,t} = {} & \left(\nu_j + 1 - \frac{\nu_j}{1 + \frac{\theta_j}{1-\theta_j} \left(\frac{o_j}{k_j} \right)^{\nu_j}} \right)^{-1} \left\{ p_{j,t} + y_{j,t} - p_{O,t} - \left(\nu_j - \frac{\nu_j}{1 + \frac{\theta_j}{1-\theta_j} \left(\frac{o_j}{k_j} \right)^{\nu_j}} \right) q_{j,t} \right. \\ & \left. + \left(\frac{\nu_j}{1 + \frac{1-\theta_j}{\theta_j} \left(\frac{o_j}{k_j} \right)^{-\nu_j}} \right) \left(u_{j,t} + k_{j,t-1} \right) \right\} \end{aligned} \tag{A7}$$

$$d_{E,t} = \mu \left(\gamma_t + p_t - p_{E,t} \right) + d_t \tag{A8}$$

$$p_t = \frac{m_t - d_t}{\phi} - \varpi_t \tag{A9}$$

$$m_{E,t} = \varrho \left(\varphi_t - p_{E,t}^F \right) + m_t \tag{A10}$$

$$x_t = \phi_F \left(\varpi_{F,t} - p_t \right) + d_{F,t} \tag{A11}$$

$$p_{E,t} = \varphi_{F,t} + p_t + \frac{x_t - x_{E,t}}{\varrho_F} \tag{A12}$$

$$y_{j,t} = a_{j,t} + \left(1 - \alpha_j \right) l_{j,t} + \frac{\alpha_j}{1 + \frac{1-\theta_j}{\theta_j} \left(\frac{o_j}{k_j} \right)^{-\nu_j}} \left(u_{j,t} + k_{j,t-1} \right) + \frac{\alpha_j}{1 + \frac{\theta_j}{1-\theta_j} \left(\frac{o_j}{k_j} \right)^{\nu_j}} \left(q_{j,t} + o_{j,t} \right) \tag{A13}$$

$$i_{j,t} = \frac{1}{\delta u_j} k_{j,t} - \frac{1 - \delta u_j}{\delta u_j} k_{j,t-1} + \frac{\delta_{j,1} u_j^{\delta_{j,2}}}{\delta u_j} u_{j,t} - z_{j,t} \tag{A14}$$

$$x_{E,t} = \frac{y_E}{x_E} y_{E,t} - \frac{d_E}{x_E} d_{E,t} + \frac{m_E}{x_E} m_{E,t} \tag{A15}$$

$$l_t = \frac{l_E}{l} l_{E,t} + \frac{l_N}{l} l_{N,t} \tag{A16}$$

$$i_t = \frac{i_E}{i} i_{E,t} + \frac{i_N}{i} i_{N,t} \tag{A17}$$

$$o_t = \frac{o_E}{o} o_{E,t} + \frac{o_N}{o} o_{N,t} \tag{A18}$$

$$y_t = \frac{y_E}{y} y_{E,t} + \frac{y_N}{y} y_{N,t} \tag{A19}$$

$$d_t = \frac{c}{d} c_t + \frac{i}{d} i_t + \frac{g}{d} g_t \tag{A20}$$

$$p_{N,t} = \frac{p_t - \lambda \left(\frac{p_E}{p}\right)^{1-\mu} \left(\mu \gamma_t + p_{E,t}\right)}{(1-\lambda)\left(\frac{p_N}{p}\right)^{1-\mu}} \tag{A21}$$

$$b_{F,t} = \left(1 + r_{F,t-1}\right) b_{F,t-1} + \frac{x}{y}(p_t + x_t) - \frac{m}{y} m_t - \frac{o}{y}\left(p_{O,t} + o_t\right) \tag{A22}$$

$$m_t = \frac{c}{m} c_t + \frac{i}{m} i_t + \frac{g}{m} g_t + \frac{x}{m} x_t - \frac{o}{m}\left(p_{O,t} + o_t\right) - \frac{y}{m} y_t \tag{A23}$$

B. Exogenous processes

This section: (i) elaborates on the steps for deriving the Wald statistic, (ii) clarifies the procedures used to extract model's error terms, showing explicitly their definitions based on model equilibrium conditions, and (iii) documents the results of the stationarity tests carried out for the twenty-two exogenous variables in Table B1.

B.1. Three steps for implementing the Wald statistic by bootstrapping

Step 1: Estimate the errors of the economic model conditional on the observed data and θ_0*.*

Estimate the structural errors, ε_t, of our two-sector open economy DSGE model, $x_t(\theta_0)$, given the observed data and stated values θ_0. The number of independent structural errors is taken to be less than or equal to the number of endogenous variables. We do not assume that the errors are normally distributed. For structural equations containing no expectation's operator, E_t, the structural errors are backed out directly from the equations and the data. With some equations that involve the calculation of expectations, we use the robust instrumental variables estimation of McCallum (1976) and Wickens (1982), [11] such that we set the lagged endogenous data as instruments and calculate the fitted values from a VAR(1)—this effectively implies that we use the auxiliary model VAR.

Step 2: Derive the simulated data.

Under the null hypothesis that the errors are omitted variables and the assumption that the above structural errors give their empirical distribution, the simulated disturbances are drawn from these errors. We also assume that the errors are generated by autoregressive processes rather than being serially independent. For this reason, we need to estimate them. The simulated data is obtained by randomly drawing the

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[11] See Section B.2 below for details on the particular errors for which we apply this method, which uses the model itself to project the expectations and since these depend on the extracted residuals, there is iteration between the two elements until convergence is attained. In practice, we estimate a VAR of all the expected variables, and we utilise these to obtain the expectations.

bootstrapped disturbances by time vector to preserve any simultaneity between them. The resulting model is solved using Dynare (Juillard, 2001). To obtain *N* bootstrapped simulations we repeat this, drawing each sample independently. We set $N = 1000$.

Step 3: Compute the Wald statistic.

Each of these *N* samples is used to estimate an auxiliary time series model, which we take to be a VAR(1)—that includes output and real exchange rate—to obtain an estimate of $a_S(\theta_0)$, and likewise, the same VAR(1) is then fitted to actual data to derive the estimate of a_T, for the vector α. The distribution of $a_T - \overline{a_S(\theta_0)}$ and its covariance matrix, $W(\theta_0)^{-1}$, are estimated by bootstrapping $a_S(\theta_0)$. The procedure for bootstrapping involves drawing *N* bootstrap samples of the structural model, and estimating the auxiliary VAR model on each, thereby obtaining *N* values of $a_S(\theta_0)$. We then obtain the covariance of the simulated variables directly from the bootstrap samples. The resulting set of a_k vectors ($k = 1, \ldots, N$) denotes the sampling variation implied by the structural model from which estimates of its mean, covariance matrix, and confidence bounds may be calculated directly. Hence, the estimate of the covariance matrix is given by:

$$W(\theta_0)^{-1} = \frac{1}{N}\sum_{k=1}^{N} (a_k - \overline{a_k})' (a_k - \overline{a_k}) \tag{B1}$$

where $\overline{a_k} = (1/N)\Sigma_{k=1}^{N} a_k$. Given this, we compute the Wald statistic for the data sample and estimate the bootstrap distribution of the Wald from the *N* bootstrap samples.

B.2. Solving for structural shocks

Shocks to government spending, world demand, foreign interest rates, oil price, and the price of imported energy-intensive goods are directly observed in the data. Based on the list of equilibrium equations provided in Section A above, we now state the expressions used to recover all the behavioural model shocks.

Labour supply:

$$\zeta_t = w_t - \omega l_t - \frac{\sigma}{1-\iota}(c_t - \iota c_{t-1}) \tag{B2}$$

Preference for aggregate imported goods:

$$\varpi_t = \frac{m_t - d_t}{\phi} - p_t \tag{B3}$$

Preference for aggregate exported goods:

$$\varpi_{F,t} = \frac{x_t - d_{F,t}}{\phi_F} + p_t \tag{B4}$$

Preference for energy-intensive goods:

$$\gamma_t = \frac{d_{E,t} - d_t}{\mu} - (p_t - p_{E,t}) \tag{B5}$$

Intertemporal preference:

$$\tau_t = \frac{\sigma(1+\iota)}{1-\iota}c_t - \frac{\sigma}{1-\iota}E_t c_{t+1} - \frac{\sigma\iota}{1-\iota}c_{t-1} + \beta rr_t \qquad (B6)$$

Preference for imported energy-intensive goods:

$$\varphi_t = \frac{m_{E,t} - m_t}{\varrho} + p_{E,t}^F \qquad (B7)$$

Preference for exported energy intensive goods:

$$\varphi_{F,t} = p_{E,t} - p_t - \frac{x_t - x_{E,t}}{\varrho_F} \qquad (B8)$$

Wage bill shifters:

$$\xi_{j,t} = (1+w)\left(p_{j,t} + y_{j,t} - l_{j,t}\right) - ww_t \qquad (B9)$$

Oil use efficiencies:

$$\begin{aligned} q_{j,t} = {} & \left(\nu_j - \frac{\nu_j}{1 + \frac{\theta_j}{1-\theta_j}\left(\frac{o_j}{k_j}\right)^{\nu_j}}\right)^{-1} \left\{ p_{j,t} + y_{j,t} - p_{O,t} - \left(\nu_j + 1 - \frac{\nu_j}{1 + \frac{\theta_j}{1-\theta_j}\left(\frac{o_j}{k_j}\right)^{\nu_j}}\right) o_{j,t} \right. \\ & \left. + \left(\frac{\nu_j}{1 + \frac{1-\theta_j}{\theta_j}\left(\frac{o_j}{k_j}\right)^{-\nu_j}}\right)\left(u_{j,t} + k_{j,t-1}\right) \right\} \end{aligned} \qquad (B10)$$

Sectoral productivities:

$$a_{j,t} = y_{j,t} - \left(1 - \alpha_j\right) l_{j,t} - \frac{\alpha_j}{1 + \frac{1-\theta_j}{\theta_j}\left(\frac{o_j}{k_j}\right)^{-\nu_j}}\left(u_{j,t} + k_{j,t-1}\right) - \frac{\alpha_j}{1 + \frac{\theta_j}{1-\theta_j}\left(\frac{o_j}{k_j}\right)^{\nu_j}}\left(q_{j,t} + o_{j,t}\right) \qquad (B11)$$

Investment technologies:

$$\begin{aligned} z_{j,t} = {} & \psi_j(1+\beta)k_{j,t} - \sigma/(1-\iota)(c_t - \iota c_{t-1}) + \sigma/(1-\iota)(E_t c_{t+1} - \iota c_t) + \tau_t \\ & - \beta\delta_{j,1} u_j^{\delta_{j,2}}(\delta_{j,2} - 1)E_t u_{j,t+1} - \psi_j\left(\beta E_t k_{j,t+1} + k_{j,t-1}\right) \end{aligned} \qquad (B12)$$

Capital cost shifters:

$$\begin{aligned} \vartheta_{j,t} = {} & \left(\frac{1}{1 + \delta_{j,1} u_j^{\delta_{j,2}}}\right)^{-1} \left\{ p_{j,t} + y_{j,t} + \left(\frac{\nu_j}{1 + \frac{1-\theta_j}{\theta_j}\left(\frac{o_j}{k_j}\right)^{-\nu_j}} - \nu_j - 1\right) k_{j,t-1} \right. \\ & + \frac{1}{1 + \frac{1}{\delta_{j,1} u_j^{\delta_{j,2}}}} z_{j,t} - \left(\frac{\delta_{j,2} - 1}{1 + \frac{1}{\delta_{j,1} u_j^{\delta_{j,2}}}} + \nu_j + 1 - \frac{\nu_j}{1 + \frac{1-\theta_j}{\theta_j}\left(\frac{o_j}{k_j}\right)^{-\nu_j}}\right) u_{j,t} \\ & \left. + \left(\frac{\nu_j}{1 + \frac{\theta_j}{1-\theta_j}\left(\frac{o_j}{k_j}\right)^{\nu_j}}\right)\left(q_{j,t} + o_{j,t}\right) \right\} \end{aligned} \qquad (B13)$$

Of the above expressions for calculating the model residuals, only B6 for intertemporal preference shock and B12 for investment technology shocks involve the calculation of expectations. More specifically, B6 includes expected consumption, $E_t c_{t+1}$, while B12 contains expected variable capital utilisation rate,

$E_t u_{j,t+1}$, and physical capital stock, $E_t k_{j,t+1}$. To obtain values of these three expected variables, we use the robust instrumental variables estimation method of McCallum (1976) and Wickens (1982), as discussed above.

B.3. Stationarity tests

We next document in Table B1 the results of the stationarity tests carried out for the twenty-two exogenous variables.

C. Data presentation

This section describes the US annual data used for estimation. The period covered is 1949 to 2013; we utilise thirty-four observable time series. The raw data was taken from a variety of sources, which, unless stated otherwise, are the U.S. Bureau of Economic Analysis (BEA), Bureau of Labor Statistics (BLS), Federal Reserve Economic Data (FRED), and Energy Information Administration (EIA). We note that all data is seasonally adjusted, in constant prices, per capita terms, and logged, except stated otherwise. The model and the estimating framework both necessitate compiling a dataset on aggregate measures for the single final output, consumption, investment, labour hours, oil use, exports, and imports. Further, we require observed time-series on the real exchange rate, wages, interest rates, and foreign bonds. Besides, we need empirical counterparts for sectoral capital stocks and capital utilisation rates. We note that, as in the model, aggregates of output, investment, labour hours and oil use are obtained as the sum of their respective sectoral values.

In general, we define data for energy-intensive sector as containing the following industries: agriculture, mining, utilities, construction, manufacturing and transportation. Wholesale and retail trade, information, finance, professional and business services, educational services, arts, and other non-government services make up the non-energy intensive sector. Practical issues faced in constructing the variables on the above-defined grounds imply the need to comment on some of our data definitions. To begin with, in measuring sectoral output, we split the output of the public sector into two due to the lack of sufficient disaggregation of government output and added half each to the summed value-added of the relevant industries for each of energy and non-energy intensive sectors.

For the investment series, we combined investment in private fixed assets, equipment, structures, and intellectual property products with the series for consumer durables (both of which are classified by type of product). Then, starting with the consumption of durable goods, we assign into investments that are non-energy intensive furnishings and durable household equipment, recreational goods and vehicles, and other durable goods. Investment in energy-intensive durable goods is given as the residual. Further, investment in energy-intensive goods is given by the sum of equipment and structures less residential equipment and improvements. We define investment in non-energy intensive type goods as the sum of residential equipment, improvements and intellectual property products.

Hours worked is obtained by following the procedure of Herrendorf et al. (2015), which involves combining GDP-by-Industry data reported using the North American Industry Classification System (NAICS) classification with the Income-and-Employment-by-Industry data reported with three different classifications over the sample period (the Standard Industrial Classification (SIC) from 1949 to 2000 (SIC72 for pre-1987 and SIC87 between 1987-2000) and NAICS since 2001). In particular, the former data representations follow the classification we would prefer, while the latter provides the industry-level information we require for assignment into energy- and non-energy intensive sectors.

Formally, the sectoral labour hours are computed using:

$$L_j = NAICS_{ft}^{HE} + \frac{NAICS_{ft}^{HE}}{NAICS_{ft}^{NE}} \times NAICS_{se} \tag{C1}$$

$$NAICS_{ft}^{HE} = SIC_{ft}^{HE} \times \frac{NAICS_{ft}^{NE}}{SIC_{ft}^{NE}} \tag{C2}$$

$$NAICS_{ft}^{NE} = SIC_{ft}^{NE} \times \frac{NAICS_{ftpt}^{NE}}{SIC_{ftpt}^{NE}} \tag{C3}$$

$$NAICS_{se} = SIC_{se} \times \frac{NAICS_{ftpt}^{NE}}{SIC_{ftpt}^{NE}} \tag{C4}$$

where *HE* = number of hours employed, *NE* = number of employees, *ft* = full-time, *se* = self-employed, and *ftpt* = full-time part-time.

We take the total energy consumption in the economy to be the aggregate consumption of primary energy. That is, the consumption of fossil fuels comprising of petroleum, coal, and natural gas (measured in trillions of British thermal units (BTUs)) in the private sector, excluding the electric power sector. We collectively refer to these fossil fuels as oil. We do not, however, include the consumption of renewables (geothermal, solar/PV, and biomass) and electricity for both theory and data reasons. On the data, if one chooses to use, for instance, total primary energy consumption data, there is no data for biomass consumption until 1981. Also, we excluded the electric power generating sector, which would have been classed as a highly energy-intensive sector, given that close to 70% of all primary energy is used or lost as this sector provides electricity to the final consumers. We have, however, not included it because we have not modelled an energy-producing sector, which would have to be the case if we had incorporated electricity into our total for energy consumption.

Table B1**:** Stationarity tests for the shocks

	ADF			PP			KPSS			
	Levels	With trend	First difference	Levels	With trend	First difference	Levels	With trend	First diffe-rence	Conclusion
Energy-intensive sector productivity	-1.48 (0.54)	-2.04 (0.57)	-6.86 (0.00)	-1.48 (0.54)	-1.99 (0.60)	-6.80 (0.00)	0.834	0.138	0.166	Non-stationary
Non-energy intensive sector productivity	-2.48 (0.13)	-3.07 (0.12)	-6.77 (0.00)	-3.09 (0.03)	-2.97 (0.15)	-9.35 (0.00)	0.951	0.172	0.450	Non-stationary
World demand	-2.13 (0.23)	-2.67 (0.25)	-7.66 (0.00)	-2.16 (0.22)	-2.66 (0.26)	-7.66 (0.00)	0.946	0.148	0.230	Non-stationary
Preference for imported energy-intensive goods	-0.42 (0.90)	-1.57 (0.79)	-6.20 (0.00)	-0.64 (0.85)	-1.45 (0.84)	-6.42 (0.00)	0.870	0.155	0.154	Non-stationary
Preference for exported energy-intensive goods	-0.51 (0.88)	-2.05 (0.57)	-8.04 (0.00)	-0.47 (0.89)	-2.08 (0.55)	-8.07 (0.00)	0.961	0.154	0.085	Non-stationary
Preference for energy-intensive goods	0.11 (0.96)	-1.95 (0.62)	-7.25 (0.00)	0.08 (0.96)	-1.95 (0.62)	-7.25 (0.00)	0.989	0.173	0.174	Non-stationary
Government spending	-1.22 (0.66)	-1.35 (0.87)	-6.30 (0.00)	-3.30 (0.02)	-2.75 (0.22)	-6.30 (0.00)	0.973	0.168	0.466	Non-stationary
Labour supply	-2.07 (0.26)	-2.04 (0.57)	-7.71 (0.00)	-2.02 (0.28)	-2.00 (0.59)	-7.84 (0.00)	0.158	0.170	0.112	Stationary
Energy-intensive sector energy efficiency	-1.86 (0.35)	-1.86 (0.66)	-7.98 (0.00)	-1.86 (0.35)	-1.89 (0.65)	-8.01 (0.00)	0.091	0.093	0.156	Stationary
Non-energy intensive sector energy efficiency	-1.92 (0.32)	-1.76 (0.71)	-7.55 (0.00)	-1.97 (0.30)	-1.78 (0.71)	-7.55 (0.00)	0.444	0.090	0.120	Stationary
Price of imported energy-intensive goods	-0.93 (0.77)	-1.43 (0.84)	-4.92 (0.00)	-0.66 (0.85)	-1.44 (0.84)	-4.93 (0.00)	0.879	0.152	0.146	Non-stationary
Oil price	-0.99 (0.75)	-1.84 (0.67)	-7.74 (0.00)	-1.03 (0.74)	-1.86 (0.67)	-7.74 (0.00)	0.475	0.079	0.115	Non-stationary
Foreign interest rate	-1.47 (0.54)	-1.91 (0.64)	-5.58 (0.00)	-0.84 (0.80)	-1.17 (0.91)	-5.29 (0.00)	0.328	0.247	0.465	Stationary
Intertemporal preference	-2.27 (0.19)	-2.14 (0.51)	-8.95 (0.00)	-2.05 (0.27)	-1.85 (0.67)	-9.53 (0.00)	0.256	0.252	0.353	Stationary
Energy-intensive sector capital cost shifter	-0.10 (0.95)	-2.03 (0.58)	-7.63 (0.00)	-0.15 (0.94)	-2.19 (0.49)	-7.66 (0.00)	0.914	0.115	0.140	Trend stationary
Non-energy intensive sector capital cost shifter	-1.27 (0.64)	-3.67 (0.03)	-6.55 (0.00)	-1.25 (0.65)	-3.67 (0.03)	-13.6 (0.00)	0.994	0.130	0.337	Trend stationary
Preference for aggregate imported goods	-0.53 (0.88)	-1.37 (0.86)	-7.58 (0.00)	-0.53 (0.88)	-1.50 (0.82)	-7.58 (0.00)	0.971	0.119	0.155	Trend stationary
Preference for aggregate exported goods	-0.40 (0.90)	-2.64 (0.26)	-6.35 (0.00)	-0.48 (0.89)	-1.99 (0.60)	-6.37 (0.00)	0.808	0.116	0.184	Trend stationary
Energy-intensive sector wage bill shifter	-0.50 (0.88)	-1.69 (0.74)	-3.80 (0.01)	-0.56 (0.87)	-1.58 (0.79)	-6.90 (0.00)	0.964	0.164	0.113	Non-stationary
Non-energy intensive sector wage bill shifter	-2.03 (0.28)	-0.15 (0.99)	-6.77 (0.00)	-1.84 (0.36)	-0.30 (0.99)	-6.54 (0.00)	0.998	0.207	0.435	Non-stationary
Energy-intensive investment-specific technology	-5.67 (0.00)	-5.62 (0.00)	-9.68 (0.00)	-5.34 (0.00)	-5.26 (0.00)	-23.6 (0.00)	0.052	0.036	0.318	Stationary
Non-energy intensive investment-specific technology	-5.61 (0.00)	-5.55 (0.00)	-9.57 (0.00)	-5.26 (0.00)	-5.17 (0.00)	-23.7 (0.00)	0.043	0.036	0.339	Stationary

Hence, aggregate energy consumption in the US is formally given by the dollar value of total primary energy use:

$$\text{VTOU} = P_{O,t} \times \frac{O_t \times 1 \text{ trillion} \div \aleph \times 1 \text{ million}}{1 \text{ billion}} \qquad (C5)$$

where $\aleph = 5.78$ represents the conversion factor for relating BTUs to barrels of oil.

Oil consumption is provided for four end-use sectors: namely, the industrial, transportation, residential and commercial sectors. Given a lack of further disaggregation, we use the primary energy consumption in both the industrial and transportation sectors as a proxy for energy use in the energy-intensive sector, and primary energy consumption in both the residential and commercial sectors as a proxy for energy use in the non-energy intensive sector. Prices of energy- and non-energy intensive goods are derived based on chain-type price indexes for value-added by industry. For the price of energy-intensive goods, we use the weighted average from agriculture, mining, utilities, construction, manufacturing, and transportation. We utilise the weighted average from wholesale and retail trade, information, finance, professional and business services, educational services, arts and other non-government services for the price of non-energy intensive goods.

Following the constructions of energy-intensive and non-energy intensive investment goods above, we construct the sectoral physical capital stocks. The energy-intensive sector capital stock is the sum of nonresidential equipment and structures. The physical capital stock of the non-energy intensive sector is obtained as the sum of residential equipment and structures, and intellectual property products. Further, non-energy intensive type capital stock is taken as the sum of furnishings and durable household equipment, recreational goods and vehicles, and other durable goods, such that capital stock in the energy intensive type consumption durable goods is given by motor vehicles and parts. For the energy-intensive sector capital utilisation rate, we use capacity utilisation rate for total manufacturing industry. Meanwhile, capacity utilisation rate for motor vehicles and parts is used to proxy capital utilisation rate in the non-energy intensive sector.

For wages, we use the real index of hourly compensation. Interest rate is the three-month Treasury bill rate for 1949-1954 (Smets and Wouters, 2007), where we have converted their quarterly data into annual data by averaging, and we use the federal funds rate for 1955-2013. The real exchange rate is US CPI for all urban consumers relative to RoW CPI. Foreign bonds are taken to be the ratio of nominal net foreign assets (total assets minus total liabilities) to nominal GDP. Consumption is measured using personal consumption expenditures, less durable goods.

Additionally, five exogenous stochastic variables are observed. Government consumption spending is defined as government consumption expenditures and gross investment. Oil price is the domestic first purchase price of crude oil divided by US CPI. Foreign interest rate is calculated as the weighted average of the interest rate for the G7 countries, excluding the US. World demand is measured as world trade less

US imports. Finally, the price of imported energy-intensive goods is taken to be the price of US imported manufactures from the ROW.

D. Auxiliary model

As our data is non-stationary, we use as the auxiliary model a vector error correction model (VECM). The VECM is reexpressed as a VARX(1) for the macroeconomic variables of interest with a time trend and with some residuals entered as exogenous non-stationary processes (these two elements help to achieve cointegration). Expressed more formally, our approach permits the following association for a log-linearised DSGE model:

$$A(L)\widetilde{w}_t = BE_t\widetilde{w}_{t+1} + C(L)x_t + D(L)e_t \tag{D1}$$

where $Ee_t = 0$, $Ee_te_t' = I$ for all *t*, $\widetilde{w}_t$ is a vector *p* endogenous variables, $E_t\widetilde{w}_{t+1}$ is a vector *q* expected future endogenous variables, and x_t is a vector *r* exogenous variables, which we assume to be driven by:

$$\Delta x_t = a(L)\Delta x_{t-1} + d + c(L)\varepsilon_t \tag{D2}$$

where $E\varepsilon_t = 0$, $E\varepsilon_t\varepsilon_t' = I$ for all *t*. In the above, both the endogenous and exogenous variables are non-stationary. It follows that the general solution to $\widetilde{w}_t$ is of the form:

$$\widetilde{w}_t = G(L)\,\widetilde{w}_{t-1} + H(L)\,x_t + f + M(L)\,e_t + N(L)\varepsilon_t \tag{D3}$$

where for the vector of constants $ð = \{A, B, C, D, a, c, G, H, M, N\}$, $ð(L)$ are polynomial functions with roots outside the unit circle and L denotes the lag operator $\tilde{z}_{t-s} = L^s\tilde{z}_t$. Given that the endogenous and exogenous variables are non-stationary, the above solution has *p* cointegrating relations:

$$\widetilde{w}_t = [I - G(1)]^{-1}[H(1)\,x_t + f] = \prod x_t + g \tag{D4}$$

The short-run solution to this model is:

$$\widetilde{w}_t - \prod x_t - g = \eta_t \tag{D5}$$

which is the error correction term.

In the long-run, however, the solution to the model becomes:

$$\overline{w}_t = \prod \overline{x}_t + g \tag{D6}$$

$$\overline{x}_t = [1 - a(1)]^{-1}[dt + c(1)\xi_t] \tag{D7}$$

$$\xi_t = \textstyle\sum_{i=0}^{t-1}\varepsilon_{t-s} \tag{D8}$$

To summarise, the long-run solution to x_t consists of two parts: a deterministic trend $\overline{x}_t^D = [1 - a(1)]^{-1}dt$ and a stochastic trend $\overline{x}_t^S = [1 - a(1)]^{-1}c(1)\xi_t$. Crucially, the behaviour of the endogenous variables depends on both parts in the long-run.

Moreover, the relation for $\widetilde{w}_t$ above allows the solution to our estimated DSGE model to be written as a VECM:

$$\Delta\widetilde{w}_t = -[I - G(1)](\widetilde{w}_{t-1} - \prod x_{t-1}) + P(L)\Delta\widetilde{w}_{t-1} + Q(L)\Delta x_t + f + \Phi_t \tag{D9}$$

where the disturbance is $\Phi_t = M(L)e_t + N(L)\varepsilon_t$, which is assumed to be a mixed moving average process.

We can, therefore, use a VARX to approximate the above VECM expression as:

$$\Delta\tilde{w}_t = \mathcal{F}[\tilde{w}_{t-1} - \prod x_{t-1}] + R(L)\Delta\tilde{w}_{t-1} + S(L)\Delta x_t + g + \Theta_t \qquad (D10)$$

and since:

$$\overline{x}_t = \overline{x}_{t-1} + [1 - a(1)]^{-1}[d + \varepsilon_t] \qquad (D11)$$

the VECM can equivalently be written as:

$$\Delta\tilde{w}_t = \mathcal{F}[(\tilde{w}_{t-1} - \overline{w}_{t-1}) - \prod(x_{t-1} - \overline{x}_{t-1})] + R(L)\Delta\tilde{w}_{t-1} + S(L)\Delta x_t + h + \Theta_t \qquad (D12)$$

where $E\Theta_t = 0$, $E\Theta_t\Theta_t' = I$ for all t. By rearranging equation (*D12*), we obtain the VARX(1) form of the auxiliary model employed during estimation; this is given as equation (20) in the paper. Doing this allows us to separate the trend component of x from the temporary deviation from its trend.

E. Simulated annealing

To calculate the minimum-value Wald statistic, we use a simulated annealing algorithm, in which a search takes place over a wide range around some initial values within some bounded parameter space (Ingber 1996). This algorithm mimics the behaviour of the steel cooling process; in which steel is cooled, with a degree of reheating at randomly chosen moments in the cooling process, thereby ensuring that the defects are minimised globally. Similarly, the algorithm searches in the chosen range and as points that improve the objective are found, it also accepts points that do not improve the objective. This helps to stop the algorithm being caught in local minima. Our approach takes a set of model parameters (excluding error processes), extracts the resulting residuals from the data using the LIML method, finds their implied autoregressive coefficients and then bootstraps the implied innovations with this full set of parameters to find the implied Wald value. The simulated annealing algorithm then works to minimise this, which in effect, is the indirect inference estimation of the model. However, this estimation is being made to find out whether the model can be rejected in itself and not for the sake of finding the most satisfactory estimates of the model parameters. Nevertheless, the method does this latter task as a by-product so that we can use the resulting unrejected model as representing the best available estimated version. The merit of this extended procedure is that we are comparing the best possible versions of each model type when finally making our comparison of model compatibility with the data.

F. Parameterisation

In Table F1, we document the values chosen as the starting values for the parameters that we estimate. They are obtained based either on the existing literature or by targeting the steady state values/ratios of US historical time-series reported in Table F2.

Table F1: Initial parameter values used to initiate the simulated annealing algorithm

	Notation	Value
Frisch elasticity of labour supply	ω	5
Elasticity of substitution in consumption	σ	2
Elasticity of substitution between K_E and O_E	ν_E	0.7
Elasticity of substitution between K_N and O_N	ν_N	0.7
Elasticity of output to labour hours plus 1 in the energy-intensive sector	α_E	0.43
Elasticity of output to labour hours plus 1 in the non-energy intensive sector	α_N	0.28
Habit formation in consumption	ι	0.7
Marginal cost of capital utilisation in the energy-intensive sector	δ_E	0.132
Marginal cost of capital utilisation in the non-energy intensive sector	δ_N	0.102
Elasticity of capital utilisation rate in the energy-intensive sector	$\delta_{E,2}$	1.463
Elasticity of capital utilisation rate in the non-energy intensive sector	$\delta_{N,2}$	1.694
Adjustment cost parameter for capital in the energy-intensive sector	ψ_E	0.001
Adjustment cost parameter for capital in the non-energy intensive sector	ψ_N	0.001
Adjustment cost parameter for foreign bonds	ψ_F	0.001
Elasticity of substitution between D_H and M	ϕ	1.5
Elasticity of substitution between D_F and X	ϕ_F	1.5
Elasticity of substitution between M_E and M_N	ϱ	0.44
Elasticity of substitution between X_E and X_N	ϱ_F	0.44
Elasticity of substitution between D_E and D_N	μ	0.99
Bias parameter for energy-intensive goods	λ	0.55

Table F2: Fixed parameter values and steady state values/ratios of observed time-series

	Notation	Value
Discount factor	β	0.96
Marginal cost of capital utilisation in the energy-intensive sector	δu_E	0.09
Marginal cost of capital utilisation in the non-energy intensive sector	δu_N	0.06
Price of crude oil	p_O	1
Oil-capital ratio in the energy-intensive sector	o_E/k_E	0.011
Oil-capital ratio in the non-energy intensive sector	o_N/k_N	0.014
Investment-capital ratio in the energy-intensive sector	i_E/k_E	0.08
Investment-capital ratio in the non-energy intensive sector	i_N/k_N	0.17
Share of investment in the energy-intensive sector to aggregate investment	i_E/i	0.7
Share of investment in the non-energy intensive sector to aggregate investment	i_N/i	0.3
Share of labour hours in the energy-intensive sector to aggregate labour hours	h_E/h	0.4
Share of labour hours in the non-energy intensive sector to aggregate labour hours	h_N/h	0.6
Share of oil use in the energy-intensive sector to aggregate oil use	o_E/o	0.78
Share of oil use in the non-energy intensive sector to aggregate oil use	o_N/o	0.22
Ratio of energy-intensive output to total output	y_E/y	0.41
Ratio of non-energy intensive output to total output	y_N/y	0.59
Share of government consumption spending in domestic absorption	g/d	0.21
Share of investment in domestic absorption	i/d	0.3
Share of consumption in domestic absorption	c/d	0.49
Ratio of domestic absorption to output in the energy-intensive sector	d_E/y_E	1.385
Ratio of exports to output in energy-intensive sector	x_E/y_E	0.1573
Ratio of imports to output in energy-intensive sector	m_E/y_E	0.205
Ratio of absorption of energy-intensive goods to total domestic absorption	d_E/d	0.37
Share of investment to total output	i/y	0.308
Share of government consumption spending in total output	g/y	0.215
Share of oil use in total output	o/y	0.037
Share of exports in total output	x/y	0.08
Share of imports in total output	m/y	0.092
Share of private consumption in total output	c/y	0.268
Domestic bonds	b	0.023
Price of imported goods	p_M	1
Interest rate	r	0.04
Wages	w	1

G. Variance decomposition for sectoral variables

Table G1: Variance decomposition for the sectoral variables

	Productivity shocks	Mark-up shocks	Demand shocks	Global shocks
Energy-intensive sector				
Output	17.97	18.49	25.05	38.49
Investment	13.33	7.69	25.32	53.66
Exports	11	7.61	11.42	69.97
Imports	10.53	3.54	13.78	72.15
Labour hours	17.81	19.13	26.83	36.23
Price (energy intensive goods)	19.71	20.92	23.15	36.22
Oil use	32.65	3	4.92	59.43
Domestic aborption	17.66	18.09	25.7	38.55
Capital	17.11	17.34	25.84	39.71
Capital utilisation rate	16.48	16.06	24.72	42.74
Non-energy intensive sector				
Output	18.2	18.93	25.77	37.1
Investment	6.98	3.84	30.25	58.93
Labour hours	18.02	19	27	35.98
Oil use	43.43	1.59	3.71	51.27
Price (non-energy intensive goods)	22.02	17.2	23.35	37.43
Capital	17.59	17.28	26.75	38.38
Capital utilisation rate	17.09	17.27	26.33	39.31

Note: Productivity shocks: productivity in the energy-intensive sector, productivity in the non-energy intensive sector, oil use efficiency in the energy-intensive sector, and oil use efficiency in the non-energy intensive sector; mark-up shocks: wage bill shifter in the energy-intensive sector, wage bill shifter in the non-energy intensive sector, capital cost shifter in the energy-intensive sector, and capital cost shifter in the non-energy intensive sector; demand shocks: intertemporal preference, labour supply, investment technology in the energy-intensive sector, investment technology in the non-energy intensive sector, government spending, preference for energy-intensive goods, preference for imported energy-intensive goods, and preference for aggregate imported goods; global shocks: world demand, preference for aggregate exported goods, preference for exported energy-intensive goods, foreign interest rate, oil price, and price of imported energy-intensive goods.

H. Results from fixing the Frisch elasticity of labour supply

Table H1: Indirect inference estimates of structural parameters with Frisch elasticity of labour supply fixed

	Notation	Value				
Firms						
Elasticity of substitution between K_E and O_E	ν_E	0.1531	0.1840	1.1373	0.8477	0.6573
Elasticity of substitution between K_N and O_N	ν_N	0.1417	0.1832	0.2808	0.2220	0.5176
Elasticity of output to labour hours plus 1 in the energy-intensive sector	α_E	0.5970	0.2106	0.3471	0.2000	0.2340
Elasticity of output to labour hours plus 1 in the non-energy intensive sector	α_N	0.2000	0.5950	0.2000	0.3540	0.2159
Households						
Frisch elasticity of labour supply (**fixed**)	ω	**1**	**2**	**3**	**4**	**5**
Elasticity of substitution in consumption	σ	3.5988	1.4797	1.6338	2.0375	4.5900
Habit formation in consumption	ι	0.0041	0.0266	0.2426	0.0940	0.0250
Marginal cost of capital utilisation in the energy-intensive sector	δ_E	0.0297	0.0274	0.0573	0.0802	0.1786
Marginal cost of capital utilisation in the non-energy intensive sector	δ_N	0.0225	0.0268	0.1434	0.0548	0.2850
Elasticity of capital utilisation rate in the energy-intensive sector	$\delta_{E,2}$	2.6314	0.2951	0.3394	1.2566	1.3179
Elasticity of capital utilisation rate in the non-energy intensive sector	$\delta_{N,2}$	0.9685	2.9446	1.1145	2.4340	2.2138
Adjustment cost parameter for capital in the energy-intensive sector	ψ_E	0.0018	0.0017	0.0004	0.0005	0.0014
Adjustment cost parameter for capital in the non-energy intensive sector	ψ_N	0.0018	0.0002	0.0006	0.0008	0.0030
Adjustment cost parameter for foreign bonds	ψ_F	0.0002	0.0002	0.0008	0.0001	0.0001
Traders						
Elasticity of substitution between D_H and M	ϕ	2.6548	0.3252	0.6179	0.4431	1.5700
Elasticity of substitution between D_F and X	ϕ_F	0.6942	0.3104	1.1861	0.3006	0.9487
Elasticity of substitution between M_E and M_N	ϱ	0.0996	0.0977	0.4551	0.3697	0.1684
Elasticity of substitution between X_E and X_N	ϱ_F	0.7888	0.7711	0.1916	0.1232	0.0287
Elasticity of substitution between D_E and D_N	μ	0.6668	0.2237	1.5892	1.4412	2.6981
Bias parameter for energy-intensive goods	λ	0.0049	0.0277	0.0010	0.5223	0.0565

Table H2: Variance decomposition for the aggregate variables for $\omega = 5$

	Domestic shocks			
	Productivity shocks	Mark-up shocks	Demand shocks	Global shocks
Output	2.68	73.89	11.01	12.42
Consumption	9.93	79.85	9.21	1.01
Investment	2.87	75.25	10.96	10.92
Exports	3.17	79.23	12.12	5.48
Imports	2.83	73.16	10.57	13.44
Labour hours	3.24	74.24	11.15	11.37
Price (real exchange rate)	2.87	71.70	10.96	14.46
Wages	2.62	69.77	11.26	16.35
Interest rate	2.91	75.57	11.25	10.27
Oil use	2.76	74.65	10.70	11.89
Domestic absorption	2.75	74.33	10.99	11.94
Foreign bonds	2.89	75.84	10.97	10.30

Note: Productivity shocks: productivity in the energy-intensive sector, productivity in the non-energy intensive sector, oil use efficiency in the energy-intensive sector, and oil use efficiency in the non-energy intensive sector; mark-up shocks: wage bill shifter in the energy-intensive sector, wage bill shifter in the non-energy intensive sector, capital cost shifter in the energy-intensive sector, and capital cost shifter in the non-energy intensive sector; demand shocks: intertemporal preference, labour supply, investment technology in the energy-intensive sector, investment technology in the non-energy intensive sector, government spending, preference for energy-intensive goods, preference for imported energy-intensive goods, and preference for aggregate imported goods; global shocks: world demand, preference for aggregate exported goods, preference for exported energy-intensive goods, foreign interest rate, oil price, and price of imported energy-intensive goods.

Table H3: Variance decomposition for the aggregate variables for $\omega = 4$

	Domestic shocks			
	Productivity shocks	Mark-up shocks	Demand shocks	Global shocks
Output	0.62	0.76	0.62	98.00
Consumption	15.27	17.05	15.28	52.40
Investment	2.86	1.93	0.74	94.48
Exports	0.76	1.86	0.04	97.34
Imports	1.33	4.09	0.45	94.13
Labour hours	11.53	18.04	0.40	70.03
Price (real exchange rate)	7.75	18.89	0.41	72.95
Wages	0.91	21.24	3.33	74.51
Interest rate	31.16	1.82	2.80	64.22
Oil use	3.20	1.50	1.39	93.91
Domestic absorption	0.46	0.79	0.40	98.34
Foreign bonds	16.76	2.53	4.23	76.47

Note: Productivity shocks: productivity in the energy-intensive sector, productivity in the non-energy intensive sector, oil use efficiency in the energy-intensive sector, and oil use efficiency in the non-energy intensive sector; mark-up shocks: wage bill shifter in the energy-intensive sector, wage bill shifter in the non-energy intensive sector, capital cost shifter in the energy-intensive sector, and capital cost shifter in the non-energy intensive sector; demand shocks: intertemporal preference, labour supply, investment technology in the energy-intensive sector, investment technology in the non-energy intensive sector, government spending, preference for energy-intensive goods, preference for imported energy-intensive goods, and preference for aggregate imported goods; global shocks: world demand, preference for aggregate exported goods, preference for exported energy-intensive goods, foreign interest rate, oil price, and price of imported energy-intensive goods.

Table H4: Variance decomposition for the aggregate variables for $\omega = 3$

	Domestic shocks			
	Productivity shocks	Mark-up shocks	Demand shocks	Global shocks
Output	4.63	29.20	0.19	65.99
Consumption	8.81	78.49	3.73	8.97
Investment	0.46	8.57	2.58	88.40
Exports	4.02	17.03	1.31	77.64
Imports	0.21	2.10	0.70	97.00
Labour hours	2.24	51.60	0.68	45.48
Price (real exchange rate)	4.91	20.81	1.60	72.68
Wages	1.67	70.60	0.63	27.09
Interest rate	3.42	42.06	6.68	47.83
Oil use	1.04	12.53	2.16	84.28
Domestic absorption	3.26	19.94	0.15	76.65
Foreign bonds	4.67	29.29	6.21	59.83

Note: Productivity shocks: productivity in the energy-intensive sector, productivity in the non-energy intensive sector, oil use efficiency in the energy-intensive sector, and oil use efficiency in the non-energy intensive sector; mark-up shocks: wage bill shifter in the energy-intensive sector, wage bill shifter in the non-energy intensive sector, capital cost shifter in the energy-intensive sector, and capital cost shifter in the non-energy intensive sector; demand shocks: intertemporal preference, labour supply, investment technology in the energy-intensive sector, investment technology in the non-energy intensive sector, government spending, preference for energy-intensive goods, preference for imported energy-intensive goods, and preference for aggregate imported goods; global shocks: world demand, preference for aggregate exported goods, preference for exported energy-intensive goods, foreign interest rate, oil price, and price of imported energy-intensive goods.

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