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# Oil Prices and the Dynamics of Output and Real Exchange Rate\*

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We examine the role of oil price shocks in effecting changes both at the aggregate and sectoral levels using an estimated dynamic stochastic equilibrium open economy model. Our main finding is that energy price shocks are not able directly to generate the magnitude of the economic downturn observed in the data. These shocks, however, do possess a strong indirect transmission link that endogenously spreads their effect through the system such that they account for a considerable portion of the U.S. business cycle movements. This leads us to conclude that previous results that attribute a minimal importance to oil price shocks must be focusing more on the energy cost share of gross domestic product and less on how they affect the intertemporal decisions of economic agents. We also find that external shocks have been responsible for explaining volatility in U.S. economic activities for a long time. This leads us to conclude that modelling the U.S. as a closed economy discounts a sizeable set of very relevant factors.

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Keywords: Two sector, non-stationary DSGE model, Oil price, Relative prices, Domestic shocks, Imported shocks.

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# I INTRODUCTION

Changes in oil prices are mostly unanticipated and are exogenous *world* events with several macroeconomic implications for many countries, developed and developing. The purpose of this study is to investigate how these occasional movements, in particular positive percentage changes, in the price of oil go on to affect the output and competitiveness (as measured by real exchange rate) of a typical oil-importing industrialised country against the rest of the world. We take the U.S. as our example domestic country for this exercise. To put this into perspective, we display in Figure I the historical data on U.S. output (1929-2013) and its trend, identified by using the Hodrick-Prescott (1997) filter in row 1, the oil price-output (1949-2013) relationship in row 2, the oil price-real exchange rate (1949-2013) relationship in row 3, and the output-real exchange rate (1949-2013) relationship in row 4.

Row 1 illustrates two of the measures by which we can represent economic downturns. First, is when outputs in consecutive periods are below the HP trend and the second is just by observing the coincidence between output drops and the shaded bars, which are the National Bureau of Economic Research (NBER) identified recession dates. The time paths of the oil price and output in row 2 show that they often travel in opposite directions, especially during periods of radical upswings in prices (i.e., oil price shocks). Clearly, however, output is a lot less volatile than oil price. Oil price leads to real exchange rate changes in row 3, but the overall picture is that they move in the same direction. The reason for this is that higher oil prices get transmitted into the consumer price index in the domestic country such that using the ratio of export price to import price as a measure of the real exchange rate implies that oil price and real exchange rate are positively correlated. The last row shows that real exchange rate appears to also follow output with roughly 2-3 lags.

So, in the current paper, we add to the significantly growing body of literature that is debating if energy price shocks still matter.<sup>1</sup> We address this issue by building on the seminal works of Kydland and Prescott (1982) and Long and Plosser (1983), which have been extended in several ways with the closest in spirit to what we are studying here being the pioneering works of Kim and Loungani (1992) and Finn (1991). In particular, we combine the Kim and Loungani model with the multi-sector approach of Long and Plosser in order to investigate the impacts of changes in the exogenous price of a factor input - the real price of oil - in influencing the U.S. business cycles and competitiveness vis-à-vis the rest of the world. Our model has the following important features: (1) production takes place in two sectors with energy explicitly included as an input; (2) there is trade in goods and services, and financial

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1. The background to this work encompasses many strands of the macroeconomic literature. An interested reader can consult Asafu-Adjaye (2000), Berndt and Wood (1975, 1979), Burbidge and Harrison (1984), Cavallo and Wu (2006), Darby (1982), De Gregorio et al. (2007), Eldestein and Kilian (2007), Griffin and Gregory (1976), Hamilton (1983, 1985, 2003, 2011), Herrera and Hamilton (2001), Herrera and Pesavento (2007), Hooker (1996, 1997, 2002), Kilian (2008a, 2008b) and Mork (1989), among others for empirical discussions; Blanchard and Gali (2007), Darby (1981), Dhawan and Jeske (2006, 2008), Dhawan et al. (2010), Finn (1991, 1995, 1996, 2000), Gillingham et al. (2009), Kim and Loungani (1992), Loungani (1986), Rotemberg and Woodford (1996), Schmidt and Zimmermann (2007), among others for theoretical underpinnings; and, for policy related papers, see, for example, Barsky and Kilian (2002), Bernanke et al. (1997), Blanchard and Simon (2001), Chakravorty et al. (1997), Leduc and Sill (2004, 2007) and Stock and Watson (2003).

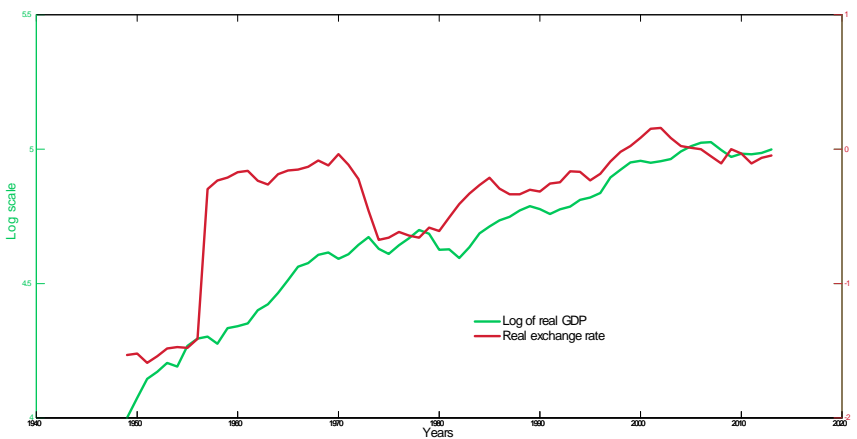
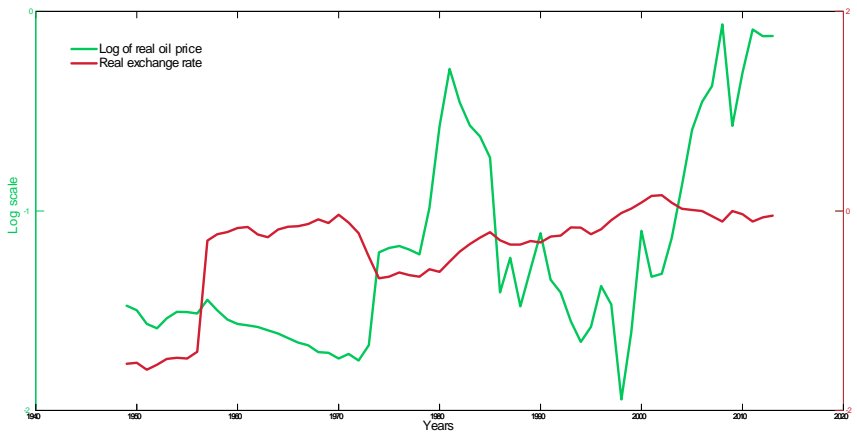
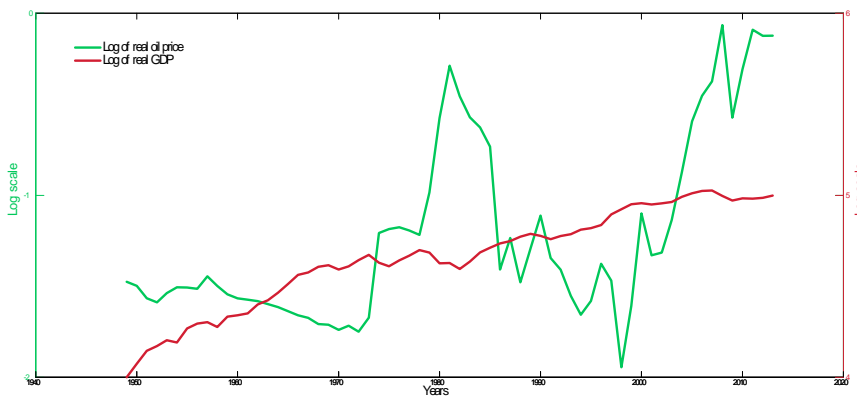
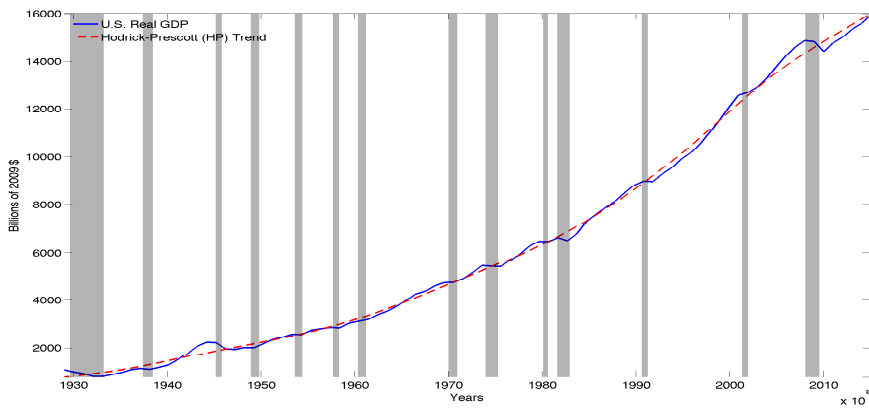


FIGURE I: OUTPUT, OIL PRICE, AND REAL EXCHANGE RATE. U.S. DATA 1929-2013

assets across countries; (3) the model is augmented with an array of real rigidities and is driven by a number of exogenous shocks; and (4) the model is estimated based on unfiltered data from the U.S. covering the period 1949-2013 on an annual frequency using the formal econometric method of indirect inference.

One useful contribution of this study is that the two-sector energy and non-energy model spelt out in the next section is, to our best knowledge, a new and, as we will see in the discussion of the results, an important set-up. The discussion above, however, also implies that it is a model that has been estimated based on non-stationary data. In reality, most macroeconomic variables are non-stationary, implying that we may be removing critical information when we filter them.<sup>2</sup> It is useful whenever technically permissible, therefore, to develop a model that can be used to describe unfiltered data. This is a major and novel contribution of this paper and, in doing this, we have responded to the call by Kim and Loungani (1992) that "... it may be fruitful, in future research, to develop versions of our model which can accommodate nonstationarity in the price process."

Our main finding is that energy price shocks are not able to directly generate the magnitude of the economic downturn observed in the data. These shocks, however, do possess a strong indirect transmission link that endogenously spreads their effect harshly through the system. This leads us to conclude that previous results that attribute a minimal importance to oil price shocks must be focusing on the energy cost share of gross domestic product. We also find that external shocks have been responsible for explaining volatility in U.S. economic activities for a long time. This leads us to conclude that modelling the U.S. as a closed economy discounts a sizeable set of very relevant factors.

The remainder of this paper proceeds as follows. In Section II, we describe the main features of the two-sector model. In Section III, we provide brief discussions of the model parameter values used to initialise the starting points for the Simulated Annealing (SA) algorithm, the econometric method of indirect inference (II) used in estimating the model, and the non-stationary data serving as the empirical counterparts to the model variables. The section concludes by reporting the results from the estimation. The main findings are discussed in Section IV, where we examine in greater depth the results from the estimated model, with the discourse including a theoretical analysis of the model's implications highlighting the transmission mechanism of the energy price shocks both at the aggregate and sectoral levels, and where we also show quantitatively how the model can replicate economic cycles.

## II THE MODEL

There are four agents in this model: a consumer, a producer per sector indexed by  $j = e, n$ , a trader, and a distributor.<sup>3</sup> We begin with the characterisation of aggregate choices in which

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2. See King and Rebelo (1993), Cochrane (1994), Cogley and Nason (1995), Canova (1998), Stock and Watson (1999), and the references in them, for a review of filtering methods and the strengths and weaknesses associated with each.

3. In sum, apart from the activities of the government, we have designed the model such that every decision in the economy is made by or on behalf of the stand-in consumer. Thus, consumers and traders may be used

the stand-in consumer chooses consumption of goods,  $C_t$ , and labour hours,  $H_t$ , in order to maximise the utility function:

$$\mathbb{E}_0 \sum_{t=0}^{\infty} \beta^t \tau_t U \left( \frac{(C_t - \iota C_{t-1})^{1-\epsilon}}{1-\epsilon} - \zeta_t \frac{H_t^{1+\omega}}{1+\omega} \right) \quad (1)$$

subject to the following sequential budget constraint:

$$\begin{aligned} B_t + \frac{F_t}{P_t} + C_t + T_t + \frac{K_t^e}{Z_t^e} + \frac{K_t^n}{Z_t^n} + \frac{\psi_e}{2} \left( \frac{K_t^e}{K_{t-1}^e} - 1 \right)^2 \frac{K_{t-1}^e}{Z_t^e} + \frac{\psi_n}{2} \left( \frac{K_t^n}{K_{t-1}^n} - 1 \right)^2 \frac{K_{t-1}^n}{Z_t^n} \quad (2) \\ + \frac{\psi_f}{2} \frac{(F_t - f)^2}{P_t} = W_t H_t + (1 + r_{t-1}) B_{t-1} + \left( R_t^e U_t^e + \frac{1 - \delta_{e0} - \delta_{e1} (U_t^e)^{\mu_e} / \mu_e}{Z_t^e} \right) K_{t-1}^e \\ + \left( 1 + r_{t-1}^f \right) \frac{F_{t-1}}{P_t} + \left( R_t^n U_t^n + \frac{1 - \delta_{n0} - \delta_{n1} (U_t^n)^{\mu_n} / \mu_n}{Z_t^n} \right) K_{t-1}^n + \Pi_t \end{aligned}$$

In the utility function,  $\mathbb{E}$  is the operator signifying mathematical expectations based on the information set available to the agents at period  $t = 0$ , thereby introducing some elements of uncertainty into the model,  $0 < \beta < 1$  is the discount factor,  $\iota$  is the external habit formation parameter,  $\epsilon$  is the elasticity of consumption,  $\omega$  is the inverse of Frisch elasticity of labour supply, and the exogenous stochastic variables are  $\tau_t$  denoting the intertemporal preference shock and  $\zeta_t$  denoting the labour supply shock.

In the budget constraint, we assume that the stand-in consumer invests in two broad types of assets: physical capital ( $K_t^j$ ) and financial assets (domestic bonds,  $B_t$ , and foreign bonds,  $F_t$ );<sup>4</sup>  $W_t$  is the wage rate,  $R_t^j$  is a sector-specific rental rate of physical capital,  $U_t^j$  is an index of sector-specific capital utilisation rate,  $r_t$  is the net return to domestic bonds,  $T_t$  is a lump-sum tax or transfer,  $\Pi_t = \Pi_t^e + \Pi_t^n$  is a lump-sum transfer of profits or losses of firms to the households,  $P_t$  is the real exchange rate, and the exogenous stochastic variables are  $Z_t^j$ , denoting a sector-specific investment-specific technology shock, and  $r_t^f$ , denoting the exogenous net return to foreign bonds. Also,  $\psi_j$  is the adjustment cost parameter for physical capital,  $\delta_{j0}$  is the constant portion of the steady state level of physical capital,  $\delta_{j1}$  is the slope of the depreciation function,  $\mu_j$  governs the elasticity of marginal depreciation with regards to the capital utilisation rate,  $\psi_f$  is the adjustment cost parameter for foreign bonds, and  $f$  is the steady state value of the stock of foreign bonds.

We proceed with the characterisation of the disaggregate choices. Particularly, these begin with the decisions of the producers. The two sectors in this economy consist of stand-in

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interchangeably in the model. We describe the key features of the model next leaving the complete list of the linearised model equations to the Appendix.

4. We have assumed a quadratic portfolio adjustment or transaction cost for both physical capital and foreign bonds following Schmitt-Grohe and Uribe (2003) - who also provide a number of alternative methods for inducing stationarity in models where foreign bonds may lead to some endogenous variables, especially consumption and the level of debt, following a unit root process. Further, Uribe and Yue (2006) provide a theoretical justification for the incorporation and use of portfolio adjustment cost in a model where a banking sector is implicit -, Iacoviello and Minnetti (2008), and Fernandez-Villaverde et al. (2011) - See also Goodfriend and McCallum (2007), Aliaga-Diaz and Olivero (2010), Curdia and Woodford (2010) and Iacoviello (2015) for similar ideas.

producers of  $Y_t^j$ , that choose the demand for labour,  $H_t^j$ , capital services,  $U_t^j K_{t-1}^j$ , and energy use,  $E_t^j$ , in order to maximise:

$$\Pi_t = \sum_{j=e,n} (P_t^j Y_t^j - (W_t + \xi_t^j) H_t^j - (R_t^j + \vartheta_t^j) U_t^j K_{t-1}^j - Q_t E_t^j) \quad (3)$$

subject to a constant-elasticity-of-substitution (CES) production function:

$$Y_t^j = A_t^j (H_t^j)^{1-\alpha_j} \left( \theta_j (U_t^j K_{t-1}^j)^{-\nu_j} + (1 - \theta_j) (O_t^j E_t^j)^{-\nu_j} \right)^{-\frac{\alpha_j}{\nu_j}} \quad (4)$$

taking as given the paths of prices,  $P_t^j$  and  $W_t$ , and the paths of the exogenous stochastic processes  $A_t^j$  denoting the sector-specific neutral productivity shock,  $\xi_t^j$  denoting the sector-specific wage bill shifter,  $\vartheta_t^j$  denoting the sector-specific capital cost shifter,  $O_t^j$  denoting the sector-specific energy efficiency shock, and  $Q_t$  denoting the exogenous world price of energy,  $0 < \alpha_j < 1$  is the elasticity of output with respect to labour hours,  $0 < \theta_j < 1$  is the weight of capital services in the CES production function, and  $0 < \nu_j < \infty$  determines the elasticity of substitution between capital services and energy services.

Exchange of goods and resources between the domestic country and the rest of the world takes three forms. First, consumers can buy domestic and foreign bonds; second, producers import crude oil from the world market; and third, trade in (semi-) finished goods. It is the latter that we discuss now and is achieved through the activities of the stand-in trader.

More formally, the trader solves:

$$P_t \sum_{z=g,l} D_t^z + IM_t - (P_t^d D_t^d + IM_t + P_t^e D_t^e + P_t^n D_t^n + P_{e,t}^{im} IM_t^e + P_{n,t}^{im} IM_t^n) \quad (5)$$

subject to the aggregator functions:

$$D_t^l = \left( \kappa^{\frac{1}{\phi}} (D_t^d)^{\frac{\phi-1}{\phi}} + (1 - \kappa)^{\frac{1}{\phi}} \varpi_t (IM_t)^{\frac{\phi-1}{\phi}} \right)^{\frac{\phi}{\phi-1}} \quad (6)$$

$$D_t^g = \left( \sigma^{\frac{1}{\zeta}} \gamma_t (D_t^e)^{\frac{\zeta-1}{\zeta}} + (1 - \sigma)^{\frac{1}{\zeta}} (D_t^n)^{\frac{\zeta-1}{\zeta}} \right)^{\frac{\zeta}{\zeta-1}} \quad (7)$$

$$IM_t = \left( \chi^{\frac{1}{\eta}} \varphi_t (IM_t^e)^{\frac{\eta-1}{\eta}} + (1 - \chi)^{\frac{1}{\eta}} (IM_t^n)^{\frac{\eta-1}{\eta}} \right)^{\frac{\eta}{\eta-1}} \quad (8)$$

taking as given the paths of prices  $P_t$ ,  $P_t^e$ ,  $P_t^n$ , and  $P_t^d$ , and the paths of the exogenous stochastic processes,  $\varpi_t$ , denoting preference for aggregate imported goods,  $\gamma_t$ , denoting preference for energy intensive goods,  $\varphi_t$ , denoting preference for imported energy intensive goods,  $P_{e,t}^{im}$ , denoting the exogenous price of imported energy intensive goods, and  $P_{n,t}^{im}$ , denoting the exogenous price of imported non-energy intensive goods. In the above problem,  $0 \leq \kappa, \sigma, \chi \leq 1$  are the relevant weights of goods in the aggregators, and  $\phi, \zeta, \eta > 0$  are the relevant measures of the intratemporal elasticity of substitution between the goods.<sup>5</sup> A stand-in trader in the

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5. We treat  $D_t^l$  and  $D_t^g$  identically as  $D_t$ . This distinction is only used here to formalise the problem and to reiterate that  $D_t$  is a bundle of four types of goods.

foreign country solves an analogous problem.

Finally, we introduce a government assumed to face the following budget constraint:

$$\mathbf{G}_t = T_t + b_t - (1 + r_{t-1}) b_{t-1} \quad (9)$$

which states that the exogenous government spending is financed by lump-sum taxes or transfers and the evolution of domestic bonds.<sup>6</sup> The government acts here mainly as a (re-) distributor. All markets clear in equilibrium and we round up this section by providing the definition of a competitive equilibrium for the model.

**DEFINITION II.1.** Taking as given **5** prices  $(p_t, p_t^e, p_t^n, w_t, r_t)$ , **22** shocks  $(\mathbf{a}_t^e, \mathbf{a}_t^n, \mathbf{d}_t^w, \varphi_t, \varphi_t^w, \gamma_t, \mathbf{g}_t, \zeta_t, \mathbf{o}_t^e, \mathbf{o}_t^n, \mathbf{p}_{e,t}^{im}, \mathbf{q}_t, \mathbf{r}_t^f, \tau_t, \vartheta_t^e, \vartheta_t^n, \varpi_t, \varpi_t^w, \xi_t^e, \xi_t^n, \mathbf{z}_t^e, \mathbf{z}_t^n)$ , the initial conditions for consumption, bonds, and physical capital stocks  $(c_{-1}, b_{-1}, f_{-1}, k_{-1}^e, k_{-1}^n)$ , and the appropriate no-Ponzi game conditions, a competitive equilibrium is characterised by a set of **29** endogenous stochastic processes  $(c_t, h_t, h_t^e, h_t^n, f_t, i_t, i_t^e, i_t^n, u_t^e, u_t^n, k_t^e, k_t^n, y_t, y_t^e, y_t^n, e_t, e_t^e, e_t^n, d_t, d_t^e, im_t, im_t^e, ex_t, ex_t^e, w_t, r_t, p_t, p_t^e, p_t^n)$  satisfied by the solutions to the stand-in consumer, producer, and trader's problems, and the bond, labour, capital, energy, and goods markets clear.

### III EMPIRICAL METHODS AND RESULTS

This section is split into two parts. First, we discuss the procedure used in evaluating the model, which requires that values be provided for model parameters. To this end, we partition the parameters into two groups given by  $\Gamma_1 = \{\beta, \delta u^e, \delta u^n, \theta^e, \theta^n\}$  and  $\Gamma_2 = \{\Gamma_{2a}, \Gamma_{2b}\}$  where  $\Gamma_{2a} = \{\omega, \varepsilon, \iota, \alpha_e, \alpha_n, \nu_e, \nu_n, \delta_{e1} u^{\mu_e}, \delta_{n1} u^{\mu_n}, \mu_e, \mu_n, \psi_e, \psi_n, \psi_f, \phi, \phi_w, \eta, \eta_w, \sigma, \varsigma\}$  and  $\Gamma_{2b}$  are the persistence and volatility parameters of the shocks. Second, we summarise the estimation findings.

#### A Parameters

We present the values chosen for the vector of parameters,  $\Gamma_1$ , in panel **a** of Table I. In particular, we fix the values of  $\beta$ ,  $\delta u^e$ , and  $\delta u^n$  throughout the exercise to 0.96, 0.09, and 0.06, respectively. The weight of capital services in the two sectors are endogenously obtained using  $\theta_j = \left[ 1 + \frac{\mathbf{q}}{\delta_{j1} u^{\mu_j}} \left( \frac{e^j}{k^j} \right)^{1+\nu_j} \right]^{-1}$ .<sup>7</sup>

Then, we estimate the sub-vector of parameters,  $\Gamma_{2a}$ , using the indirect inference method developed in Le et al. (2011) extended to the non-stationary model and data in Meenagh et al. (2012). An interested reader is referred to these papers for details; nonetheless, we provide a brief overview here.

6. As in Correia et al. (1995), An and Schorfheide (2007), and Justiniano et al. (2010), the fiscal stance of the government is fully Ricardian.

7. The values yielded by these expressions will alter to the extent that estimated elasticity parameters,  $\nu_e$  and  $\nu_n$ , change during the Simulated Annealing searching for a set of optimal values for the model parameters. Hence, the values reported in Table I of  $\theta_e = 0.997$  and  $\theta_n = 0.993$ .



TABLE I: STRUCTURAL PARAMETERS

<b>a. <math>\Gamma_1</math></b>		
Discount factor	$\beta$	0.96
$e$ investment-capital ratio	$\delta u^e$	0.09
$n$ investment-capital ratio	$\delta u^n$	0.06
<b>b. <math>\Gamma_{2a}</math></b>		
Frisch elasticity	$\omega$	6.03
Consumption elasticity	$\varepsilon$	1.24
Habit formation	$\iota$	0.30
$e$ share of capital and energy	$\alpha_e$	0.25
$n$ share of capital and energy	$\alpha_n$	0.37
$e$ elasticity of substitution between capital and energy	$\nu_e$	0.29
$n$ elasticity of substitution between capital and energy	$\nu_n$	0.27
$e$ marginal cost of capital utilisation	$\delta_{e1} u^{\mu_e}$	0.03
$e$ depreciation elasticity of capital utilisation	$\mu_e$	1.90
$n$ marginal cost of capital utilisation	$\delta_{n1} u^{\mu_n}$	0.06
$n$ depreciation elasticity of capital utilisation	$\mu_n$	4.72
$e$ adjustment cost parameter	$\psi_e$	0.0001
$n$ adjustment cost parameter	$\psi_n$	0.0007
Adjustment cost parameter for foreign bonds	$\psi_f$	0.0001
Substitution elasticity, $d_t^d - im_t$ goods	$\phi$	0.97
Substitution elasticity, $d_t^f - ex_t$ goods	$\phi_w$	0.43
Substitution elasticity, $im_t^e - im_t^n$ goods	$\eta$	0.07
Substitution elasticity, $ex_t^e - ex_t^n$ goods	$\eta_w$	0.04
Weight of $d_t^e$ goods	$\sigma$	0.26
Substitution elasticity, $d_t^e - d_t^n$ goods	$\varsigma$	0.44
$e$ weight on capital services	$\theta_e$	0.997
$n$ weight on capital services	$\theta_n$	0.993

*Note:*  $e$  is energy intensive,  $n$  is non-energy intensive.

Adapting the notation of Le et al. (2015), our approach permits the following association for linearised DSGE model:

$$A(L) w_t = B(L) E_t w_{t+1} + C(L) x_t + D(L) e_t \quad (10)$$

where  $Ee_t = 0$ ,  $Ee_t e_t' = I$  for all  $t$ ,  $w_t$  is a vector  $m$  endogenous variables and  $x_t$  is a vector  $n$  exogenous variables, which we assume to be driven by:

$$\Delta x_t = a(L) \Delta x_{t-1} + d + c(L) \epsilon_t \quad (11)$$

where  $E\epsilon_t = 0$ ,  $E\epsilon_t \epsilon_t' = I$  for all  $t$ . In the above, both the endogenous and exogenous variables are non-stationary. Further, the general solution to  $w_t$  takes the form:

$$w_t = G(L) w_{t-1} + H(L) x_t + f + M(L) e_t + N(L) \epsilon_t \quad (12)$$

where for  $\varrho = \{A, B, C, D, a, c, G, H, M, N\}$ ,  $\varrho(L)$  are polynomial functions with roots

outside the unit circle, with  $L$  denoting the lag operator  $z_{t-s} = L^s z_t$ , and since  $w_t$  and  $x_t$  are non-stationary, the above solution has  $m$  co-integrating relations:

$$w_t = [I - G(1)]^{-1} [H(1)x_t + f] = \prod x_t + g \quad (13)$$

where, in the long-run, the above solution becomes  $\bar{w}_t = \prod \bar{x}_t + g$  with  $\bar{x}_t = \bar{x}_t^{\text{det}} + \bar{x}_t^{\text{sto}}$  being defined by the sum of two parts, namely the deterministic trend  $\bar{x}_t^{\text{det}} = [1 - a(1)]^{-1} dt$  and the stochastic trend  $\bar{x}_t^{\text{sto}} = [1 - a(1)]^{-1} c(1) \xi_t$  where  $\xi_t = \sum_{i=0}^{t-1} \epsilon_{t-s}$ . It is the relation in (13) that allows the solution to the estimated model to be written as a vector error correction model (VECM):

$$\Delta w_t = -[I - G(1)](w_{t-1} - \prod x_{t-1}) + P(L)\Delta w_{t-1} + Q(L)\Delta w_t + f + \Phi_t \quad (14)$$

where the disturbance is  $\Phi_t = M(L)e_t + N(L)\epsilon_t$  and is assumed to be a moving average process. We can, therefore, use a VARX to approximate (14) as:

$$\Delta w_t = \mathbf{K}[(w_{t-1} - \bar{w}_{t-1}) - \prod(x_{t-1} - \bar{x}_{t-1})] + \mathbf{R}(L)\Delta w_{t-1} + \mathbf{S}(L)\Delta w_t + g + \Theta_t \quad (15)$$

where  $E\Theta_t = 0$ ,  $E\Theta_t\Theta_t' = I$  for all  $t$ , and (15) serves as our auxiliary model during estimation.

## B Estimation Findings

Using, unfiltered logarithmically transformed, real per capita (except the wage rate, interest rate, real exchange rate, relative prices, and capital utilisation rates) U.S. annual data covering the period 1949-2013, the model parameters are estimated. A detailed description of the data sources and construction of the empirical counterparts to the 29 variables in DEFINITION II.1 are presented in the Appendix. We report the estimates for the parameters in  $\Gamma_{2a}$  and  $\Gamma_{2b}$  in panel **b** of Table I and Table II, respectively.

The estimate of the inverse of consumption elasticity,  $\varepsilon$ , is 1.24, which is within the range of estimates found in many DSGE models.<sup>8</sup> Compared to the initial value, the estimated value of 0.3 for the habit formation parameter, interestingly, is suggesting households' reduced consumption inertia.<sup>9</sup> Labour elasticities in the two sectors are 0.75 and 0.63 for the energy and non-energy intensive sector, respectively. A high value is found for Frisch elasticity ( $\omega^{-1} =$

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8. See for example Hall (1988) and Smets and Wouters (2003). The consumption elasticity of 0.81 found here implies that households are more willing to smooth consumption across time in response to a change in real interest rate. This implies that agents would respond more to the substitution effect than to the wealth effect. A value of between zero and one is uncontroversial in the literature [e.g., Kocherlakota (1988) advocated for a value close to zero]. Meanwhile, Campbell (1994) used values ranging from zero to infinity in his analysis. For more on the range of values and other estimates of consumption elasticity, see, for example, Nelson and Nikolov (2004), Bergin (2003), and Cromb and Fernandez-Corugedo (2004).

9. Theoretically, there is no judgement against this result as the focus of our research is not accounting for asset market relations, but quantitatively, it is quite low for a developed country [see Boldrin et al. (2001) who estimated a value of 0.7; Smets and Wouters (2003, 2005) who reported a value of 0.55, 0.57; Christiano et al. (2005) who obtained a point estimate of 0.65]. In fact, low habit persistence is usually associated with developing nations; for example, Uribe and Yue (2006) found this to be 0.2 using panel data for emerging countries.

0.17), meaning that labour hours react more to changes in real wage. The findings of  $\nu_e = 0.29$  and  $\nu_n = 0.27$  imply that there are high elasticities of substitution between the two factors in both sectors.

All estimates for the adjustment cost parameters are nearly zero, and are all smaller than the initial values by at least 30%. Further, the estimate of the marginal cost of capital utilisation is 3% in the energy intensive sector, while it is 6% in the non-energy intensive sector. These estimates might be indicative that the return to investment, or the marginal product of capital services is higher in the non-energy intensive sector. We obtained 1.90 and 4.72 for  $\mu_e$  and  $\mu_n$ , respectively. Finally, in regard to the structural parameters of the model, the elasticities of all the substitution parameters are sensibly in the ballpark of other estimates found in the literature.

In addition, there are 22 exogenous stochastic processes in the model: 17 behavioural shocks and 5 exogenous variables. The time series for these errors are either extracted from the model's Euler conditions, as in the cases of the behavioural shocks, or observed directly in the data, as in the cases of the exogenous variables. Regarding the former group, 14 of the relevant equations are without expectations, such that the structural errors are backed out directly as residuals; for the remaining 3 that are with expectations (intertemporal preference, and energy and non-energy intensive investment-specific technology shocks), the residuals are derived by using the instrumental variable method recommended by McCallum (1976) and Wickens (1982), where the instruments are the lagged values of the endogenous variables.<sup>10</sup>

Until now we have been silent about the processes that these shocks follow. Given that we are working with unfiltered data, one cannot arbitrarily impose a first-order autoregressive process in levels on them all; hence we provide along with the Appendix reports for the unit root tests carried out for each of the shocks (based on calibrated values) showing the conclusions we reached. In particular, we specify in our econometric procedure 11  $I(1)$  shocks modelled as ARIMA(1, 1, 0) processes and 11  $I(0)$  shocks modelled as ARIMA(1, 0, 0). Then, we estimate the former group of shocks as first-order autoregressive processes in first differences and estimate the latter group of shocks as first-order autoregressive processes in levels. An examination of Table II reveals that many of the shocks are mildly persistent except for the AR parameters coming out of first-differenced annual data for the shocks that are treated as non-stationary; the highest AR coefficient belongs to world interest rate. It is also observed that the sectoral energy efficiency shocks are the most volatile, while intertemporal preference, world interest rate, and energy and non-energy intensive investment-specific technology shocks are among the least volatile.

Finally, Table III reports the statistics for the model based on the estimated structural parameters and actual errors backed out of the data. We focus on the estimated model and observe that the model fits the joint distribution of the data well passing the Wald test at the 90% level. The variables included in our auxiliary (VECM) model are output and real exchange rate. The preceding result is supported by the transformed Mahalanobis distance ( $TMD$ ) of

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10. We provide the assumptions made regarding the shock processes and calculations of the series used in estimating the parameters of  $\Gamma_{2b}$  in the Appendix.

TABLE II: SHOCK PROCESSES

<i>Autocorrelation</i>		
$e$ productivity shock	$\rho_{\mathbf{a}^e}$	-0.004
$n$ productivity shock	$\rho_{\mathbf{a}^n}$	-0.006
World demand shock	$\rho_{\mathbf{d}^w}$	0.0051
Preference shock for $im_t^e$	$\rho_{\varphi}$	0.0453
Preference shock for $ex_t^e$	$\rho_{\varphi^w}$	-0.062
Preference shock for $d_t^e$	$\rho_{\gamma}$	0.2459
Government spending shock	$\rho_{\mathbf{g}}$	0.5057
Labour supply shock	$\rho_{\zeta}$	-0.010
$e$ energy efficiency shock	$\rho_{\mathbf{o}^e}$	0.6601
$n$ energy efficiency shock	$\rho_{\mathbf{o}^n}$	0.5678
$im_t^e$ price shock	$\rho_{\mathbf{p}_e^{im}}$	0.0371
Energy price shock	$\rho_{\mathbf{q}}$	-0.006
World interest rate shock	$\rho_{r^f}$	0.9601
Intertemporal preference shock	$\rho_{\tau}$	0.6453
$e$ capital cost shock	$\rho_{\vartheta^e}$	0.0936
$n$ capital cost shock	$\rho_{\vartheta^n}$	0.0364
Preference shock for $im_t$	$\rho_{\varpi}$	0.6785
Preference shock for $ex_t$	$\rho_{\varpi^w}$	0.0666
$e$ wage bill shock	$\rho_{\xi^e}$	0.0297
$n$ wage bill shock	$\rho_{\xi^n}$	0.0395
$e$ investment-specific technology shock	$\rho_{\mathbf{z}^e}$	0.3407
$n$ investment-specific technology shock	$\rho_{\mathbf{z}^n}$	-0.003
<i>Standard deviation</i>		
$e$ productivity shock	$\sigma_{\mathbf{a}^e}$	0.0263
$n$ productivity shock	$\sigma_{\mathbf{a}^n}$	0.0470
World demand shock	$\sigma_{\mathbf{d}^w}$	0.1555
Preference shock for $im_t^e$	$\sigma_{\varphi}$	0.3094
Preference shock for $ex_t^e$	$\sigma_{\varphi^w}$	0.5527
Preference shock for $d_t^e$	$\sigma_{\gamma}$	0.0347
Government spending shock	$\sigma_{\mathbf{g}}$	0.0230
Labour supply shock	$\sigma_{\zeta}$	0.3584
$e$ energy efficiency shock	$\sigma_{\mathbf{o}^e}$	2.7803
$n$ energy efficiency shock	$\sigma_{\mathbf{o}^n}$	2.7600
$im_t^e$ price shock	$\sigma_{\mathbf{p}_e^{im}}$	0.1470
Energy price shock	$\sigma_{\mathbf{q}}$	0.2086
World interest rate shock	$\sigma_{r^f}$	0.0086
Intertemporal preference shock	$\sigma_{\tau}$	0.0072
$e$ capital cost shock	$\sigma_{\vartheta^e}$	0.0099
$n$ capital cost shock	$\sigma_{\vartheta^n}$	0.0057
Preference shock for $im_t$	$\sigma_{\varpi}$	0.2038
Preference shock for $ex_t$	$\sigma_{\varpi^w}$	0.6232
$e$ wage bill shock	$\sigma_{\xi^e}$	0.3234
$n$ wage bill shock	$\sigma_{\xi^n}$	0.3241
$e$ investment-specific technology shock	$\sigma_{\mathbf{z}^e}$	0.0077
$n$ investment-specific technology shock	$\sigma_{\mathbf{z}^n}$	0.0231

Note:  $e$  is energy intensive,  $n$  is non-energy intensive.

TABLE III: MODEL FIT

	<i>Statistics</i>	
	Wald	TMD
Initial values	100	49.64
Estimated model	89.2	1.04

*Note:* Statistics reported are based on estimation of the model on data for output and real exchange rate; TMD is transformed Mahalanobis distance.

1.04, where a value less than 1.645 for the *TMD* shows that the model is not rejected.

## IV DISCUSSION

One of our main aims in this section is to interrogate the estimated model about the role of energy price shocks in causing the U.S. business cycles, especially in an economic environment littered with a host of other shocks, chief among which are productivity and other imported shocks. The main result is that the model can explain the observed quantitative response of output to oil price increases, and we provide a theoretical explanation to account for the empirical outcome. We start with the theoretical interpretation of the results.

### A The Propagation Mechanism of Oil Price Shocks

We begin the illustration of the model's implications for economic activities by providing some qualitative interpretations for the propagation mechanism of energy price shocks in our model. We focus the exposition on two markets, namely labour and capital markets, with references to how these effects translate into the goods market, and ultimately, affect the import-export market (and thus, the real exchange rate and the current account positions). In any case, these are all interesting because they have implications for both output and real exchange rate dynamics. To this end, we make two propositions.

**PROPOSITION IV.1.** *Impact effect:* oil price increases depress the economic system intratemporally by working through the labour-consumption channel.

*Proof.*

The analysis is illustrated in Figure II. Working with the general forms of the model described in Section II, and abstracting from other shocks and real frictions (like habit formation and adjustment costs), households' decisions in the labour market are given by  $-U_H(C_t, H_t)/U_C(C_t, H_t) = W_t$  for all  $t$ , which is the condition equating the marginal rate of substitution between labour and consumption to the marginal product of labour - the left-hand side determines the schedule for labour supply; they also obtain  $U_C(C_t, H_t)/\beta U_C(C_{t+1}, H_{t+1}) = (1 + r_t)$  in the capital market for all  $t$ , which is the condition that makes them indifferent between consuming today or tomorrow. Further, combining the two previous first-order conditions yields:

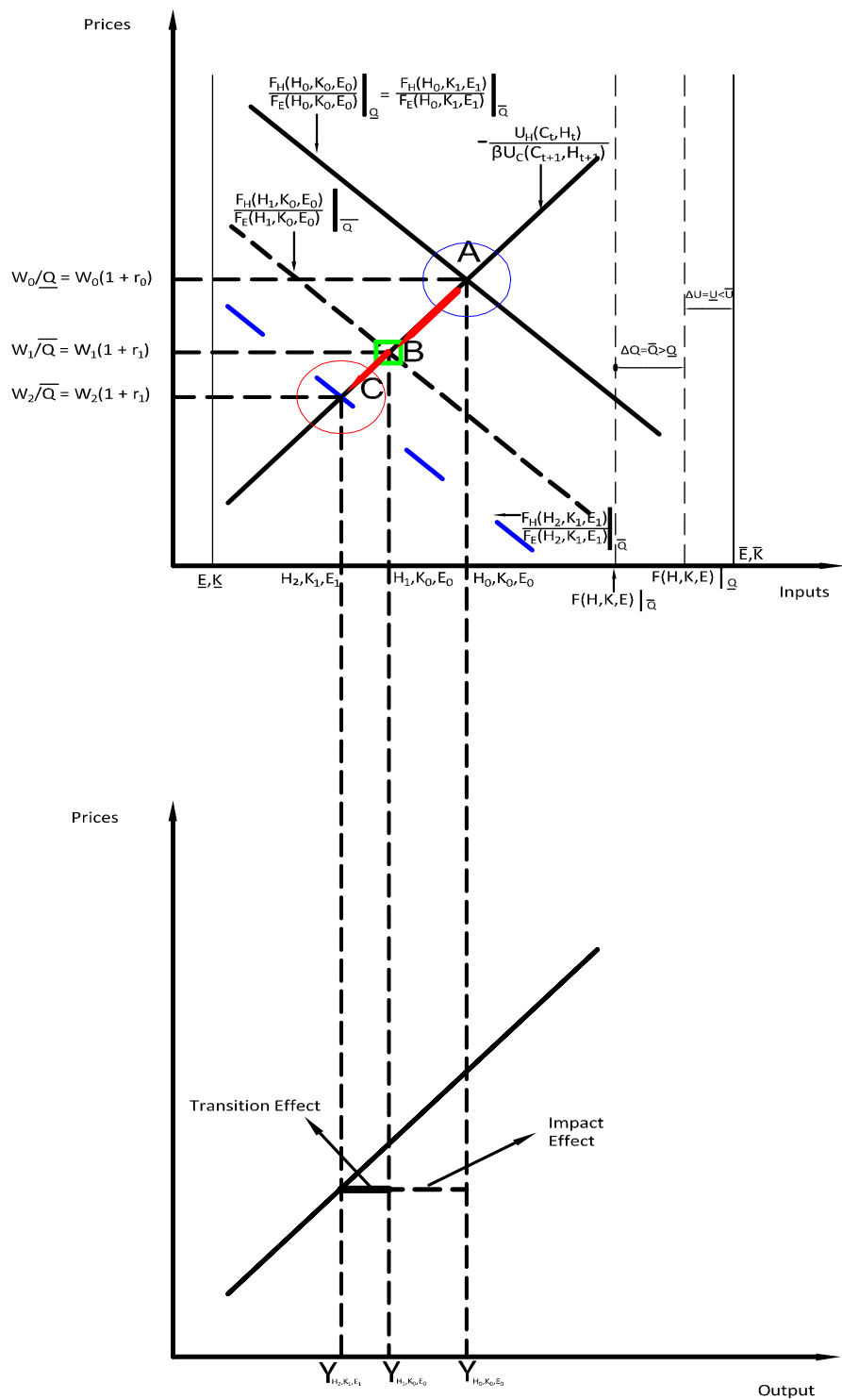


FIGURE II: PROPAGATION MECHANISM OF OIL PRICE SHOCK.

$-U_H(C_t, H_t) / \beta U_C(C_{t+1}, H_{t+1}) = (1 + r_t) W_t$ , which is the intertemporal labour-consumption choice determining the ability to smooth not just consumption, but also labour, over time. This particular representation makes explicit that households' supply of labour depends on both the wage rate and the stock of initial or current wealth (this is represented by the upward sloping curve in Figure II). Meanwhile, on the production side, and imposing symmetry between sectors (or working with the aggregate economy for the moment) to simplify the analysis, it is straightforward to derive the labour-energy ratio as  $F_H(H_t, K_t, E_t) / F_E(H_t, K_t, E_t) = W_t / Q_t$ , where the relative productivities on the left-hand side determines the schedule for labour demand (this is represented by the downward sloping curve in Figure II). For a required level of crude oil, a positive shock to its price, *ceteribus paribus*, will lead to a fall in demand for labour. Specifically, all things being equal, as  $Q_t$  rises,  $W_t / Q_t$  falls such that, to maintain the equal sign, the ratio  $F_H(H_t, K_t, E_t) / F_E(H_t, K_t, E_t)$  must likewise go down, and supposing that the required quantity of energy is fixed, the labour quantity demanded falls.<sup>11</sup> Moreover, without assuming the fixed energy necessary for production, labour demand can still fall because of the fall in  $W_t / Q_t$  that signals to the firms falling productivity of labour relative to energy use.<sup>12</sup> Bringing the consumers and the producers together, equilibrium in the labour market is given by:  $-U_H(C_t, H_t) / \beta U_C(C_{t+1}, H_{t+1}) = (1 + r_t) W_t = W_t / Q_t = F_H(H_t, K_t, E_t) / F_E(H_t, K_t, E_t)$ . This is more useful broken up into prices  $(1 + r_t) W_t = W_t / Q_t$  implying that  $Q_t = 1 / \beta (1 + r_t)$ , and quantities  $-U_H(C_t, H_t) / U_C(C_{t+1}, H_{t+1}) = F_H(H_t, K_t, E_t) / F_E(H_t, K_t, E_t)$ , which equates intertemporal labour-consumption decision to the ratio of the two marginal products. The price relation gives a hint as to the connection to investment, implying that when  $Q_t$  goes up,  $r_t$  must fall to maintain equilibrium since the discount factor is constant.<sup>13</sup> All things being equal, the resource drain effect can be shown to be given by:  $\frac{dY_t}{dQ_t} \Big|_{H,K} = \Psi(\cdot) \leq 0$  where  $\Psi$  always takes a negative value for a net oil-importing country like the U.S. and  $(\cdot)$  includes energy use and structural model parameters (e.g., share of energy use in production and elasticity of substitution parameter).<sup>14</sup> As drawn, the demand for labour is that which achieves point B in the top panel of Figure II, with a corresponding lower output level  $Y_{H_1, K_0, E_0}$  in the bottom panel. ■

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11. As is standard in the literature when analysing short-run production function, labour is the input that can be varied most quickly. An alternative way to see how this may happen is to write an expression for the marginal cost of energy input as  $Q = \frac{W_t}{F_H(H_t, K_t, E_t) / F_E(H_t, K_t, E_t)}$ . Obviously, as  $Q$  rises the numerator and/ or the denominator of the right-hand side must change appropriately to ensure equality.

12. Formally, we assume that  $E \in [\underline{E}, \bar{E}]$ , indicating that there is a minimum level of energy required,  $\underline{E}$ , for firms to be operational, and a maximum level,  $\bar{E}$ , at which the firms would import depending either on cost or the production possibility frontier. Further, note that the effects of oil price shocks in this model are not direct on households because they are not modelled to use imported crude oil [see, for example, Dhawan and Jeske (2008) for an analysis that integrated imported crude oil into household utility function]. The return to households' investment will be affected to the same extent as the profits of the firms, however. This is one of the channels by which the negative spiral of this shock permeates the system.

13. A re-arrangement of the intertemporal indifference curve of the households that would lead to similar conclusion is  $U_C(C_t, H_t) / \beta U_C(C_{t+1}, H_{t+1}) = (1 + r_t) = -U_H(C_t, H_t) / \beta U_C(C_{t+1}, H_{t+1}) W_t$ , which implies that  $U_C(C_t, H_t) W_t = -U_H(C_t, H_t)$ .

14. This value,  $\Psi(\cdot)$ , lost by the oil-importer is gained by the oil-exporter, at least to the extent that the supply of exports fails to match this amount [see for example Darby (1981)].

The above result appears rooted in the notion that the model is able to generate intertemporal labour-consumption substitution. This in itself is not a new idea but, to the best of our knowledge, this particular re-interpretation in relation to the *impact effect* on aggregate and sectoral macroeconomic variables is novel.<sup>15</sup>

PROPOSITION IV.2. *Transition effect*: oil price increases depress the economic system intertemporally by working through the consumption-investment channel.

*Proof.*

The proof of the *transition effect* follows from that of the *impact effect*. Specifically, the domestic firms, having absorbed the *impact effect* transfer it to households in the form of job losses, possible lower wage rates, and lower returns to the last period's investment (end-of-period  $t$  profit declines). All told, this implies that the households' stock of wealth has declined and, since it is the households that make investment decisions in this model, what they have available to supply for capital formation against the next period is reduced, creating the link to probable further output decreases in period  $t + 1$ . We illustrate this outcome in Figure II, shown by point C in the top panel and output level  $Y_{H_2, K_1, E_1}$  in the bottom panel. ■

This sub-section rounds up by looking at the sectoral output fluctuations to which the above results are tied in order to show how these have an effect on aggregate output. Specifically, when the price of imported energy goes up, this takes resources from the domestic country and transfers it to the RoW - this is easily seen by examining the economy-wide resource constraint. The resulting effect is that the total net imports must fall, unless the oil exporter buys at least an equivalent amount of goods from the domestic country. We abstract from this possibility and explain the complementary outcome to the above propositions in relation to the international trade and competitiveness of the domestic country. Additionally, an increase in the price of energy means that the price of those goods that are more energy intensive in their production also rises. These mechanisms of propagating the effects of energy price shocks via the sectors are explained next.

From the first-order conditions, the prices of both energy and non-energy intensive goods in the domestic country are derived endogenous, but it is significant that we can write the solution to the price of non-energy intensive goods as a function of both the aggregate price level and the price of energy intensive goods. The focus here is on the latter, and Figure III is used to illustrate this mechanism. Note that the vertical axes on both the left and the right panels of the graph are labelled  $P_t^e$  because of the reason just given. In particular, because the energy intensive sector is assumed to be relatively both oil and capital more intensive, its supply curve is drawn to be steeper, such that the increase in the supply of energy intensive goods due to  $P_t^e$  rising is less than the drop in the supply of non-energy intensive goods due

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15. See Lucas and Rapping (1972) and Lucas (1972a, 1972b, 1973) for the theoretical development of labour smoothing. Meanwhile, a closely related interpretation, brought to our attention after this analysis was put forth, is that of factor-price frontier done for an aggregate economy by Blanchard and Gali (2007), in which oil is allowed to enter both consumption and production functions. While they discussed results that are similar to the *impact effect* for their aggregate economy, they did not discuss *transition effect*. Arguments in Eastwood (1992) appear to follow this line of enquiry.



to a fall in  $P_t^n$ . Thus, output falls and the demand for both types of goods fall to reduce net exports, since consumers are poorer. The effect on real exchange rate is actually ambiguous as this depends on a host of other factors.<sup>16</sup>

## B Accounting for Two Recessions

Using the U.S. annual data, we define an episode as involving *abnormal* growth if there is an annual growth of gross domestic product (GDP) above 3.5%, which is the average growth rate of U.S. GDP over the sample period. Also, we define recession as any negative change in output. For both growth and recession, we take as one episode every successive occurrence. We then seek to understand these *excessive* U.S. business cycles. To undertake this study, we adopt the dating of the U.S. recessions used by the National Bureau of Economic Research (NBER) and the dating (and causes) of oil crises and recession based on Hamilton's (1985, 2011) calculations.<sup>17</sup>

Then, we carry out the following experiments: **(1)** for output and real exchange rate, for which we have fitted the model to the data, and working with two selected sub-samples (1967-1984 and 1995-2012), we decompose each growth and recession according to the model based on the twenty-two structural shocks, with the results as depicted in Figure IV;<sup>18</sup> **(2)** we generate pseudo data for 62,000 years using Monte Carlo techniques and use it to evaluate the oil price-macroeconomic relationship.

In experiment **(1)**, we construct the time paths for output and real exchange rate for the two sub-periods,<sup>19</sup> we see in Figure IV that other exogenous variables generally drive output,

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16. See Krugman (1983) and some of the references therein for factors that work to determine real exchange rate position after an oil price shock.

17. Hamilton's dates for oil price episodes (% of price change, some of the principal causal factors) are: 1947-1948 (37, strong demand vs. supply constraints; shorter work week; European reconstruction), 1952-1953 (10, Iranian nationalisation; strike; abandonment of controls), 1956-1957 (9, Suez Crisis), 1969 (7, Secular decline in U.S. reserves; strike), 1970 (8, Rupture of Trans-Arabian pipeline; strike; strong demand vs. supply constraints (Libyan production cutbacks)), 1973-1974 (16-51, Stagnating U.S. production; strong demand vs. supply constraints (Arab-Israeli war)), 1978-1979 (57, Iranian revolution), 1980-1981 (45, Iran-Iraq War; price control removal), 1990 (93, Gulf War I), 1999-2000 (38, Strong demand), 2002-2003 (28, Venezuela unrest; Gulf War II), and 2007-2008 (145, Strong demand vs. supply constraints).

18. The shock decompositions for the variables are analysed in groups, however, viz: productivity shocks, which include the energy and non-energy intensive sectors' neutral productivities ( $\mathbf{a}_t^e$  and  $\mathbf{a}_t^n$ ), energy and non-energy intensive sectors' energy efficiencies ( $\mathbf{o}_t^e$  and  $\mathbf{o}_t^n$ ), and energy and non-energy intensive goods' investment-specific technologies ( $\mathbf{z}_t^e$  and  $\mathbf{z}_t^n$ ); preference shocks, which include the intertemporal preference ( $\tau_t$ ), labour supply ( $\zeta_t$ ), preference for imported energy intensive goods ( $\varphi_t$ ), preference for exported energy intensive goods ( $\varphi_t^w$ ), preference for energy intensive goods ( $\gamma_t$ ), preference for aggregate imported goods ( $\varpi_t$ ), and preference for aggregate exported goods ( $\varpi_t^w$ ); cost-push shocks, which include energy and non-energy intensive capital cost shifters ( $\vartheta_t^e$  and  $\vartheta_t^n$ ), energy and non-energy intensive sectors' wage bill shifters ( $\xi_t^e$  and  $\xi_t^n$ ); energy price shock ( $\mathbf{q}_t$ ); and the exogenous variables, which include world demand ( $\mathbf{d}_t^w$ ), government spending ( $\mathbf{g}_t$ ), the price of imported energy intensive goods ( $\mathbf{p}_{e,t}^{im}$ ), and foreign interest rate ( $r_t^f$ ). The primary results for both the impulse response functions and variance decompositions below have also been presented in these groupings for convenience of seeing the overall picture at a glance. For more detailed impulse response functions and variance decompositions, see Oyekola (2015).

19. The orthogonalisation scheme adopted orders energy price shock first followed by the remaining permanent shocks and then the transitory shocks. To this end, any contribution due to the correlation between the shocks, say energy price shocks and the remaining shocks (take the energy intensive sector productivity shock for example) is attributed to the energy price shock. We extend this approach down the line until we reached the

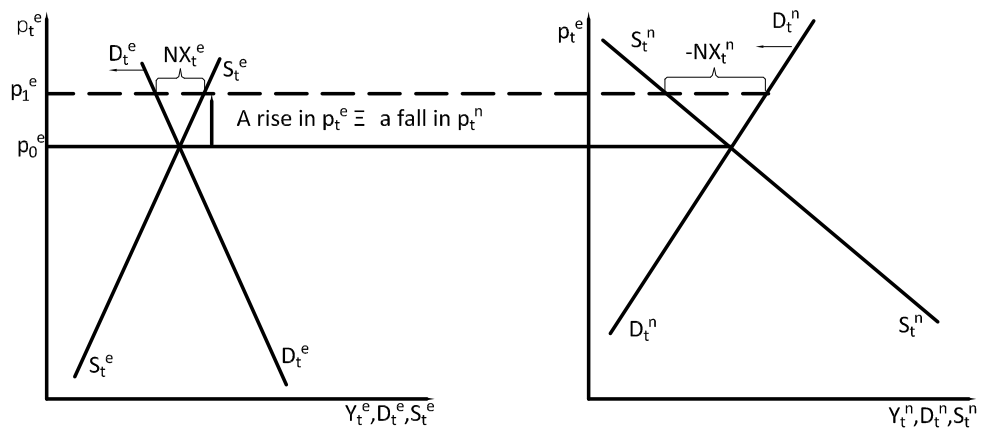


FIGURE III: SECTORAL PROPAGATION MECHANISM OF OIL PRICE SHOCK.

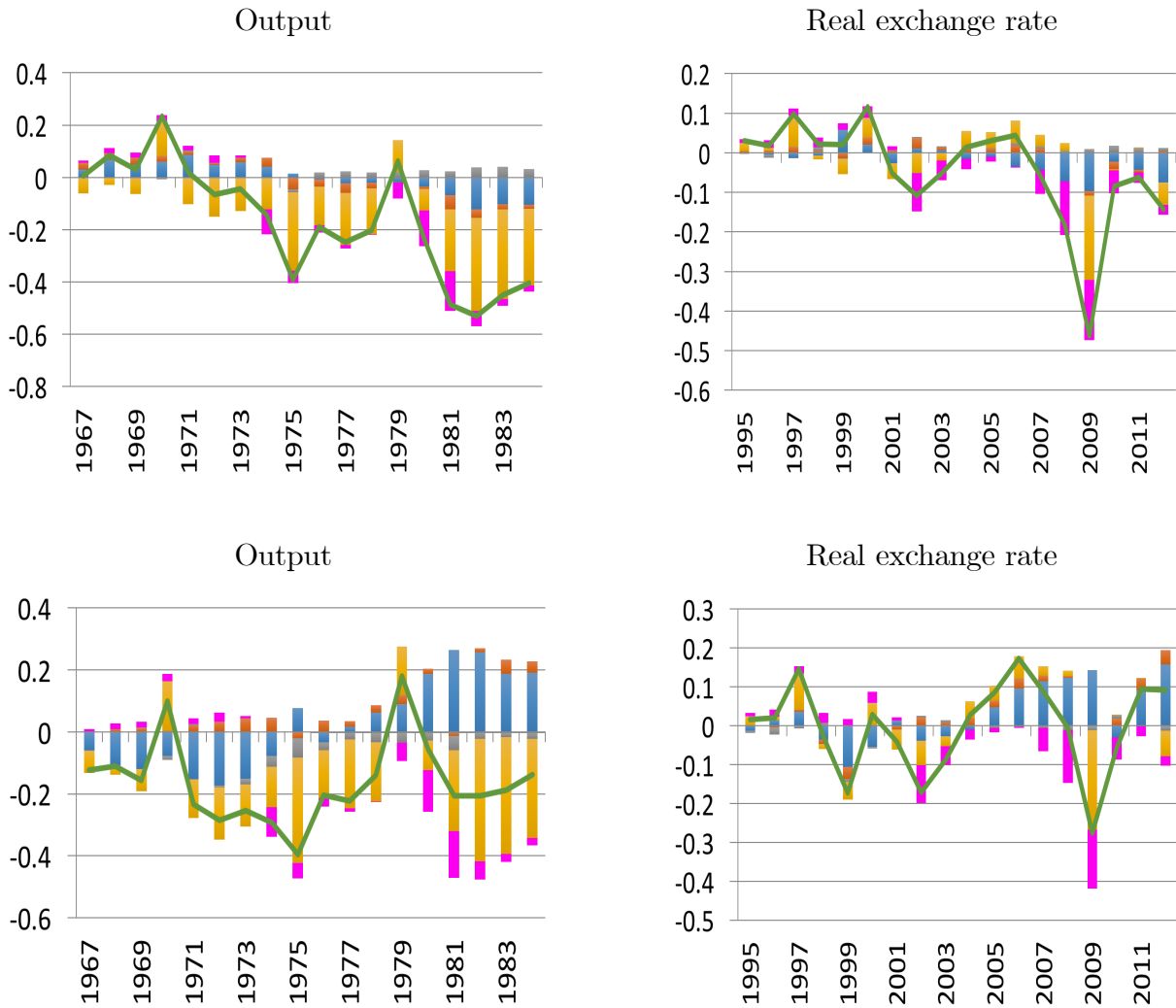


FIGURE IV: SHOCK DECOMPOSITION OF THE ESTIMATED MODEL.

albeit more in the earlier sub-period; these are again very important in 2009 when the U.S. output dropped massively. Our model was able to predict the year-on-year direction of output changes correctly over the two sub-periods and more importantly, we show in Figure IV that the model's predicted time path for output in the Great Recession preserved the ranking of changes observed in the actual data. We can tell a similar story for productivity shocks, although they have lesser effects in moving output in the face of these other shocks. It is notable, meanwhile, to observe that productivity shocks were responsible for keeping output up in the late 1960s in the face of negative pulls from the exogenous variables.

Moreover, energy price shocks are occasional disturbances whose influences on output fluctuations can be underlined by the downward trajectory of output in the 1973-74, 1979-82, 2002 and 2009 shocks, which all correspond to specific times when energy prices experienced a hike. We observe an exception though when the predicted response of output to energy price is shown to rise in 1999-2000. This can probably be explained by the sustained and widespread impact of the dot-com boom of the mid-1990s to Y2K. Then, in Figure IV for the real exchange rate, the exogenous variables and energy price shocks continue to dominate the other shocks last shock, which according to our ordering is the non-energy intensive investment-specific technology shock.

TABLE IV: MODEL PREDICTIONS OF ABNORMAL GROWTH AND RECESSION

	Sample		
	1950 – 2013	1950 – 1981	1982 – 2013
<i>Frequency of growth episodes</i>			
Normal growth + no oil price ↓	1.80	1.78	1.82
Abnormal growth + no oil price ↓	4.82	5.00	4.72
Normal growth + oil price ↓	5.62	5.50	5.70
Abnormal growth + oil price ↓	17.09	18.14	16.15
<i>Frequency of recession episodes</i>			
No recession + no oil price ↑	1.79	1.77	1.81
Recession + no oil price ↑	4.89	5.07	4.76
No recessions + oil price ↑	5.72	5.60	5.77
Recession + oil price ↑	16.23	17.17	15.59

*Note:* A growth (recession) is defined as two or three consecutive quarters of output above (below) the trend growth summing to one year for annual frequency. For both growth and recession, we take as one episode every successive occurrence. For each sample period, we simulate the model 1000 times; the statistics reported are, therefore, to be viewed as having a hypothetical sample  $n \times 1000$  years of observations; ↓ (↑) denotes decreases (increases).

followed by the productivity shocks. For the most part of the earlier sub-period, productivity and exogenous variables reinforced each other against the energy price shocks. This trend is reversed in the 1980s when exogenous variables and energy price teamed up against productivity and preference shocks. In all, preference shocks worked to keep the real exchange rate positive. For the latter sub-sample, energy price and exogenous variables move the real exchange rate in the same direction, while it goes in the opposite direction because of productivity shocks.

In addition to this, our assessment of the bootstrap simulated data in experiment (2) reveals a few interesting facts a couple of which we emphasise here - see Table IV: the first is the frequency of occurrence of the two events (abnormal growth and recession) in tandem with oil price changes (down and up); the second is the percentage of events involving oil price changes. More specifically, we find that of the times when there has been an abnormal growth (a recession), about 17 (16) per cent involve oil price decreases (increases). Unfortunately, we are unable to quantify the magnitude of the effects of these price changes on output fluctuation, and thus are unable to say much on the asymmetric effects of oil price changes on output. Additionally, the experiment suggests that there will be no recession (abnormal growth) and no oil price increases (decreases) in about every 2 years, and that, on average, in about every 5 years, there is an oil price rise (fall) that does not impact on output fluctuation. We split the sample period into two periods (pre-1980 and post-1980) and find that the results remain similar across time.

## C Impulse Response Functions

We now turn to a discussion of some of the impulse response functions in order to grasp the dynamics implied by the model shocks, focusing on the effects of a one-off standard deviation positive shock on output (Figure V) and real exchange rate (Figure VI).<sup>20</sup> We begin with the productivity shocks by first looking at the sectoral Solow residuals. Clearly, the impact effects generated by sectoral productivity shocks in the  $e$  sector are different to that of sectoral productivity shocks of the  $n$  sector. Given that there are positive shocks to both sectoral productivities,  $A_t^e$  and  $A_t^n$ , one would expect the outputs of both sectors to increase, causing an increase in factor demand accompanied by increased factor prices and falling relative prices for each sector's goods. Our model did not particularly lead to these standard outcomes, which are mainly generalisations of expected results in aggregate, or one sector, economic models.

The transmission mechanisms at work in multi-sector models, however, sometimes lead to contradicting dynamics as we observe here. In fact, it is the case that permanent productivity shocks in the two sectors have different effects on variables of interest. For instance, productivity in the  $n$  sector leads to standard results in output (aggregate and sectoral), consumption, wages, sectoral relative prices, real exchange rate, and components of the balance of payments (BOP), but less so for the productivity of the  $e$  sector. We surmise that what is going on here is a form re-structuring of resources. More specifically, the model suggests that a positive productivity shock in the  $e$  sector will raise productivity and, hence, output of the  $e$  sector, but the spillover effects to the  $n$  sector are negative.

Given that the magnitude of the increased output of the  $e$  sector is far smaller to that of the fall in the  $n$  sector output, aggregate output declines after an  $e$  sector productivity shock hits the system. Consequently, there is an accompanying fall in the demand for factor inputs, mainly because aggregate demand (of output and investment) dropped significantly more than the rise of consumption aggregate demand. Moreover, the marginal costs of inputs and the prices of the goods fell. The former is due to firms reducing demand for inputs while the latter serves as a device to encourage more aggregate economic activities.<sup>21</sup> With regards to international trade, a fall in income implies that there is an immediate drop in imports and a rise in exports since foreigners are relatively more well off. Real exchange rate depreciation occurs to assist in the re-balancing of BOP accounts and, thus, imports and exports begin to gradually travel in opposite directions.

We note the following about the remaining shocks in the group of productivity shocks. First, the energy efficiency shocks have the model implications of lowering the energy BTU input per volume unit of output. Hence, all energy (aggregate and sectoral) usage drops in response to these shocks and, because the amount of an input required has fallen, the cost of production also falls, such that the sectoral prices of goods followed suit. Second, we point out

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20. See Oyekola (2015) for detailed plots.

21. This negative response of hours to the productivity shock has also been found in other studies [see, for example, Christiano et al. (2003)]. However, the mechanism by which this contraction is effected in their model is different to that in ours, however: we put forth a story of structural/ sectoral re-allocation of resources, while they explore the notion of nominal rigidity of prices.

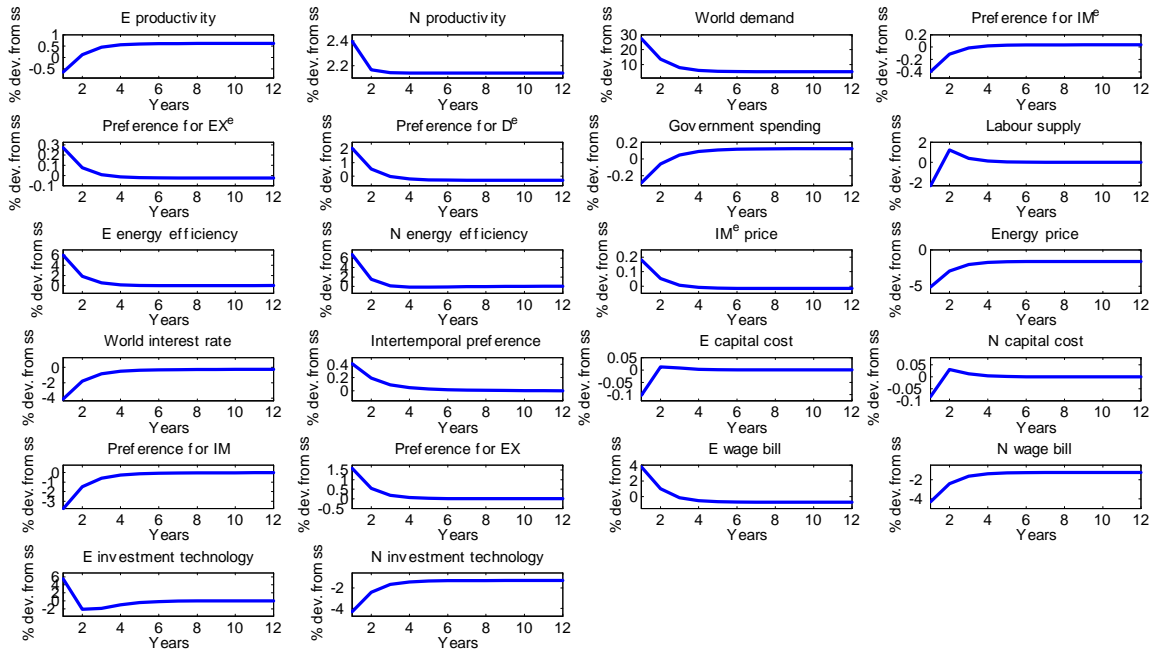


FIGURE V: IMPULSE RESPONSES OF OUTPUT TO THE SHOCKS.

the effects of two investment-specific technology shocks on consumption: because these shocks move resources from consumption to investment, it can be seen how the dynamic responses of consumption and investment are almost a perfect mirror image of each other.

Let us turn to the analysis of the impulse response functions to a positive standard deviation shock to the energy price. A rise in the energy price will lead to a decline in energy usage with the immediate effect being that of reducing capital utilisation. Concurrently, under-utilisation of other factors of production sets in, such that output has to fall. There are strong intratemporal and intertemporal substitution effects at work here acting to re-allocate resources because of capital utilisation rate. For instance, given a lowered capital utilisation rate, there is a lower marginal product of labour (i.e. the wage rate falls), and investment falls in response to lower marginal product of capital (the interest rate falls) so that consumption falls due to the created negative wealth effect. Energy usage falls because its cost as an input has gone up, and there is a decrease in capital demand because of the complementarity with energy. Two things to note regarding trade with the rest of the world: first, we observe that an increase in the price of energy has the effects of worsening the current account balance of a net oil importer like the U.S.; second, to stimulate demand, firms have to lower the sectoral prices of goods, with the rest of the world benefitting the most as exports increased. Then, as the real exchange rate begins to rise, the trade balance improves.

Next, we investigate the impulse responses to the preference shocks beginning with the labour supply shock for which a positive shock has a negative correlation with output. This indeed has both the intratemporal and intertemporal effects of reductions in both the aggregate consumption and investment, although the latter still rose in the  $n$  sector. Additionally, the

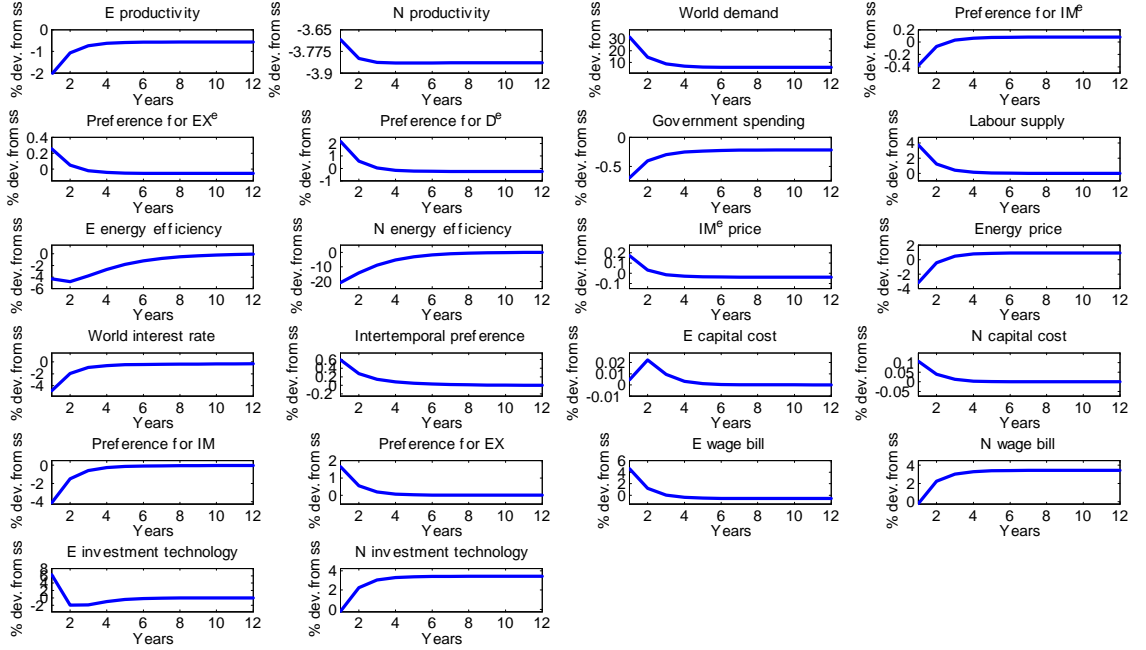


FIGURE VI: IMPULSE RESPONSES OF REAL EXCHANGE RATE TO THE SHOCKS.

substitution assumption between labour hours and the CES of capital services and energy use implies that the capital utilisation rate, capital, and energy use, all had to increase. This is what we observe, except for capital demand in the  $e$  sector, which also fell. An explanation for this can be offered: the model is, in this sense, indicating that labour hours and capital are complements in this sector. This contraction in labour supply and investment would lead to a rise in wages and interest rate. It is now more costly to produce output in the two sectors; hence, the jump in the sectoral prices. The consequence is a rise in the country's real exchange rate, signifying a drop in competitiveness vis-a-vis the rest of the world so that imports and exports go up and down, respectively. That is, as would be expected, the substitution effects kicks into full gear as the domestic economy runs down its foreign reserves.

Turning now to the intertemporal preference shocks and shocks to the preference for  $e$  goods, with the former, utility per unit of consumption rises for households such that they are content to smooth consumption intertemporally leading to higher investment and thus, growth in output. This will lead to higher factor demands and, concurrently, increases in factor prices to incentivise the households to supply. Higher costs of production means higher sectoral prices such that imports increases and exports decreases. Clearly, the real exchange rate appreciates as the domestic country becomes less competitive relative to the rest of the world. Likewise, the impulse responses of the model's variables to the one-off standard deviation of a positive shock to the preference for  $e$  goods are qualitatively similar, except for the effects on consumption and  $n$  output and inputs. These results can be due to: (1) the estimated weight of  $e$  goods in the aggregator function, which is found to be 26%; (2) there is re-allocation of resources from

the  $n$  sector to the  $e$  sector as demand increases for output of the latter.<sup>22</sup>

Now, we consider responses of the endogenous variables to the observed exogenous variables. A positive world demand shock leads to a rise in output, consumption, investment, hours, wages, and sectoral relative prices. It is easy to interpret the distinct responses of the sectoral variables to this shock. Considering each sector's level of openness to international trade, the share of  $e$  sector goods in cross-border trade is much larger such that the world demand shock affects the sector's output more. Further, the real exchange rate appreciation occurred because the rest of the world increased their demand for domestic exports. The impulse responses to world interest rate are qualitatively alike to that of the energy price shock. This is because both are aggregate price increases, unlike a positive one-off standard deviation shock to the imported price of  $e$  goods.

Essentially, an increase in  $P_{e,t}^{im}$  leads to a fall in the import of such goods, and consumption falls because aggregate consumption is a composite of imported energy intensive goods and because domestic sectoral prices have also been driven up. Moreover, the crowding out effects of government spending means that consumption and investment fall on the impact of the shocks and, because government spending is non-productive in the current model, it leads to a decrease in output, which sharply contradicts some findings in the literature.<sup>23</sup> We note that the fall in consumption is trivial since households are able to smooth consumption over time. A further effect is that both aggregate and sectoral labour hours increased on impact reflecting households' willingness to sacrifice some leisure during hard times. Thus, wages fall as labour supply increases. This causes output to start rising and to lessen the adverse wealth effect accompanying the government spending shock.

Finally, we examine the effects of the group of shocks labelled cost-push. These shocks are predominantly sector-specific and any impacts they generate on other variables are secondary effects. Moreover, only the energy intensive sector wage bill shifter generated non-standard results and so we only discuss this shock and in relation, basically, to output. We conjecture that the fall in labour hours demanded by firms in the  $e$  sector due to wage bill hikes does not lead to a fall in output of the  $e$  sector that is sufficient to lower aggregate output because of the different levels of input intensities.

## D Variance Decompositions

To explain the percentage of variation in each variable that is due to the different shocks, one can examine Table V, which documents the variance decomposition of the endogenous variables. Looking at these broad categorisations, exogenous variables are the most important to output, followed by the preference shocks, and energy price is the least useful. In fact, for all variables, energy price shocks make the least contribution to accounting for their movements. This is not sufficient to shake our belief that energy price shock is (should be) a main covariate

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22. The dynamics of the remaining shocks in the group (preference shocks) can be interpreted similarly to the case of the preference for  $E$  goods. Specifically, they act as a switcher of preferences between goods contemporaneously.

23. See, for example, Finn (1998) and Ravn et al. (2012).



TABLE V: VARIANCE DECOMPOSITIONS

Variable, symbol	Shocks				
	Productivity	Preference	Energy Price	Cost-push	Exogenous Variables
Aggregate output, $y_t$	18.06	26.20	8.86	17.56	29.32
Energy intensive output, $y_t^e$	18.22	24.76	8.30	18.49	30.22
Non-energy intensive output, $y_t^n$	18.37	25.56	8.58	18.93	28.57
Aggregate investment, $i_t$	12.69	12.72	5.15	10.20	59.25
Energy intensive investment, $i_t^e$	27.56	9.89	3.67	7.69	51.20
Non-energy intensive investment, $i_t^n$	31.64	4.40	2.15	3.83	57.98
Aggregate hours, $h_t$	18.15	27.20	9.06	18.19	27.41
Energy intensive hours, $h_t^e$	17.84	26.81	8.89	19.13	27.34
Non-energy intensive hours, $h_t^n$	18.03	26.98	8.97	19.00	27.02
Aggregate energy use, $e_t$	29.32	3.96	24.9	3.74	38.09
Energy intensive energy use, $e_t^e$	34.10	2.85	23.0	3.00	37.10
Non-energy intensive energy use, $e_t^n$	44.55	2.03	24.8	1.60	27.06
Domestic absorption, $d_t$	17.69	25.83	8.76	17.36	30.37
Aggregate imports, $im_t$	14.23	9.11	1.98	4.50	70.18
Energy intensive imports, $im_t^e$	13.83	8.65	1.48	3.53	72.51
Domestic absorption of energy intensive goods, $d_t^e$	17.91	25.30	8.55	18.09	30.14
Aggregate exports, $ex_t$	12.43	26.87	4.41	9.21	47.08
Energy intensive exports, $ex_t^e$	11.22	27.79	3.69	7.62	49.68
Wage, $w_t$	10.64	9.00	3.22	22.18	54.97
Interest rate, $r_t$	32.53	3.78	1.51	3.53	58.66
Price of energy intensive goods, $p_t^e$	19.96	22.75	7.59	20.90	28.80
Price of non-energy intensive goods, $p_t^n$	22.32	22.85	7.65	17.20	29.98
Net foreign assets, $b_t^f$	22.81	25.91	7.63	15.32	28.33
Consumption, $c_t$	18.61	26.60	9.04	18.18	27.57
Energy intensive capital, $k_t^e$	17.20	25.59	8.65	17.35	31.21
Non-energy intensive capital, $k_t^n$	18.14	26.10	8.67	17.28	29.81
Energy intensive capital utilisation rate, $u_t^e$	17.29	23.62	7.99	16.07	35.02
Non-energy intensive capital utilisation rate, $u_t^n$	17.65	25.66	8.64	17.27	30.77
Real exchange rate, $p_t$	26.24	18.20	6.15	13.82	35.59

Note: Productivity shocks: sum of sectoral Solow residuals ( $\mathbf{a}_t^e$  and  $\mathbf{a}_t^n$ ), energy and non-energy intensive investment-specific technologies ( $\mathbf{z}_t^e$  and  $\mathbf{z}_t^n$ ), and energy and non-energy intensive energy efficiencies ( $\mathbf{o}_t^e$  and  $\mathbf{o}_t^n$ ); preference shocks: sum of intertemporal preference ( $\tau_t$ ), labour supply ( $\zeta_t$ ), preference for imported energy intensive goods ( $\varphi_t$ ), preference for exported energy intensive goods ( $\varphi_t^w$ ), preference for energy intensive goods ( $\gamma_t$ ), preference for aggregate imported goods ( $\varpi_t$ ), and preference for aggregate exported goods ( $\varpi_t^w$ ); energy price shock ( $\mathbf{q}_t$ ); exogenous variables: sum of world demand ( $\mathbf{d}_t^w$ ), government spending ( $\mathbf{g}_t$ ), the price of imported energy intensive goods ( $\mathbf{p}_{e,t}^{im}$ ), and foreign interest rate ( $r_t^f$ ); cost-push shocks: sum of energy intensive sector capital cost shifter ( $\vartheta_t^e$ ), non-energy intensive sector capital cost shifter ( $\vartheta_t^n$ ), energy intensive sector wage bill shifter ( $\xi_t^e$ ), non-energy intensive sector wage bill shifter ( $\xi_t^n$ )

of macroeconomic variables. For example, while energy price shocks only approximately 4.55% of the shocks in the model, they account for 8.86% of movements in aggregate output, while the productivity shocks make up approximately 27.27%, but are only able to account for 18.06% of the movements in aggregate output. Proportionally, and as would be expected, energy price shocks are more important to aggregate and sectoral energy usage, being responsible for nearly a quarter, which will in turn lead to a drop or rise in output/ welfare depending on whether it was a positive or a negative energy price shock. This latter comparison is even more pronounced when it is observed that preference shocks, which make up roughly 32% of the shocks, can only determine 3.96% of aggregate energy use fluctuation, 2.85% of energy intensive sector energy use fluctuation, and 2.03% of non-energy intensive sector energy use fluctuation. This is not surprising, however, given that energy use is not modelled for the household and so there is a weak link between preference shocks and energy usage.

A more disaggregated look at the shocks provides a better insight into which shocks are individually most (least) important.<sup>24</sup> The key shocks are the permanent shocks accounting for well over 90% of movements in all variables considered, with the other shocks appearing

24. Tables of detailed variance decompositions are available upon request.

to be passengers in most contexts. For instance, the two sectoral Solow residuals are the most important of the productivity shocks, causing over 97% of the 18.06% share of productivity shock in aggregate output volatility. This evidence can be seen in the share of permanent shocks in the remaining categories reported in Table V. It is interesting to see that variability in imports (aggregate and energy intensive), exports (aggregate and energy intensive), and interest rate are dominated by world demand (66.5%, 69.7%, 38.3%, 42.3%, and 56.5%, respectively). It is, however, startling that 48.9% of the volatility in the U.S. wage rate is explained by world demand.

Further, labour supply, foreign interest rate, intertemporal preference, and energy and non-energy intensive sector capital cost shifters play a very negligible role in causing volatilities in any of the model variables. Regarding labour supply shocks, our finding disagrees with Meenagh et al. (2010) who find that it contributed 25.34% and 28.11% to output and consumption, respectively. Our results on the importance of interest rate shocks agree with studies by Mendoza (1991), Schmitt-Grohe (1998), and Correia et al. (1995) who all find that it exerts too minimal an influence on model variables to be a source of big variations. This is in sharp contrast to the findings of Blankenau et al. (2001) that interest rate shock transmission channels may induce large responses from model variables. Moreover, unlike Stockman and Tesar (1995) and Javier et al. (2010), we did not find that introducing intertemporal preference shock added anything to the variability of model variables.

## V CONCLUSION

We have developed and estimated a two-sector dynamic stochastic equilibrium open economy model of the United States in which imported oil is assumed to be crucial to production in order to study the response of output and real exchange rate to the exogenous positive movement in the price of oil. The main channels through which this shock works are by raising the costs of production (when energy price shoots up) with the added effect of lowering the marginal productivity of the remaining inputs (i.e., labour and capital) on the production side, and by acting as a resource drain in the economy-wide resource constraint. Qualitatively, we show that output is affected both intratemporally, which we call the *impact effect*, and intertemporally, which we call the *transition effect*, and we assess these results quantitatively in the estimated model. We find that the macroeconomic effect of oil price shock is still sizeable and that real exchange rate moves to account for these changes after each shock.

It would be interesting to carry out the preceding exercises for a number of countries, so as to study how their output and their competitiveness, measured by real exchange rate, change with changes in the exogenous world price of crude oil. To achieve this, it is preferable, and perhaps necessary, to extend this model to include an energy-producing sector if we are fully to grasp the effects of oil price increases on the general price level and the relative sectoral prices. Further, it may be important to investigate more extensively the cross-country sectoral terms of trade. One may want to study if there are any cross-country sectoral correlations of recessions.

An advantage to this would include the opportunity also to study the sectoral competitiveness along with the aggregate. In addition, it is likely that there is a gap between theory and data regarding certain measurements that we have used. Thus, it may be informative for future research to develop a version of this model augmented with an estimate of measurement error.

Finally, in the current paper we have explained what happens to output and real exchange rate when there is an exogenous increase in the real price of oil, but we have not attempted to offer any plausible policy recommendations for accommodating such occurrences. As a next step, therefore, it will be interesting to incorporate a monetary and/ or fiscal channels by which there could be policy responses. Although this has already been done by many authors, we think such an exercise within our theoretical framework, when properly motivated, could lead to a more optimal plan of actions.

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