ESSAYS ON ENERGY AND MACROECONOMICS

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... if we learn our limitations too soon, we never learn our power.

Hannibal Lecter

Abstract

This thesis represents largely the two sides to both theory and econometrics of dynamic macroeconomics, namely stationary and non-stationary models and data. The stationary part concludes with Chapter 3 and in Chapter 4, I look at the non-stationary side.

More specifically, I preview the thesis in Chapter 1 highlighting the modelling and econometric approaches commonly found in the economics literature; also I report some key results. In Chapter 2, I provide a comprehensive, but certainly far from being exhaustive, review of the literature dating back to the publication of Stanley Jevon's (1866) *The Coal Question*, but with the main discussion beginning with Harold Hotelling's (1931) *The Economics of Exhaustible Resources*. I develop a two-sector open economy extension to the Kydland and Prescott (1982), Long and Plosser (1983) and Kim and Loungani (1992) models in Chapter 3 and estimate it on H-P filtered annual U.S. data covering 64 years, with the main purpose of discovering how energy price along with other supply-side and demand-side shocks (imported and domestic) impacts on the U.S. economy. The model presented only contains the current account and I restrict trade to balance in every period. I find that model fits the data for my benchmark variables of interest in the auxiliary model: output, real exchange rate, energy use, and consumption. When more variables and in particular sectoral variables are added, meanwhile, to the auxiliary model, I find that the model's performance especially as it relates to this estimated model parameters did not fit. What I take from this is that the estimated structural parameters are not globally applicable within this economic environment.

This model is then further extended by including the capital account in Chapter 4 before re-estimation, but now also on non-stationary data, which I suppose is more representative of reality. I focus on the fit of the model to output and the economy's measure

of competitiveness: the real exchange rate. I find that the energy price and technology shocks have major effects on the U.S. output and relative competitiveness. The mechanisms by which these effects are transmitted are two-fold. First is via the terms of trade occurring as a resource drain on the economy as the U.S. would need to find extra resource to commit to the import of crude oil. The second is via household's reduced investment activity. Both channels can be explained by the fact that the substitution away from oil is happening at too slow a pace because of low estimated elasticities parameters. This agrees with Hamilton who argued that oil shock works via demand contraction. I have in this thesis verified his conjecture via a well-motivated and detailed microfounded dynamic stochastic general equilibrium (DSGE) model.

Finally, I review the thesis speculating on possible future extensions in Chapter 5.

Biographical Sketch

I was born on the 30th December 1979 in Ibadan, the capital city of Oyo State, in Nigeria where I sat my primary school leaving certificate exam at Ijokodo Community Primary School in 1990 and attended Loyola College (1991-1996). I also obtained a National Diploma in Accountancy from Abia State Polytechnic (2002-2004) graduating with a Distinction. I moved to the United Kingdom in 2006 to further my studies and have completed undergraduate (2007-2010) graduating with a First-Class, Masters (2011), Masters in Research (2012), and PhD (2013-2015) in Economics all from Cardiff University. My areas of interest are macroeconomic modelling and applied energy macro econometrics. Upon graduating, I will continue to work as a research economist in these areas.

To my family.

My parents:

Olanrewaju Solomon Oyekola and Olakunle Janet Adelekan-Oyekola.

My siblings and their spouses:

Banji and Oluwafunmilola Kehinde, Olubayo and Oluwabayonle Omotoso, Akinwole and Laitan Adelekan, Oluwatumininu Oyewole, Adewumi and Iyabo Oyekola, and Olawale and Bukola Oyekola.

My nephews and nieces:

Adetola Kehinde, Obaloluwa Kehinde, Ikeoluwa Osunsami, Oluwabusola Omotoso, Kikelomo Omotosho, Ebunlomo Omotoso, Omololu Omotoso, Akinkunmi Adelekan, Akindeji Adelekan, Precious Adelekan, Praise Adelekan, Peter Adelekan, Pious Adelekan, Sunbo Akinade, Taiwo Oyewole, Kehinde Oyewole, Fortune Oyekola, Marvelous Oyekola, Paul Oyekola, Funmilayo Oyekola, David Oyekola, Timothy Oyekola, Jonathan Oyekola, and Jason Oyekola.

My great nephews and nieces:

Divine Kehinde, Oluwasikemi Osunsami, and David Kehinde.

I am more because you are.

Acknowledgements

Mine is a life indebted to a lot of people most are real but a few are imaginary! Of the real, I must say thank you to the rest of *my* family (yes, I come from a big one) and friends: Fisayo Ishola, Kola Tayo, Kunle Tayo, Ademola and Tomilola Adedeji, Olumide and Taiwo Ojo, Grandpa and Grandma Julius Fadimilehin, Soji Akintayo, Sola Akintayo, Titi Adebiyi, Yemisi Onaolapo, Chidinma Emmanuel, Kunle Oyekola, and Niyi Oyekola. Of this group are Oladipo, Yetunde, Praise, Ephraim, and Phillip Adedokun - they have served as a massive guide and constant reminder of "where we came from!" I would also like to thank Javaria Nawaz who has practically been there for the duration of my PhD - what a reservoir of encouragement you have been.

I believe that everybody has someone destined to raise them up if they are ever fortunate enough to meet them. I did not miss mine in Adelaja and Nnenna Ojobo, my role models. Thank you for making yourself available to be used of God to ensure that I stayed the course of my found path. Thanks to Oluwadamilola, Oluwatosin, and Oluwabusayo for sharing their parents with me. You guys deserve your own paragraph.

I have partaken of the talents of many in my life and I would like to say thank you. So, thank you to you all. I would like to mention a few. Thank you to Bishop Francis Wale Oke for accepting the call of God. It is to your *alter call* that I responded those years ago and the influence of the youth ministry of Christ Life Church, Ibadan, in forming the dreams that I am now beginning to realise cannot be contested. Also, I would like to thank all my friends from this period. Please let this suffice as we all know that I would need a few pages to list all your names. In addition, I would like to thank Pastor Esther Olufunlayo for all her advice and prayers.

A few other organisations have been important to my growth over the years. In particular, I would like to thank both the faculty and members of staff of Abia State Polytechnic during the 2002-2004 academic sessions. I must mention of course the patron of *The Book Forum*, Elder Onukaogu and the executive members. Those are days I really wish I could replicate on a much larger scale, and it is because you chose to serve. Representative of this group of selfless individuals are Bello Kolawole, Clinton Madukwe, Ogbonnaya Kanu, Emmanuel Uduma, Gloria Ogiefo Kelani, Gloria Nwosu Adebayo, Amity Uche Kalu, and Chima Okafor.

I want to say to the Economics Class of 2010 that you are about to have a Dr in your ranks; thanks for all you do. For about 8 years, All Nations Church in Cardiff was my home church and what a blessed, wonderful family of God. Thank you everybody. I thank the following people especially for specific acts of kindness: Ayodeji and Tayo Rotibi, Andrew and Deborah Guy, Rob and Annie Sherwin, David and Cheryl Walker, Neil and Delyth Killen, and Kola and Tina Oduwaiye.

I am grateful to the faculty members (past and present) of Cardiff Business School especially of the Economics Section for these past 8 years. Your combined wealth of knowledge has been invaluable. In particular, I thank John Shorey, Caroline Joll, Max Gillman, Laurence Copeland, Gerry Makepeace, Huw Dixon, Calvin Jones, Mai Le, Panayiotis Poupourides, Akos Valentinyi, Kul Luintel, Michael Arghyrou, Helmuts Azacis, Kent Matthews, Jack Li and Zhirong Ou. I also want to thank Elsie Phillips, Laine Clayton, and Sara Bragg for all the support. In addition, I want to acknowledge Emmanuel Ogbonna of the Business Management Section for being a quiet inspiration.

Now, a big fat thank you to two people without which there would be no thesis to write an acknowledgement for. At some point, in the not so distant past, I had enough questions in me to do six PhDs (I had a six chapter proposal, but as it turns out, any of it was all I needed!) It was the tireless Patrick Minford who kept reminding me to set aside all these important questions till I finished my PhD. And, when I went off course as I did repeatedly, his carrot and stick approach was sufficient to lead me to writing a thesis I am now proud to put my name on. So, thank you Patrick. He did not do it alone, my second advisor, David Meenagh was very encouraging and is undoubtedly one of the most generous people I know professionally. Here is your big fat thank you.

Finally, I acknowledge the financial support of Julian Hodge Foundation and the Petroleum Trust Development Fund.

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List of Abbreviations

ACP: Adjustment Cost Parameter
ADF: Augmented Dickey-Fuller
AR: Autoregressive
ARIMA: Autoregressive Integrated Moving Average
BEA: Bureau of Economic Analysis
BLS: Bureau of Labour Statistics
BOP: Balance of Payments
BTU: British Thermal Units
CES: Constant Elasticity of Substitution
CDSGE: Computable Dynamic Stochastic General Equilibrium
CoCU: Cost of Capital Utilisation
CPI: Consumer Price Index
DC: Domestic Country
DF: Depreciation Function
DSGE: Dynamic Stochastic General Equilibrium
EIA: Energy Information Agency
EoCU: Elasticity of Capital utilisation
EoS: Elasticity of Substitution
FC: Foreign Country
FD: First-difference
FOC: First-order Condition
GDP: Gross Domestic Product
HP: Hodrick-Prescott
IMF: International Monetary Fund
IFS: International Financial Statistics
II: Indirect Inference
IRF: Impulse Response Function
KPLPKL: Kydland-Prescott-Long-Plosser-Kim-Loungani
KPSS: Kwiatkowski–Phillips–Schmidt–Shin
LIML: Limited Information Maximum Likelihood
NAICS: North American Industry Classification System
NBER: National Bureau of Economic Analysis
NGDP: Nominal Gross Domestic Product
NNFA: Nominal Net Foreign Assets
POP: Population Index
PP: Phillips-Perron
RBC: Real Business Cycles
RGDP: Real Gross Domestic Product
RoW: Rest of the World
SA: Simulated Annealing
SIC: Standard Industrial Classification

SoCE: Share of Capital Services and Energy
TMD: Transformed Mahalanobis distance
UIP: Uncovered Interest Parity
VAR: Vector Autoregressive
VECM: Vector Error Correction Model
WW II: World War II

List of Symbols

The following notations are used.

Chapter 3

UPPER-CASE ("^", lower-case) letters denote variables in their level (log-linear, steady state) form; time, t, sub-scripts are generally omitted.

Endogenous Variables

$Y\ \left(\widehat{Y}\right)$: Aggregate output

$Y_e\ \left(\widehat{Y}_e\right)$: Energy intensive sector output

$Y_n\ \left(\widehat{Y}_n\right)$: Non-energy intensive sector output

$C\ \left(\widehat{C}\right)$: Consumption

$I\ \left(\widehat{I}\right)$: Aggregate investment

$I_e\ \left(\widehat{I}_e\right)$: Energy intensive investment goods

$I_e\ \left(\widehat{I}_n\right)$: Non-energy intensive investment goods

$H\ \left(\widehat{H}\right)$: Aggregate labour hours

$H_e\ \left(\widehat{H}_e\right)$: Energy intensive sector labour hours

$H_n\ \left(\widehat{H}_n\right)$: Non-energy intensive sector labour hours

$K_e\ \left(\widehat{K}_e\right)$: Energy intensive sector capital

$K_n\ \left(\widehat{K}_n\right)$: Non-energy intensive sector capital

$U_e\ \left(\widehat{U}_e\right)$: Energy intensive sector capital utilisation rate

$U_n\ \left(\widehat{U}_n\right)$: Non-energy intensive sector capital utilisation rate

$E\ \left(\widehat{E}\right)$: Aggregate primary energy use

$E_e\ \left(\widehat{E}_e\right)$: Energy intensive sector primary energy use

$E_n\ \left(\widehat{E}_n\right)$: Non-energy intensive sector primary energy use

$P_e\ \left(\widehat{P}_e\right)$: Relative price of energy intensive goods

$P_n\ \left(\widehat{P}_n\right)$: Relative price of non-energy intensive goods

$W\ \left(\widehat{W}\right)$: Wages

$R\ \left(\widehat{R}\right)$: Gross interest rate

$R_e\ \left(\widehat{R}_e\right)$: Rental rate of energy intensive capital

R_n $\left(\widehat{R}_n\right)$: Rental rate of non-energy intensive capital
P $\left(\widehat{P}\right)$: Real exchange rate
D $\left(\widehat{D}\right)$: Domestic absorption
D_e $\left(\widehat{D}_e\right)$: Domestic absorption of energy intensive goods
D_n $\left(\widehat{D}_n\right)$: Domestic absorption of non-energy intensive goods
IM $\left(\widehat{IM}\right)$: Aggregate import
IM_e $\left(\widehat{IM}_e\right)$: Import of energy intensive goods
IM_n $\left(\widehat{IM}_n\right)$: Import of non-energy intensive goods
EX $\left(\widehat{EX}\right)$: Aggregate export
EX_e $\left(\widehat{EX}_e\right)$: Export of energy intensive goods
EX_n $\left(\widehat{EX}_n\right)$: Export of non-energy intensive goods
D^d $\left(\widehat{D}^d\right)$: Total domestic demand of domestically produced goods
D^f $\left(\widehat{D}^f\right)$: Total foreign demand of foreign-produced goods
P^d $\left(\widehat{P}^d\right)$: Price index for the bundle of domestically produced goods
P^f $\left(\widehat{P}^f\right)$: Price index for the bundle of foreign-produced goods
λ/ λ^C: Marginal utility of consumption
λ^H: Marginal disutility of labour hours

Exogenous Variables

A_e $\left(\widehat{\mathsf{A}}_e\right)$: Energy intensive sector productivity
A_n $\left(\widehat{\mathsf{A}}_n\right)$: Non-energy intensive sector productivity
D^w $\left(\widehat{\mathsf{D}}^w\right)$: World demand
G $\left(\widehat{\mathsf{G}}\right)$: Government spending
ζ $\left(\widehat{\zeta}\right)$: Labour supply
O_e $\left(\widehat{\mathsf{O}}_e\right)$: Energy intensive sector energy efficiency
O_n $\left(\widehat{\mathsf{O}}_n\right)$: Non-energy intensive sector energy efficiency
P_e^{im} $\left(\widehat{\mathsf{P}}_e^{im}\right)$: Price of imported energy intensive goods
P_n^{im} $\left(\widehat{\mathsf{P}}_n^{im}\right)$: Price of imported non-energy intensive goods
Q $\left(\widehat{\mathsf{Q}}\right)$: Energy price
τ $(\widehat{\tau})$: Intertemporal preference
Z_e $\left(\widehat{\mathsf{Z}}_e\right)$: Energy intensive investment-specific technology
Z_n $\left(\widehat{\mathsf{Z}}_n\right)$: Non-energy intensive investment-specific technology
P^{im} $\left(\widehat{\mathsf{P}}^{im}\right)$: Price of composite import (the numeraire)

Parameters

β: Discount factor
ω: Inverse of Frisch elasticity of labour supply

ε: Consumption elasticity
ι: Habit formation parameter
α_e: Energy intensive sector share of capital services and energy
α_n: Non-energy intensive sector share of capital services and energy
ν_e: Energy intensive sector elasticity of substitution between capital services and energy
ν_n: Non-energy intensive sector elasticity of substitution between capital services and energy
$\delta_{e1} u^{\mu_e}$: Energy intensive sector marginal cost of capital utilisation
μ_e: Energy intensive sector depreciation elasticity of capital utilisation
$\delta_{n1} u^{\mu_n}$: Non-energy intensive sector marginal cost of capital utilisation
μ_n: Non-energy intensive sector depreciation elasticity of capital utilisation
ψ_e: Adjustment cost parameter for energy intensive goods
ψ_n: Adjustment cost parameter for non-energy intensive goods
ϕ: Domestic country's elasticity of substitution between domestic and imported final goods
ϕ_w: Foreign country's elasticity of substitution between foreign and exported final goods
η: Domestic country's elasticity of substitution between imported energy and non-energy goods
η_w: Foreign country's elasticity of substitution between exported energy and non-energy goods
σ: Share of energy intensive goods in the domestic country
ς: Domestic country's elasticity of substitution between energy and non-energy intensive goods
δu_e: Steady-state depreciation function of energy intensive investment goods
δu_n: Steady-state depreciation function of non-energy intensive investment goods
θ_e: Weight on capital services of the energy intensive sector
θ_n: Weight on capital services of the non-energy intensive sector
$\frac{e_e}{k_e}$: Steady state energy intensive energy-capital ratio
$\frac{e_n}{k_n}$: Steady state non-energy intensive energy-capital ratio
$\frac{i_e}{k_e}$: Steady state energy intensive investment-capital ratio
$\frac{i_n}{k_n}$: Steady state non-energy intensive investment-capital ratio
$\frac{k_e}{y_e}$: Steady state energy intensive capital-output ratio
$\frac{k_n}{y_n}$: Steady state non-energy intensive capital-output ratio
$\frac{p_e}{p}$: Steady state ratio of the price of energy intensive goods to the general price level
$\frac{p_n}{p}$: Steady state ratio of the price of non-energy intensive goods to the general price level
$\frac{i_e}{i}$: Steady state ratio of energy intensive investment to aggregate investment
$\frac{i_n}{i}$: Steady state ratio of non-energy intensive investment to aggregate investment
$\frac{y_e}{y}$: Steady state ratio of energy intensive output to aggregate output
$\frac{y_n}{y}$: Steady state ratio of non-energy intensive output to aggregate output
$\frac{h_e}{h}$: Steady state ratio of energy intensive hours to aggregate hours
$\frac{h_n}{h}$: Steady state ratio of non-energy intensive hours to aggregate hours
$\frac{e_e}{e}$: Steady state ratio of energy intensive energy use to aggregate energy use
$\frac{e_n}{e}$: Steady state ratio of non-energy intensive energy use to aggregate energy use
$\frac{d_e}{y_e}$: Steady state ratio of domestic absorption of energy intensive goods to energy intensive output
$\frac{ex_e}{y_e}$: Steady state ratio of the export of energy intensive goods to energy intensive output
$\frac{im_e}{y_e}$: Steady state ratio of the import of energy intensive goods to energy intensive output
$\frac{ex}{e}$: Steady state ratio of aggregate export to aggregate energy use
$\frac{im}{e}$: Steady state ratio of aggregate import to aggregate energy use

$\frac{c}{y}$: Steady state share of consumption in output
$\frac{i}{y}$: Steady state share of investment in output
$\frac{g}{y}$: Steady state share of government expenditure in output
r: Steady state interest rate

Chapter 4

UPPER-CASE (lower-case) letters denote variables in their level (log-linear) form; note that the Greek-lettered exogenous variables are used loosely as they appear for both their level and log-linear forms.

Endogenous Variables

Y_t (y_t): Aggregate output
Y_t^e (y_t^e): Energy intensive sector output
Y_t^n (y_t^n): Non-energy intensive sector output
C_t (c_t): Consumption
I_t (i_t): Aggregate investment
I_t^e (i_t^e): Energy intensive investment goods
I_t^n (i_t^n): Non-energy intensive investment goods
H_t (h_t): Aggregate labour hours
H_t^e (h_t^e): Energy intensive sector labour hours
H_t^n (h_t^n): Non-energy intensive sector labour hours
K_t^e (k_t^e): Energy intensive sector capital
K_t^n (k_t^n): Non-energy intensive sector capital
U_t^e (u_t^e): Energy intensive sector capital utilisation rate
U_t^n (u_t^n): Non-energy intensive sector capital utilisation rate
E_t (e_t): Aggregate primary energy use
E_t^e (e_t^e): Energy intensive sector primary energy use
E_t^n (e_t^n): Non-energy intensive sector primary energy use
P_t^e (p_t^e): Relative price of energy intensive goods
P_t^n (p_t^n): Relative price of non-energy intensive goods
W_t (w_t): Wages
R_t: Gross interest rate
r_t: Net interest rate
R_t^e (r_t^e): Rental rate of energy intensive capital
R_t^n (r_t^n): Rental rate of non-energy intensive capital
P_t (p_t): Real exchange rate
D_t (d_t): Domestic absorption
D_t^e (d_t^e): Domestic absorption of energy intensive goods
D_t^n (d_t^n): Domestic absorption of non-energy intensive goods
IM_t (im_t): Aggregate import
IM_t^e (im_t^e): Import of energy intensive goods
IM_t^n (im_t^n): Import of non-energy intensive goods
EX_t (ex_t): Aggregate export
EX_t^e (ex_t^e): Export of energy intensive goods
EX_t^n (ex_t^n): Export of non-energy intensive goods
D_t^d (d_t^d): Total domestic demand of domestically produced goods
D_t^f $\left(d_t^f\right)$: Total foreign demand of foreign-produced goods
P_t^d (p_t^d): Price index for the bundle of domestically produced goods
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λ_t/ λ_t^C: Marginal utility of consumption
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Exogenous Variables

A_t^e (a_t^e): Energy intensive sector productivity
A_t^n (a_t^n): Non-energy intensive sector productivity
D_t^w (d_t^w): World demand
φ_t (φ_t): Preference for imported energy intensive goods
φ_t^w (φ_t^w): Preference for exported energy intensive goods
γ_t (γ_t): Preference for energy intensive goods
G_t (g_t): Government spending
ζ_t (ζ_t): Labour supply
O_t^e (o_t^e): Energy intensive sector energy efficiency
O_t^n (o_t^n): Non-energy intensive sector energy efficiency
$\mathsf{P}_{e,t}^{im}$ $\left(\mathsf{p}_{e,t}^{im}\right)$: Price of imported energy intensive goods
$\mathsf{P}_{n,t}^{im}$ $\left(\mathsf{p}_{n,t}^{im}\right)$: Price of imported non-energy intensive goods
Q_t (q_t): Energy price
R_t^f $\left(\mathsf{r}_t^f\right)$: Foreign interest rate
τ_t (τ_t): Intertemporal preference
ϑ_t^e (ϑ_t^e): Energy intensive sector capital cost shifter
ϑ_t^n (ϑ_t^n): Non-energy intensive sector capital cost shifter
ϖ_t (ϖ_t): Preference for aggregate imported goods
ϖ_t^w (ϖ_t^w): Preference for aggregate exported goods
ξ_t^e (ξ_t^e): Energy intensive sector wage bill shifter
ξ_t^n (ξ_t^n): Non-energy intensive sector wage bill shifter
Z_t^e (z_t^e): Energy intensive investment-specific technology
Z_t^n (z_t^n): Non-energy intensive investment-specific technology
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Parameters

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μ_n: Non-energy intensive sector depreciation elasticity of capital utilisation
ψ_e: Adjustment cost parameter for energy intensive goods
ψ_n: Adjustment cost parameter for non-energy intensive goods
ψ_f: Adjustment cost parameter for foreign bonds
ϕ: Domestic country's elasticity of substitution between domestic and imported final goods
ϕ_w: Foreign country's elasticity of substitution between foreign and exported final goods
η: Domestic country's elasticity of substitution between imported energy and non-energy goods

η_w: Foreign country's elasticity of substitution between exported energy and non-energy goods
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$\frac{e^n}{k^n}$: Steady state non-energy intensive energy-capital ratio
$\frac{i^e}{k^e}$: Steady state energy intensive investment-capital ratio
$\frac{i^n}{k^n}$: Steady state non-energy intensive investment-capital ratio
$\frac{k^e}{y^e}$: Steady state energy intensive capital-output ratio
$\frac{k^n}{y^n}$: Steady state non-energy intensive capital-output ratio
$\frac{p^e}{p}$: Steady state ratio of the price of energy intensive goods to the general price level
$\frac{p^n}{p}$: Steady state ratio of the price of non-energy intensive goods to the general price level
$\frac{i^e}{i}$: Steady state ratio of energy intensive investment to aggregate investment
$\frac{i^n}{i}$: Steady state ratio of non-energy intensive investment to aggregate investment
$\frac{y^e}{y}$: Steady state ratio of energy intensive output to aggregate output
$\frac{y^n}{y}$: Steady state ratio of non-energy intensive output to aggregate output
$\frac{h^e}{h}$: Steady state ratio of energy intensive hours to aggregate hours
$\frac{h^n}{h}$: Steady state ratio of non-energy intensive hours to aggregate hours
$\frac{e^e}{e}$: Steady state ratio of energy intensive energy use to aggregate energy use
$\frac{e^n}{e}$: Steady state ratio of non-energy intensive energy use to aggregate energy use
$\frac{d^e}{y^e}$: Steady state ratio of domestic absorption of energy intensive goods to energy intensive output
$\frac{ex^e}{y^e}$: Steady state ratio of the export of energy intensive goods to energy intensive output
$\frac{im^e}{y^e}$: Steady state ratio of the import of energy intensive goods to energy intensive output
$\frac{c}{y}$: Steady state share of consumption in output
$\frac{i}{y}$: Steady state share of investment in output
$\frac{\mathsf{g}}{y}$: Steady state share of government expenditure in output
$\frac{e}{y}$: Steady state share of energy use in output
$\frac{ex}{y}$: Steady state share of export in output
$\frac{im}{y}$: Steady state share of import in output
$\frac{c}{d}$: Steady state share of consumption in domestic absorption
$\frac{i}{d}$: Steady state share of investment in domestic absorption
$\frac{\mathsf{g}}{d}$: Steady state share of government spending in domestic absorption
w: Steady state wage rate
r: Steady state interest rate
f: Steady state foreign bonds

Chapter 1

Preview

Energy has different meanings to different people hence an engineer's view of energy and that of an economist is different. In fact, how we discuss energy may be as varied as the number of different professionals at the table. This is why the study and interpretation of energy related affairs would differ markedly across the many interconnected disciplines of energy economics. The ramifications of these views are observable in what interests the researchers in such fields of studies. There are two issues at least that are paramount and to which virtually every one of us may agree: (1) that energy is *progressive*; and (2) that the availability and the cost of energy is a *security concern.*

This thesis provides a macroeconomics take on the two points raised above whose combined effect is what I refer to as the energy question. It will evaluate the interrelationship of energy and energy price with other prices (aggregate and sectoral, global and local) and key macroeconomic variables like output, real exchange rate and consumption. Throughout this thesis, the theme remains the same, which is to investigate how noticeable on economic activities are changes in the energy market henceforth taken to be the crude oil market.

The thesis is a collection of three essays beginning in Chapter 2, where I provide a comprehensive, but not exhaustive, review of the economic literature on energy (price) and aggregate economic fluctuations. It catalogues a number of influential contributions and debates by many esteemed economists to this strand of economic research. In doing this, a few econometric and theoretical models are discussed in more details than the rest, but the message is clear: social scientists, just like the pure scientists, have been grappling with the energy question.

Building on the literature, I study an open economy that is subjected to vagaries of decisions by its trading partners especially the oil bloc. The question in mind then is can a model be organised to approximate the behaviour of a multi-sector economy such as the U.S. given a supply-side shock such as an energy (price) shock? Further, given an array of supply- and demand-side shocks perturbing the economy per period, how important is the effect of energy (price) shock? How are these shocks transmitted through the economy? Which is more disturbing between the impact and the transition effects of an energy (price) shock?

Developing functional model(s) to represent such a system could be a daunting exercise because of the several numbers of contending variables and parameters. Thus beginning with Chapter 3, I turn my attention to designing a two-sector computable dynamic stochastic general equilibrium (CDSGE) open economy model of the U.S. that formally admit energy into the production process in a way that can generate plausible parameter values with which an applied study can deal with a broad range of economic issues. The model in this chapter falls in the lineage of Kydland-Prescott-Long-Plosser-Kim-Loungani (KPLPKL, 1982, 1983, 1992) model in which I assume that (1) representative agents reside in a perfectly competitive economy making decisions regarding consumption, labour, investment, and output; (2) representative agents in the domestic country trade with their foreign counterparts; (3) imported crude oil is essential for production; and also (4) production takes place in two sectors and four types of goods are available for consumption and investment purposes.

Twelve shocks, domestic and imported, are allowed in the model and I require as a benchmark that the model fits the data for output, real exchange rate, energy use, and consumption: output because it serves as a measure of a country's total income; real exchange rate because it serves as a determinant of a country's relative competitiveness;

energy use because it serves as an indicator of special inputs into a country's production process; and consumption because it serves as a yardstick for evaluating a country's welfare. In Chapter 4, I examine the role of energy price shocks in effecting changes both at the aggregate and sectorial levels further by extending the model of the previous chapter to include capital account and re-estimating the model on non-stationary sets of data. I review the thesis, make concluding remarks, and speculate on possible future extensions in Chapter 5.

Chapter 2

The Energy Question

It borders on intrigue that we are still faced by many energy related questions almost a century on since Harold Hotelling's (1931) *Journal of Political Economy* paper, "The Economics of Exhaustible Resources." The problem of the day was financial as America and the rest of the world were neck-deep in the Great Depression. This work, therefore, was visionary. It was a general exposition on the problem of limits that is placed on a society's economic growth and development by its continued access to, or not, cheaply sourced commodity inputs of which energy in the form of crude oil was and remains principal.

He posed several questions many of which the profession is yet to satisfactorily provide answers to. It, however, goes without saying that he laid a very solid foundation for the study of resource economics theorising by exploiting his mathematical prowess on integrals with finite and infinite constraints - calculus of variations. The work stood out - fresh and robust, but still alone. A renowned outcome of this bold effort is the Hotelling's rule

$$p = p_0 e^{\gamma t} \tag{2.1}$$

which states that each unit of an exhaustible resource costs exactly same in every time period, where the period t price is denoted by p, starting date $t = 0$ price is denoted by

p_0, and γ denotes interest rate.[1]

Now, go back some 65 years and there was Stanley Jevons having a similar experience as he wrote that "... coal is all powerful" referring to the "Iron Age" as the "Age of Coal". These show how commodities (replaceables and exhaustibles alike) have always been very material to progress, but was never really given a prime seat in the congress of aggregate macroeconomic determinants. It seems that mankind often focused on the marvel (*Iron*) at the expense of the what derived it (*Coal*).

This is of course not intended to be an exhaustive review of the history of energy, or the discovery of its usefulness for that matter. Thus, for the purpose of the present review, let us fast forward to the 1970s when what happens in the energy sector began to also pronouncedly affect what happens in the non-energy sectors *adversely*.[2] In the current review, there is a tendency of bias towards pure consideration of the empirics and theories of energy macroeconomics as relating to how these energy market changes impact on output without much thoughts given to presumably demacating approaches that will come to the fore when authors are grouped into schools or methodologies. When this approach is taken, it must be for convenience of delivering the *message*.

In this period, the primary task of many of the authors was to improve the econometric modelling of output-input relations. The problem was the assumption of negligible substitutability between energy and the other more traditional inputs (capital and labour), which formed the main ingredients in the neoclassical considerations of production as captured by authors such as Cobb and Douglas (1927) and Leontief (1953). Also, other intermediate materials' inputs are treated mostly in isolation.[3] A major limitation of the empirical practices in these *early* periods is that energy (inputs) and prices are either completely excluded from the procedure or treated as the only inputs.

[1] This result has been questioned on a few grounds. One is that it only holds under perfect competition as already pointed out by Hotelling himself. Another one is that future cumulative production would run up the costs of extraction such that it gets costlier to postpone extraction in which case Hotelling's rule breaks down [see for example studies by Cummings (1969), Schulze (1974), Weinstern and Zeckhauser (1975), Peterson and Fisher (1977), and Arrow and Chang (1978) for early contributions in this area].

[2] See Devarajan and Fisher (1981) for comments on what transpired in the intervening years between Hotelling's paper and the oil crises of the 1970s.

[3] See Darmstadler et al. (1971), Dupree and West (1972), Schurr et al. (1960), Baxter and Rees (1968), and Mount et al. (1973) for such analysis.

Parks (1971) is one of the first authors to bring output and inputs together in a macro econometric environment where cross-price elasticities of substitution and complementarity can be studied. Building on this approach and in the aftermath of the 1973-74 oil crisis, Berndt and Wood (1975) investigated how firms choose their technology when presented with the prices of both their energy and non-energy input factors. So, they went a step further than Parks (1971) by explicitly including energy inputs in their production function. They argued that the firms'decision depends on the substitution possibilities available and considered the case where the required level of output comes from employing capital, labour, energy, and materials (KLEM). They devised a translog (production) cost function[4] and using the iterative three-stage least squares (I3SLS) estimator on the U.S. manufacturing time series data for the period 1947-1971, they find that energy demand is price responsive with own price elasticity of roughly -0.5, that the Allen partial elasticity of substitution between energy and labour is approximately 0.65 implying that the two have low substitutability, that energy and capital are complements with Allen partial elasticity of substitution of about -3.2, and also, their finding lends support to the already established high substitutability between capital and labour [see, for example, Berndt and Wood (1975), Tables 4-5, pp. 264-265].[5]

To validate the results in the above studies Griffin and Gregory (1976) applied the same translog methodology to a panel of international manufacturing time series data, which according to them is pertinent to the improvement they sought. Specifically, they observed that there is too little variability in the price data from the previous studies, and they stated three reservations of which I only mention the one they investigated, which is that the results of both Berndt and Wood (1975) and Hudson and Jorgensen (1974) have only general implications for the short-run cost functions. The following difference must be noted: unlike Berndt and Wood (1975) and Hudson and Jorgensen (1974), Griffin and Gregory assumed weak separability because of non-reliable intercountry price for intermediate materials such that they supposed that their translog cost function is homothetic in capital, labour and energy (KLE) taking the form $\Omega = \Omega\left[Y, \Omega_1\left(P_k, P_l, P_e\right), P_m, t\right]$ where

[4]This belongs to a class of cost functions that are twice differentiable. For more on this type of cost function, see Christensen et al. (1971, 1973).

[5]For corroborating results, see Berndt and Jorgensen (1973), Denny and Pinto (1976), Fuss (1977), among others.

$P_{i=k,l,e,m}$ denote the input prices. Then, they collected data for manufacturing in nine industrialised countries and estimated the model using iterative Zellner efficient (IZEF) procedure.

In presenting their results, they stated that if the assumption of weak separability is not upheld, their results may be biased just as it could do from simultaneous equation bias by not applying iterative three-stage least squares (I3SLS) estimator. Notwithstanding, the main contribution of their work is that they point out the likelihood of sign reversals in the estimates of capital-energy elasticities depending on time horizons: they obtained positive numbers ranging from 1.02 for Belgium and 1.07 for the U.S. [see Griffin and Gregory (1976), Table 2, p. 851].[6] The story would then be that long-run elasticities are better captured by using panel data if the model one adopts involves a translog cost function.

Beginning with the seminal contribution of Hamilton (1983), variations in the price of oil has become an important correlate to study in relation to observed variations in many indicators of aggregate and sectoral economic activities. In this work, Hamilton showed with evidence that representing relative price of energy as an exogenous process is a good practice. A large strand of theoretical and empirical literature has since been built around this idea with results dividing macroeconomists on the relative importance of primary energy or its price. It is not surprising today, with the benefits of more time series data available and with characteristics that are indeed distinct to those that Hamilton studied, to see all these opposing viewpoints. In fact, the economic effects of energy price changes on macroeconomic variables such as output, consumption, and investment appear to have been reversed in studies that spanned beyond the Hamilton's sample period to say late 1980s, or early 1990s [see, for example, Hooker (1997), Dhawan and Jeske (2008), and

[6] The intuition they provided for their result is supported by Berndt and Wood who argued that in response to (positively) large and persistent changes in the price of factor inputs, e.g. Organisation of Petroleum Exporting Countries (OPEC) causing energy price rises of 1973, the engineering profession would seek "the redesign and retrofitting potential of durable capital to facilitate interfuel substitution or improved energy efficiency..." [see Berndt and Wood (1977, p. 2)]. Given this, the economics profession would solve its cost minimisation problem on the grounds that the engineer's technological optimisation problem has been solved. Thus, in the long-run, energy and capital are expected to be substitutes especially when the reference for energy is fossil fuel. A word of caution is that Berndt and Wood (1977) submitted that this explanation is based on a two-input analysis and holds up the result of complementarity between capital and energy citing their 1975 econometric account. Still, Pindyck (1977) also using KLE approach on international pooled cross-section and time-series data, finds in support of Griffin and Gregory (1976).

Blanchard and Gali (2007)].

Just as empirical studies between output and inputs suffered from not including energy and non-energy inputs simultaneously prior to Berndt and Wood (1975), theoretical model did before the pioneering work of Kim and Loungani (1992) who studied the role of energy in a real business cycle (RBC) model of the U.S. Their work can be viewed as a second wave of extensions brought to the first generation refitting of Solow's (1956) neoclassical growth model. Here, I consider Kydland and Prescott (1982) and Long and Plosser (1983) as the first generation extension of Solow's concept to technology shocks. Due to the success of these papers, many extensions were carried out in the decade following to someimes lend support to the findings while at some other times to point out their shortcomings. See Kim and Loungani for references to some of the extensions, which I refer to as the first wave extensions to Solow's first generation extensions.

With many calls that the proponents of the RBC model should find a way other than unobserved Solow residual technology to evaluate its explanatory powers. Kim and Loungani picked up on the suggestions of, or perhaps, the challenge posed by two papers. First, McCallum (1989) asks for the need to start incorporating more supply-side effects such as the energy price shocks into the RBC model, "Presumably, future RBC studies will explicitly model these terms-of-trade effects and thereby reduce their reliance on unobserved technology shocks." The fact was that Kydland and Prescott and Long and Plosser have no foreign sectors such that imported shocks were localised wrongly as part of Solow residuals.[7]

Second, Christiano and Eichenbaum (1991) points out that RBC models were over-predicting the correlation between real wage and hours proposing that a way to resolve this issue would be to introduce measurable shocks, which they took to be government spending shocks. Reconciling the two propositions, what was important in the contribution of Kim and Loungani is that the very introduction of the energy price shocks was able to achieve both goals of reducing reliance on unobserved Solow residuals and of moving the theory closer to the data regarding its prediction of wage-productivity correlation.

[7] The finding by Hall (1988) that Solow residual measurement is sensitive to changes in energy prices also supports this standpoint.

I now briefly summarise their model and results. They worked with a modified version of Kydland and Prescott and Hansen's (1985) indivisible labour model in which prices and wages are perfectly flexible. Like Kydland and Prescott, they chose a constant-elasticity-of-substitution (CES) production function with constant returns to scale property, but unlike them, they included primary energy input in the production function instead of inventory stock; while they admitted to have worked with both divisible and indivisible labour economy, they presented results for only the latter. Further, while their model is still a closed economy model of the U.S. it indeed is implicitly an open economy model because the U.S. is a net importer of crude oil.[8]

Overall, they find that the model that simplifies to the Cobb-Douglas production function with three inputs achieves better results than the model with the CES form. Specifically, a model with the energy price only was able to explain about 35% of output volatility in the Cobb-Douglas case but just 16% in the CES case and when the Kydland-Prescott-Hansen basic RBC model augment with energy price shock is considered, the predicted correlation between real wage and productivity dropped by 17% in the Cobb-Douglas case and by 11% in the CES case.[9] Meanwhile, they obtained mixed results in regards to the importance of energy shocks as mechanised by the exogenous relative price of energy citing three possible channels of transmission via which their work could be improved: (1) introduction of price and wage rigidity as in, for example, Gordon (1975) and Phelps (1978), among others; (2) consideration of the effects of uncertainty on irreversible investment decisions as in Bernanke (1983); and (3) incorporating energy price shocks into a multi-sector RBC model as pushed for by, for example, Loungani (1986) and Hamilton (1988), among others.

Consequently, in an attempt to amplify the effects of the changes in energy price shocks on the variations in output volatility, Rotemberg and Woodford (1996) introduced imperfect competition into the mix. They had two main intentions in the paper. The first was to show that a model of imperfect competition can replicate the magnitude of the quantitative effects of energy price shocks on economic activity, especially output and

[8] Finn (1991) clarifies this interpretation of openness. Nevertheless, both theirs and Finn's models are still treated as closed economy because trade in other goods and services are not admitted.

[9] They noted that the drop in hours-wages correlation of 17% is comparable to the effects of 20% brought about by government spending shock in Christiano and Eichenbaum (1991).

real wage, better than would a perfectly competitive model. The second was to observe the innovations in the energy price shock that is exogenous part observable in the data based on a previous study in which they investigated the role of innovations to military purchases on output and real wages [Rotemberg and Woodford (1992)].

I find their approach to be quite interesting for two reasons. One, though the important variable is the real price of crude oil, they followed Hamilton (1985) in identifying the exogeneity of energy price shocks using the nominal price of oil. They referenced the fact that Texas Railroad Commission (TRC) hugely controlled the nominal price of oil in the U.S. In fact, Hamilton (pp. 99-100) wrote that

> The standard operating procedure of the commission was to forecast each month the demand for next month's production and use this forecast to prorate allowable production levels for each of the state's producing wells. As a result, gradual fluctuations in demand for petroleum were matched one-for-one by regulatory adjustments in supply, so that discounts or premiums were rarely allowed to continue long enough to lead to a change in posted prices. The state commissions were largely successful in accomodating gradual adjustments in demand associated with cyclical economic factors and the secular trends of imports and new discoveries. However, I will argue ... that they were generally unable to or unwilling to accomodate sudden shocks of an essentially supply-based character, and ... that a "regulatory filter" has been applied to the obvious endogenous economic factors responsible for changes in petroleum demand, so that only large exogenous shocks specific to petroleum sector show up in the historical price series. For this reason, I argue that the nominal posted price of crude oil in the United States ... uniquely tracked a series of exogenous historical shocks to the petroleum sector during the regulatory regime.

Thus, to exclude the innovations in the real price of crude oil that may be due to other domestic shocks, e.g. technology, taste, investment, or inflation shocks, they opted to recover the shocks to the real price of oil through the nominal price of oil. Two, they set up a structural model that nests four types of market assumptions and simulate the models to see which best matched their estimated responses of output and real wage to the exogenous energy price shocks extracted from the above procedure. I next briefly review their model's distinct features and summarise their findings.

More specifically on the model, they considered Kim and Loungani (1992) and Finn (1991) type model under imperfect competition - this is implemented via the production structure. To this end, they worked with a modified production function of Gordon (1984) and Bruno and Sachs (1985), where symmetric firms combine an index of value-added input, V_t,[10] energy input, E_t, and materials input, M_t, to produce gross output, Y_t.[11]

Moreover, their specification of the economy-wide resource constraint is also worth mentioning. In a way, they stated that: $C_t + I_t + G_t = Y_t - M_t$ explaining that there are no resource cost to be associated with energy production. Some collusive oligopolistic firms are just the 'lucky' ones to be selling energy at the exogenous price, p_{Et}, and redistributing the resulting gains back to households who are the shareholders in the firms. This is clearly different from the interpretation of the economy-wide resource constraint in Kim-Loungani-Finn specification: $C_t + I_t + G_t = Y_t - M_t - p_{Et}E_t$, which carries with it the more realistic idea that it is what is left over after the costs of both materials and energy inputs have been deducted from output that is available to the economy for use as either consumption, investment, or government expenditure. Having said this, one must admit that the results from both specifications are going to be congruent in that it really does not matter whether the firms or the households paid directly for the energy input.

Also important for mention is that four theories of mark-ups, denoted by μ_t, were considered, viz: (1) perfect competition where $\mu_t = 1$; (2) monopolistic competition with homothetic tastes where $\mu_t = \mu > 1$; (3) customer market model of Phelps and Winter (1970) where $\mu_t = \mu(X_t/Y_t)$ is decreasing in its arguments; and (4) implicit collusion model of Rotemberg and Saloner (1986) where $\mu_t = \mu(X_t/Y_t)$ is increasing in its arguments.[12] Finally, they stated an ad hoc equation to take into account the fact that output of the economy contains domestic supply of energy but this was not modelled.

[10] V_t is composed of capital, K_t, and labour, H_t.
[11] Formally, $Y_t = Q(V_t, G(E_t, M_t))$ with $V_t = F(K_t, z_t H_t) - \Phi_t$.
[12] See Rotemberg and Woodford (1991, 1992, 1995) for details.

This they did by assuming that some constant fraction, $s_D \in (0,1)$, of energy, E_t, used for production in the economy is domestically-produced, E_t^d, and imposed this on the economy-wide resource constraint to obtain: $Y_t - M_t - p_{Et}E_t + p_{Et}E_t^d$. They set $s_D = 0.5$ claiming that it approximates the share of U.S. oil usage that is produced domestically.

They find the following. The contraction in output generated by the competitive model after a positive shock to the energy price is smaller than indicated by the data plus this version failed to predict that output decline in the second year after the shock should be greater than in the first year. On the static monopolistic competition model, they showed that by just making the mark-up, μ, equal to 1.2 instead of unity the contraction of output $5-8$ quarters after the shock is double what it was under the perfect competition model though the impact effect is less. The customer market model was less successful in predicting the second year level of output decline but got the most decline on impact. The most successful of the models they presented is the implicit collusion model where output contraction after 5 quarters is biggest and most persistent. More importantly, given their parameterisation, only the implicit collusion model has a predicted path that lies within the estimated confidence interval. Finally, just as in the case of output, the implicit collusion model achieves the best outcome of replicating the data statistics for real wage.

Now, in a series of papers spanning over a decade and especially as a response to Rotemberg and Woodford, Finn (2000)[13] maintains that perfect competition can achieve the same results so far capital utilisation rate is modelled to depend on energy usage - this way, the main channel via which energy enters the production function is capital utilisation, and not directly. A unique feature of this model is that capital utilisation rate works endogenously to reduce output when energy prices go up while at the same time posing a higher cost to the use of capital via increased depreciation costs. What is important here is that Rotemberg and Woodford did not model endogenous capital utilisation probably because Kim and Loungani's perfect competition model on which they base their version of perfect competition model did not.

[13]See also Finn (1991, 1995, 1996).

On the other hand, Finn describes a production function giving a standard neoclassical appearance (output is produced using labour and services of capital as inputs) albeit with a hidden trick - capital services is given as a function of capital utilisation.[14] Formally, assuming a Cobb-Douglas form, Finn derived: $y_t = (z_t l_t)^{\theta} (k_t u_t)^{(1-\theta)} = (z_t l_t)^{\theta} \left[k_t^{\left(1-\frac{1}{\upsilon_1}\right)} \left(\frac{\upsilon_1}{\upsilon_0} e_t\right)^{\frac{1}{\upsilon_1}} \right]^{(1-\theta)}$ because energy-capital complementarity is assumed to be given by the technology relation: $\frac{e_t}{k_t} = a(u_t)$ where $a(u_t) = \frac{\upsilon_0 u_t^{\upsilon_1}}{\upsilon_1}$ such that $u_t = \left(\frac{\upsilon_1}{\upsilon_0} \frac{e_t}{k_t}\right)^{\frac{1}{\upsilon_1}}$.

The above is the direct channel as in Kim and Loungani and Rotemberg and Woodford, which Finn claims needed the addition of the indirect channel under the perfect competition model to generate effects of the magnitude obtained in models assuming imperfect competition particularly the implicit collusion model.[15] Finn presents results for the endogenous capital utilisation and the constant capital depreciation models. She finds that the former model performs better than the latter and can match the estimated responses of output and real wage to energy price increases just as did the imperfect competition models of Rotemberg and Woodford.

My focus in this thesis is not to join the debate on which theory, perfect or imperfect competition, is right or wrong in explaining the question posed by the large negative impact caused by energy price jump, especially when one considers its size in national output. However, I find it odd though that limited research effort has gone into consistently building dynamic stochastic general equilibrium (DSGE) models around this clearly important macroeconomic variable.

[14] This can be interpreted as a version of the idea of utilised capital put forth in Jorgensen and Griliches (1967). Instead of having a composite of energy and capital, Finn introduces a form of energy usage that is an increasingly costly function of capital utilisation.

[15] See a few references in Finn (2000) of models with endogenous capital utilisation. Today, this is now almost common place to allow for this real rigidity in RBC modelling, where it is modelled to primarily transmit via the capital accumulation equation, and is based on Keynes' idea of user cost of capital.

Chapter 3

Energy Business Cycles

> ... the interesting question raised by the ... model is surely not whether it can be accepted as 'true' ... Of course the model is not 'true': this much is evident from the axioms on which it is constructed. We know from the outset in an enterprise like this (I would say, in *any* effort in positive economics) that what will emerge - *at best* - is a workable approximation that is useful in answering a limited set of questions. Robert E. Lucas, Jr. (Models of Business Cycles, 1987, p. 45).

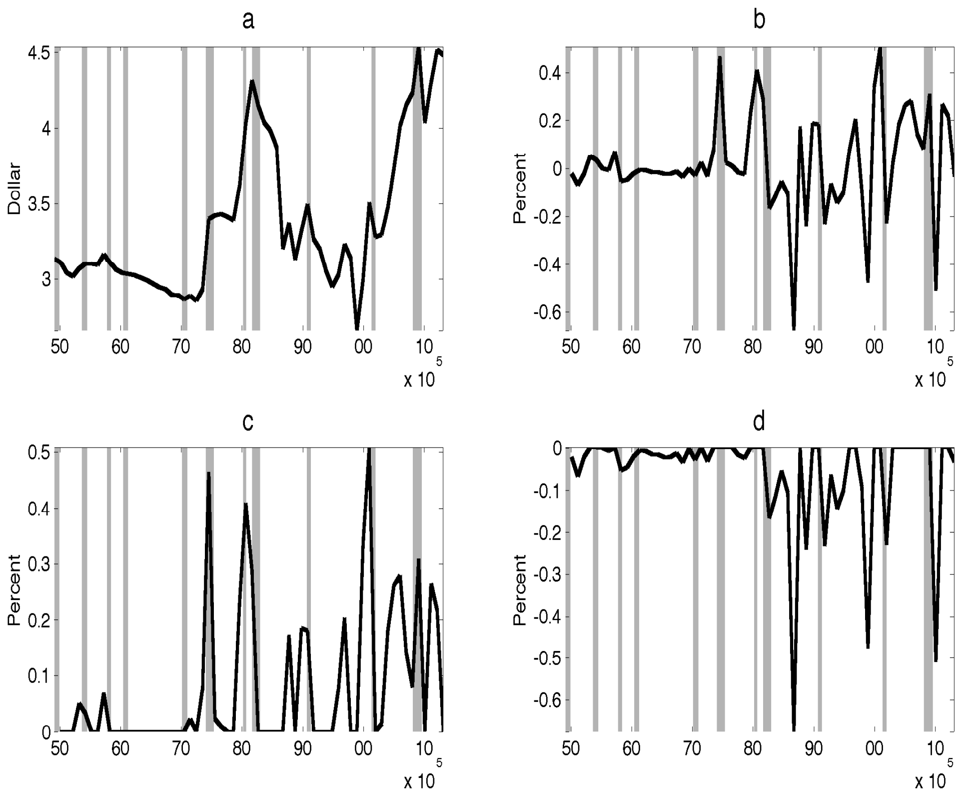
3.1 Introduction

Shocks come and they go often leading to and leaving behind unusual business cycle realisations. Like the Hurricanes we like to name these events with examples including the Great Depression in the 1930s, Stagflation of the 1960s, Oil Crises in the 1970s, the Great Moderation commencing in the 1980s, Japan's lost decade for the 1990s, and the Great Recession of the 2000s. Accompanying each of these experiences are usually influxes of research efforts trying to explain what has happened, and sometimes offer policy instruments for resolving the problem(s). The current chapter is related to such studies seeking to explain causes, consequences, and paths to recovery following an adverse shock. It is however different in one important dimension: it is a study not reacting per se to a particular oil price shock but mainly adding to the ever growing body of work on energy economics. Meanwhile, as in Blanchard and Gali (2007) exempting the policy implications, this work is connected to the literature on both the impact effect of energy price movements on economic activities as put forth by Bruno and Sachs (1985) and the surprisingly small changes to economic activities over time when energy prices move.

The above raised two further points of debate. First is that one of the important questions that have been circulating in the economics profession since the Great Moderation is, "Is the reduced influence of energy price shocks on output volatility observed in the data since the mid-1980s the new norm? This is a legitimate concern if we consider for instance that the positive percentage energy price change reached a high of 145% in 2008 having been climbing from 2002 and yet the Great Recession was attributed to the demand shock of housing default and supply shock of financial credit constraint.

To answer this question, among others, a large strand of theoretical and empirical literature has been built around a dividing line with many continuing to lend support to the seminal contribution of Hamilton (1983), which showed that variations in the price of oil is an important correlate to study in relation to observed variations in many indicators of aggregate and sectoral economic activities. However, it is not surprising that with the benefits of more time series data that is available and with economic characteristics that are distinct to those that Hamilton studied, the economic effects of energy price changes on macroeconomic variables such as output, consumption, and investment appear to have been reversed in studies that spanned beyond the Hamilton's sample period to say late 1980s, or early 1990s [Hooker (1997)].

The second is like the first: there seems to be no agreement in outcome because of the linear structure between oil (prices) and output assumed originally in Hamilton's empirical work, which technical interpretation and specification has been carried over into theoretical modelling [see, for example, Kim and Loungani (1992), Rotemberg and Woodford (1996), and Finn (2000)]. This is a problem arising from treating energy price shocks symmetrically. Indeed, researchers of oil-macroeconomic relationships in the late



Note: Crude oil price series is from the Energy Information Administration (EIA). Shaded bars are the NBER-dated recessions for 1949-2012. a: log of real crude oil price scaled up by 100; b: first-difference of the log of real crude oil price; c: net oil price increases obtained by setting negative first-differences to zero; d: net oil price decreases obtained by setting positive first-differences to zero.

Figure 3.1: Crude oil price and the U.S. recessions

1970s and early 1980s did not face this problem because the evidence before them was that energy shocks were mainly price rises. This has made Mork (1989) to advocate the need to correct for the true effects of energy price shocks by assuming asymmetry. That is, given the log of real crude oil price series as depicted in panel a of Figure 3.1, Hamilton's original approach of symmetry would admit panel b, which is equivalent to the first-difference of the log of real crude oil price, while Mork's treatment encourages to split panel b into panels c and d, which respectively, defines the first-difference of the positive and negative regions of panel b. His point is that we should study the respective contributions towards output variations of price rising and falling separately.

While this adaptation of the oil price series may appear unnecessary pre-1970, it clearly seems like a convincing experiment to carry out post-1970 as the decades of true oil volatilities was ushered in. However, my benchmark approach is to treat energy price shocks symmetrically. Hooker's (1997) finding that data does not support nonlinear and asymmetric representation of the oil-macroeconomic variable interaction permits this launch pad plus I am mainly interested in how energy price shocks impact aggregate macroeconomic variables. Moreover, on theoretical grounds, this is the right place to start given that my model does not capture asymmetric response of macroeconomic variables.

The remainder of this chapter proceeds as follows. In Section 3.2, I describe the main features of the two-sector model in general form. In Section 3.3, I provide brief discussions of the econometric method of indirect inference (II) used in estimating the model, the data serving as the empirical counterparts to model variables, and the initial parameter values used to initialise the starting points for the Simulated Annealing (SA) algorithm. I present the main findings in Section 3.4 and conclude with Section 3.5.

3.2 The Model

The model is based on Long and Plosser (1983) as augmented by the model of Kim and Loungani (1992). I set this up as a two-sector open economy model that is essential to characterising the data properties of a two-sector U.S. open economy. I suppose that the finished goods of the two sectors are imperfect substitutes for similar products being produced abroad; that is, trade is assumed necessary and made possible by representative households in different countries who are willing to buy from other countries goods similar to those being produced in their own countries mainly because they attribute different qualities to products based on production origin. In what follows, I suppose that the economy is populated by a continuum of mass 1 of households, and a continuum of mass 1 of firms for each sector in each country. On the supply side, there are two production sectors consisting of firms producing two types of goods with different levels of energy intensities. The firms requiring greater amount of energy for production make up the energy intensive, e, sector producing energy intensive goods, Y_e, and the remaining firms are the non-energy intensive, n, sector producing non-energy intensive goods, Y_n. The crude assumption is that any product that is energy (non-energy) intensive in its production is likewise energy (non-energy) intensive in its consumption. As is appropriate in this economy, the firms are supposed to engage three factors of production, namely: labour hours, capital services, and primary energy. Labour hours and capital services are assumed to be internationally immobile, but the domestic firms import their primary energy requirement.[1] Further, the demand side consists of the households who demand composite consumption good, C, make decisions on investment, I, pay taxes to or receive benefits from the government, T, and supply aggregate labour hours, H, which is costlessly shared to the two production sectors of the domestic economy given the wage rate, W. Households can invest in two types of physical capital, K_e and K_n, assumed to be subject to capital adjustment cost, and have access to domestic bonds, B. Hence, they accumulate income from hiring their labour hours and capital services out to the firms and from profits accruing due to their ownership of the firms and government debts. Lastly, I assume that households carry out all trades in goods and services with the rest of the world while firms trade in crude oil. To simplify matters, the model economy has been described in terms of the domestic country.[2] Meanwhile, all prices have been expressed relative to the general price level in the rest of the world, which has been chosen to be the numeraire, $\mathsf{P}^{im} = 1$. I next characterise the activities of domestic agents mostly in general forms.[3]

[1] The U.S. is a net oil importer.

[2] Many open economy models, at least, whenever countries being modelled are allowed to produce more than one good, are usually assumed to have such products as tradable and non-tradable, exportable (importable) and non-exportable (non-importable), etc. This is a valid assumption, however, given that this has been studied extensively, but also and very importantly due to the focus of my study, I have shut down the non-tradable (/ non-exportable/ non-importable) of the model economies such that for the purpose of my exercise, I have assumed that all produced goods and services are tradable between the domestic country and the rest of the world. It is meant to be heuristic and I then use this to draw attention to a four-goods world. This is supported by Engel (1999) and Chari et al. (2002): they found that variations in the relative price of non-tradable are unimportant for accounting for the changes in real exchange rate. Hence, unlike in Stockman (1980), there is no complete specialisation in the production of goods.

[3] I present the main functional forms in a later section, but for detailed and explicit set-up and characterisation of the agents' optimisation problems, the first-order conditions, and the log-linearised version, see the Supplementary Notes: Chapter 3. Foreign agents' problems and solutions can be inferred from those of the domestic agents. On the notation, I use the following: UPPER-CASE letters $X' \equiv X_{t+1}$, $X \equiv X_t$, and $X_{-1} \equiv X_{t-1}$ for dynamic variables for next, current, and last period, respectively; lower-case letters, say x, to denote non-stochastic steady state of variables; hatted letters, "$\hat{}$", to denote variables in their log-linear form; and sans serif along with the Greek letters denote the exogenous state variables.

Households

The discussion begins with the households' decisions by considering first their links with the domestic firms and I leave till later their links with the rest of the world. The lifetime utility function of the representative households is described by

$$\mathbb{E}\sum_{0}^{\infty}\beta\tau U\left(C-\iota C_{-1},\zeta H\right) \tag{3.1}$$

where β denotes the fixed discount factor, τ denotes the exogenous intertemporal preference shock, C denotes aggregate consumption, ζ denotes the exogenous labour supply shock, H denotes the supply of labour hours, and ι denotes the degree of habit formation. The function $U(\cdot)$ is assumed to obey standard regularity conditions.

The sequential budget constraint of the household is given by

$$\mathbb{E}R'B'+C+I+T=B+WH+R_eU_eK_{e,-1}+R_nU_nK_{n,-1}+\Pi \tag{3.2}$$

which states that households' expenditure must be equated by their income. $\mathbb{E}$ is an expectation's operator, $\mathbb{E}R'=\frac{1}{R}$ denotes the stochastic discount factor with $\mathbb{E}R'B'$ defining period t's price of period $t+1$'s random payment of B', and R denoting interest rate, B denotes domestic government's bonds, T denotes lump-sum taxes or transfers, W denotes consumer real wage rate, R_e and R_n are sector-specific rental rates of capital services, U_e and U_n are sector-specific indexes of capital utilisation rates of the beginning-of-the-period sector-specific capital stocks, $K_{e,-1}$ and $K_{n,-1}$, and Π denotes the profit income from their ownership of firms.

Further, it is assumed that households choose the stocks of physical capital, $K_{e,-1}$ and $K_{n,-1}$, which are, for $j=e,n$, the beginning-of-the-period t stock of capital in j sector. Essentially, households determine these variables in period $t-1$, and are assumed to have access to the following technologies for altering the quantities of e and n capital stocks from period $t-1$ to period t

$$K_e = (1 - \delta(U_e)) K_{e,-1} + \mathsf{Z}_e I_e - \Psi_e \left(\frac{K_e}{K_{e,-1}} \right) \tag{3.3}$$

and

$$K_n = (1 - \delta(U_n)) K_{n,-1} + \mathsf{Z}_n I_n - \Psi_n \left(\frac{K_n}{K_{n,-1}} \right) \tag{3.4}$$

respectively, where I_j denotes sector-specific gross investment, Z_j denotes sector-specific exogenous investment-specific technological shock, $\delta(\cdot)$ denotes sector-specific time-varying depreciation rate of physical capital and is assumed to possess the following properties: $0 \leq \delta(\cdot) \leq 1$, $\Delta\delta(\cdot) > 0$, and $\Delta\Delta\delta(\cdot) > 0$,[4] and $\Psi_j(\cdot)$ denotes the assumption that changing the stocks of physical capital is subject to convex adjustment costs[5] and is assumed to possess the following properties: $\Psi_j(\cdot) = \Delta\Psi_j(\cdot) = 0$, and $\Delta\Delta\Psi_j(\cdot) > 0$ as in Baxter and Crucini (1995). Aggregate investment is defined as the sum of the sector-specific investments

$$I = I_e + I_n \tag{3.5}$$

Households choose sequences $\{C, H, I, I_e, I_n, B', U_e, U_n, K_e, K_n\}_0^\infty$ by maximising the utility function (3.1) subject to equations (3.2), (3.3), (3.4), (3.5), and a borrowing constraint of the form

$$\lim_{t \to \infty} \mathbb{E} R' B' \geq 0 \tag{3.6}$$

Hence, the first-order necessary conditions of the households' maximisation problem consist of the sequential budget constraint (3.2), capital accumulation equation for the energy intensive investment goods (3.3), capital accumulation equation for the non-energy intensive investment goods (3.4), aggregate investment (3.5), the borrowing constraint (3.6)

[4] Δ denotes first derivative; $\Delta\Delta$ denotes second derivative.

[5] Where I have followed Kose (2002) in assuming that there is capital adjustment costs for both types of capital goods.

holding with equality, and the following

$$-\frac{\zeta U_2\left(C-\iota C_{-1},\zeta H\right)}{U_1\left(C-\iota C_{-1},\zeta H\right)}=W \tag{3.7}$$

$$\frac{\tau U_1\left(C-\iota C_{-1},\zeta H\right)}{\beta\mathbb{E}\tau' U_1\left(C'-\iota C,\zeta' H'\right)}=R \tag{3.8}$$

$$R_e=\frac{\Delta\delta\left(U_e\right)}{\mathsf{Z}_e} \tag{3.9}$$

$$R_n=\frac{\Delta\delta\left(U_n\right)}{\mathsf{Z}_n} \tag{3.10}$$

$$\begin{aligned}\left(1+\Psi_e\left(\frac{K_e}{K_{e,-1}}\right)\right)=\beta\mathbb{E}\frac{\tau' U_1\left(C'-\iota C,\zeta' H'\right)}{\tau U_1\left(C-\iota C_{-1},\zeta H\right)}\frac{\mathsf{Z}_e}{\mathsf{Z}'_e}\Bigg\{1-\Psi_e\left(\frac{K'_e}{K_e}\right)\\+R'_eU'_e\mathsf{Z}'_e-\delta\left(U'_e\right)+\Delta\Psi_e\left(\frac{K'_e}{K_e}\right)\frac{K'_e}{K_e}\Bigg\}\end{aligned} \tag{3.11}$$

and

$$\begin{aligned}\left(1+\Psi_n\left(\frac{K_n}{K_{n,-1}}\right)\right)=\beta\mathbb{E}\frac{\tau' U_1\left(C'-\iota C,\zeta' H'\right)}{\tau U_1\left(C-\iota C_{-1},\zeta H\right)}\frac{\mathsf{Z}_n}{\mathsf{Z}'_n}\Bigg\{1-\Psi_n\left(\frac{K'_n}{K_n}\right)\\+R'_nU'_n\mathsf{Z}'_n-\delta\left(U'_n\right)+\Delta\Psi_n\left(\frac{K'_n}{K_n}\right)\frac{K'_n}{K_n}\Bigg\}\end{aligned} \tag{3.12}$$

where U_ϱ denotes partial derivative of U with respect to its $\varrho-th$ argument. Equilibrium condition (3.7) states that the marginal rate of substitution between labour and aggregate consumption is equal to the wage rate. Equilibrium condition (3.8) states that the intertemporal marginal rate of substitution in the aggregate consumption is equal to the relative price of bonds such that households are indifferent between consumption and saving, or put another way, they are indifferent between consumption today and consumption tomorrow. Equilibrium conditions (3.9)-(3.10) equate, for each type of physical capital stocks, marginal user cost to marginal use benefits. Lastly, equilibrium conditions (3.11)-(3.12) relate marginal costs and returns to optimal choices between consumption and investments in the two types of physical capital stocks.

Firms

Aggregate output of the domestic country, denoted by Y, is defined as the sum of the gross output[6] of the two production sectors of the economy

$$Y = Y_e + Y_n \tag{3.13}$$

where output has been measured in volumes to follow standard practices in computing national accounts. The energy intensive sector output, Y_e, is assumed to be produced with a homogeneous-of-degree-one production function, which differs from the standard neo-classical production function mainly because I have included primary energy use specific to this sector, E_e, as an essential input into production

$$Y_e = \mathsf{A}_e F^e \left(H_e, U_e K_{e,-1}, \mathsf{O}_e E_e\right) = D_e^d + EX_e \tag{3.14}$$

where A_e denotes the neutral sector-specific productivity shock, H_e denotes the sector's demand for labour hours, $U_e K_{e,-1}$ denotes the sector's demand for capital services, and O_e denotes an exogenous sector-specific shock to the productive efficiency of energy input, capturing the productivity effect of changing the quantity/ type of energy, and/ or the impacts of developing or gaining access to a better technology for delivering the energy input into the production process.[7] The expression to the right of the second equal sign says that the output of the energy intensive sector can either be absorbed domestically, D_e^d, or exported to the rest of the world, EX_e.[8] Further, the function $F^e(\cdot)$ is assumed to obey standard regularity conditions.

Firms in this sector are assumed to be perfectly competitive in both the product and

[6]Following Kydland and Prescott (1982) and Christiano (1988), these should actually be defined as value added output. That is, gross output less the usage of energy, and also to match the measurement of the empirical counterparts to Y_e and Y_n.

[7]Suggestions by Greenwood (1983) and McCallum (1989) among others prompted the need to study an environment where production function is allowed to have other exogenous flavour other than the unobserved technology shock.

[8]Note that these two decisions are households' after they have taken delivery of Y_e. This is assumed also for the output of the non-energy intensive sector.

factor markets, maximising their profits, which is given by

$$\max\{P_e Y_e - [W H_e + R_e U_e K_{e,-1} + \mathsf{Q} E_e]\} \tag{3.15}$$

subject to (3.14), where P_e denotes the relative price of energy intensive goods in the domestic country, and Q denotes the exogenous price of primary energy assumed to be determined on the world market. This is one channel of openness in this model given that it is assumed that all primary energy input by firms are imported from the rest of the world.

The demand for labour hours, capital services, and primary energy by firms in this sector are given, respectively, by

$$P_e \mathsf{A}_e F^e_{H_e}\left(H_e, U_e K_{e,-1}, \mathsf{O}_e E_e\right) = W \tag{3.16}$$

$$P_e \mathsf{A}_e F^e_{U_e K_{e,-1}}\left(H_e, U_e K_{e,-1}, \mathsf{O}_e E_e\right) = R_e \tag{3.17}$$

and

$$P_e \mathsf{A}_e \mathsf{O}_e F^e_{E_e}\left(H_e, U_e K_{e,-1}, \mathsf{O}_e E_e\right) = \mathsf{Q} \tag{3.18}$$

Likewise, output of the non-energy intensive sector, Y_n, is produced using a homogeneous-of-degree-one production function given by

$$Y_n = \mathsf{A}_n F^n\left(H_n, U_n K_{n,-1}, \mathsf{O}_n E_n\right) = D^d_n + EX_n \tag{3.19}$$

where all the variables now have non-energy intensive sector interpretations analogous to those given to the energy intensive sector variables, and the function $F^n(\cdot)$ is also assumed to obey standard regularity conditions. The profit-maximisation problem is similar

$$\max\{P_n Y_n - [W H_n + R_n U_n K_{n,-1} + \mathsf{Q} E_n]\} \tag{3.20}$$

subject to (3.19), such that the demand for labour hours, capital services, and primary energy by firms in this sector are given, respectively, by

$$P_n \mathsf{A}_n F^n_{H_n}\left(H_n, R_n U_n K_{n,-1}, \mathsf{O}_n E_n\right) = W \tag{3.21}$$

$$P_n \mathsf{A}_n F^n_{U_n K_{n,-1}}\left(H_n, R_n U_n K_{n,-1}, \mathsf{O}_n E_n\right) = R_n \tag{3.22}$$

and

$$P_n \mathsf{A}_n \mathsf{O}_n F^n_{E_n}\left(H_n, R_n U_n K_{n,-1}, \mathsf{O}_n E_n\right) = \mathsf{Q} \tag{3.23}$$

Note that perfect competition implies that the firms' first-order conditions in both sectors simply equate the marginal product of each input to its marginal cost.

Government

The government is also included in the current model and assumed to face the following sequential budget constraint

$$\mathsf{G} + B = T + \mathbb{E} R' B' \tag{3.24}$$

where G denotes the exogenous government spending shock, and I follow An and Schorfheide (2007) and Justiniano et al. (2009) in assuming that the fiscal stance of the government is fully Ricardian. Thus, the government through the Treasury can raise or reduce taxes or transfers, and via the Federal Reserve increase or lower the short-term nominal interest rate to achieve its policy stance.

Trade in Goods with the Rest of the World

So far I have discussed the model economy as if it was a closed one except for the mention of the purchase of primary energy by firms on the world market. This has been done intentionally hoping that this structure helps in making the model interactions more intelligible. I am now ready to open the model up more both between sectors and between countries. My working assumption is that consumption, investment, and government spending in the domestic country and rest of the world are composites of domestic and the rest of the world's energy and non-energy intensive goods. Clearly, I have assumed away any extra costs that may arise due to import or export of a good or service such as transport costs. Thus, I can define the bundles of consumption, investment, and government spending, respectively, as

$$C = \Phi_C \left(C_e^{dp}, C_n^{dp}, C_e^{fp}, C_n^{fp} \right) \tag{3.25}$$

$$I = \Phi_I \left(I_e^{dp}, I_n^{dp}, I_e^{fp}, I_n^{fp} \right) \tag{3.26}$$

and

$$\mathsf{G} = \Phi_{\mathsf{G}} \left(\mathsf{G}_e^{dp}, \mathsf{G}_n^{dp}, \mathsf{G}_e^{fp}, \mathsf{G}_n^{fp} \right) \tag{3.27}$$

where, for $f = C, I, \mathsf{G}$, the aggregator function Φ_f is supposed to be increasing and homogeneous-of-degree-one in all its arguments, and for variable $V = C, I, \mathsf{G}$, superscript dp (fp) with subscript e (n) implies demand for domestically produced (foreign-produced) energy (non-energy) intensive goods.

One way to proceed from here would be to choose a functional form for Φ_f, and given that households and the government have chosen their expenditures on C, I, and G, then their respective problems reduce to that of maximising their utilities and profits by optimally allocating their aggregate expenditures among the components of each of C, I, and G. This will yield the result I am looking for, but the number of variables and expressions will, indeed, increase with this approach, and needlessly so, especially given that my research goal does not require this much level of disaggregation. So, I do not pursue this approach.

A second approach would be to continue to think in terms of aggregate variables as much as is possible without compromising on the research goal. In fact, it so happens that an easier way to deal with this is to remember that the sum of aggregate consumption, aggregate investment, and aggregate government spending defines the aggregate spending of domestic households (or equivalently, is the domestic absorption), which can be formalised as

$$D = C + I + \mathsf{G} \tag{3.28}$$

where, by implication, D is a composite of all the four types of goods

$$D = \boldsymbol{\kappa}\left(D^d, IM\right) \tag{3.29}$$

where the aggregator function $\boldsymbol{\kappa}$ is supposed to be increasing and homogeneous-of-degree-one in both its arguments, D^d denotes the quantity of domestically produced goods demanded by domestic residents, and IM denotes total spending of domestic residents on imports. I find it more tractable, therefore, to pursue the analysis this way in terms of aggregate demand rather than in terms of its components. As shown by Backus, et al. (1995), the above aggregator function is sufficient for use if one is modelling two countries with two goods as they did. However, I have a model of two countries and four goods such that I need further disaggregation.

Again, at this junction, I could proceed in either of two ways. First, one could define the components of D as functions of energy and non-energy intensive goods; that is, $D^d = \Sigma_d\left(D_e, D_n\right)$ and $IM = \Sigma_m\left(IM_e, IM_n\right)$. Second, one could just go back and deal with D itself first defining it as a function of energy and non-energy intensive goods, and given that, one could also split IM into a function of energy and non-energy intensive goods. I favour this latter approach. Hence, both D and IM are defined, respectively, by

$$D = \Sigma\left(D_e, D_n\right) \tag{3.30}$$

and

$$IM = \Xi\left(IM_e, IM_n\right) \tag{3.31}$$

where the aggregator functions Σ and Ξ are supposed to be increasing and homogeneous-of-degree-one in their arguments, D_e denotes total spending of domestic residents on energy intensive goods, D_n denotes total spending of domestic residents on non-energy intensive goods, IM_e denotes total spending of domestic residents on imported energy intensive goods, and IM_n denotes total spending of domestic residents on imported non-energy intensive goods.

Next, I cast the problems facing domestic residents in light of choices between domestically produced and imported of each type of goods. First, they

$$\min\{P^d D^d + IM - PD\} \tag{3.32}$$

subject to equation (3.29), where P^d is the price index for composite domestically produced goods, P is the consumer price index in the domestic country, and the assumption is that the consumer price index in the rest of the world, or equivalently the price of imported composite goods, P^{im}, is the numeraire. Hence, P is also the real exchange rate.[9]

I can likewise state another problem for the agents, which consists in

$$\min\{P_e D_e + P_n D_n - PD\} \tag{3.33}$$

subject to equation (3.30). Then, relying on Walras' law, I shut down activities in the

[9]This is a crude appropriation of the purchasing power parity hypothesis by using the ratio of the export and import prices to proxy the exchange rate between two economies.

market for the non-energy intensive goods since when the market for energy intensive goods clear, the law implies that the market for the non-energy intensive goods clear.[10]

In addition, domestic residents choose the share of expenditure on imported goods that must be allocated to the purchase of imported energy intensive goods by

$$\min\{\mathsf{P}_e^{im} IM_e + \mathsf{P}_n^{im} IM_n - IM\} \tag{3.34}$$

subject to equation (3.31), where P_e^{im} and P_n^{im} are prices of imported energy and non-energy intensive goods, respectively, and are treated as exogenous variables to the domestic agents.[11]

Hence, domestic agents choose sequences $\{D_e, IM, IM_e\}_0^\infty$ and the first-order conditions associated with these choices are

$$\boldsymbol{\kappa}_2\left(D^d, IM\right) = \frac{1}{P} \tag{3.35}$$

$$\Sigma_1\left(D_e, D_n\right) = \frac{P_e}{P} \tag{3.36}$$

and

$$\Xi_1\left(IM_e, IM_n\right) = \mathsf{P}_e^{im} \tag{3.37}$$

where for function $\lambda = \boldsymbol{\kappa}, \Sigma, \Xi$, λ_ϱ denotes partial derivative of λ with respect to its $\varrho - th$ argument.

In the same vein, I assume that the problems of agents in the rest of the world are a mirror image to that of agents in the domestic country. Hence, I use the import functions of foreign households to infer the export functions for the domestic country. More explicitly, I want to know the quantities of aggregate exported goods and exported energy intensive

[10] Clearly, $D_n = D - D_e$. Thus, having obtained aggregate domestic absorption and domestic absorption of energy intensive goods implies a solution for the non-energy intensive goods and its components.

[11] Only P_e^{im} appears in the model simulation because of the reason given in the previous footnote.

goods. To do this, I assume for the rest of the world that

$$\mathsf{D}^w = \boldsymbol{\kappa}^w \left(D^f, IM^f\right) \tag{3.38}$$

where $\mathsf{D}^w = C^w + I^w + \mathsf{G}^w$ denotes the aggregate world spending or demand, D^f denotes rest of the world's demand for its own goods, and IM^f denotes the aggregate import of goods by the rest of the world from the domestic economy, which incidentally is equal to the export of goods to the rest of the world by the domestic country denoted by EX. So, I find it convenient to replace IM^f (and its components) with EX (and its components). Also, $\boldsymbol{\kappa}^w$ is supposed to be increasing and homogeneous-of-degree-one in both its arguments. The required first-order condition is with respect to EX and is given by

$$\boldsymbol{\kappa}_2^w \left(D^f, EX\right) = P \tag{3.39}$$

where $\boldsymbol{\kappa}_\varrho^w$ denotes partial derivative of $\boldsymbol{\kappa}^w$ with respect to its $\varrho - th$ argument. Noting that EX is also a composite defined by

$$EX = \Xi^w \left(IM_e^f, IM_n^f\right) = \Xi^w \left(EX_e, EX_n\right) \tag{3.40}$$

where the aggregator function Ξ^w is supposed to be increasing and homogeneous-of-degree-one in both its arguments. The required first-order condition is with respect to EX_e and is given by

$$\Xi_1^w \left(EX_e, EX_n\right) = \frac{P_e}{P} \tag{3.41}$$

where Ξ_ϱ^w denotes partial derivative of Ξ^w with respect to its $\varrho - th$ argument.

I conclude this sub-section by defining the real exchange rate, P, in the domestic country as a function of the relative prices of energy and non-energy intensive goods

$$P = \Sigma (P_e, P_n) \tag{3.42}$$

Market Clearing and Equilibrium Constraints

In order to close the model, I define some aggregate variables and market-clearing conditions. Aggregate demand for labour hours by the firms is the sum of the two sectors' demand for labour hours and is equal to the supply of labour hours by the households

$$H = H_e + H_n \tag{3.43}$$

Aggregate demand for primary energy input by the firms is the sum of the two sectors' demand for primary energy imported from the rest of the world

$$E = E_e + E_n \tag{3.44}$$

I assume for feasibility that the current account constraint is satisfied in each period

$$PEX = \mathsf{Q}E + IM \tag{3.45}$$

That is, the value of exports equals the value of imports: foreign demand for domestically produced goods equals domestic demand for primary energy and foreign-produced goods. A re-interpretation of the prices in the above is that P is the terms of trade in goods and services, while P/Q is the oil terms of trade.

Given that the current account holds, total demand is, therefore, equal to total supply

$$D = Y \tag{3.46}$$

Additionally, the sectoral market for energy intensive goods clear

$$Y_e = D_e + EX_e - IM_e \tag{3.47}$$

I am now able to round up this section by providing the definition of a competitive equilibrium for the model.

Definition 1 *A competitive equilibrium is a set of 28 endogenous stochastic processes* $\{C, I, I_e, I_n, H, H_e, H_n, K_e, K_n, U_e, U_n, E, E_e, E_n, Y, Y_e, Y_n, D, IM, IM_e, D_e, EX, EX_e, P, P_e, P_n, W, R\}_0^\infty$ *satisfying equations (3.3), (3.4), (3.5), (3.7), (3.8), (3.11), (3.12), (3.13), (3.14), (3.16), (3.17), (3.18), (3.19), (3.21), (3.22), (3.23), (3.28), (3.35), (3.36), (3.37), (3.39), (3.41), (3.42), (3.43), (3.44), (3.45), (3.46), and (3.47), given the set of 12 exogenous stochastic AR(1) processes* $\{\mathsf{A}_e, \mathsf{A}_n, \mathsf{D}^w, \mathsf{G}, \zeta, \mathsf{O}_e, \mathsf{O}_n, \mathsf{P}_e^{im}, \mathsf{Q}, \tau, \mathsf{Z}_e, \mathsf{Z}_n\}_0^\infty$*, and the initial conditions* C_{-1}*,* K_{-1}^e*,* K_{-1}^n *and* B_0*.*[12]

3.3 Econometric Methodology

In this section, I discuss the method of indirect inference used to evaluate and estimate the model, and provide a documentation of the data used for estimation.

Indirect Inference

The econometric method of indirect inference (II) is adopted to evaluate the model's capacity to fit the data. This procedure is originally proposed in Minford et al. (2009) and subsequently with a number of refinements by Le et al. (2011) who evaluate the method using Monte Carlo experiments. I only provide a brief overview here.[13] The approach employs an auxiliary model that is completely independent of the theoretical

[12] Note that in defining the competitive equilibrium and in the model simulation, I have combined the firms' first-order conditions with respect to capital services, (3.17) and (3.22) with the households' first-order conditions with respect to capital utilisation rates, (3.9) and (3.10).

[13] Interested readers may consult Minford et al. (2009) and Le et al. (2011, 2012), and the references therein for details.

one to produce a description of the data against which the performance of the theory is evaluated indirectly. Such a description can be summarised either by the estimated parameters of the auxiliary model or by functions of these; I will call these the descriptors of the data. While these are treated as the 'reality', the theoretical model being evaluated is simulated to find its implied values for them.

II has been widely used in the estimation of structural models [see, for example, Smith (1993), Gregory and Smith (1991, 1993), Gourieroux et al. (1993), Gourieroux and Monfort (1995), Canova (2005)]. Here I make a further use of II, which is to evaluate a calibrated or estimated structural model. The common element is the use of an auxiliary time series model. In model estimation the parameters of the structural model are chosen such that when this model is simulated it generates estimates of the auxiliary model similar to those obtained from the actual data. The optimal choices of parameters for the structural model are those that minimise the distance between a given function of the two sets of estimated coefficients of the auxiliary model. Common choices of this function are the actual coefficients, the scores or the impulse response functions.

In model evaluation the parameters of the structural model are taken as given. The aim is to compare the performance of the auxiliary model estimated on simulated data derived from the given estimates of a structural model - which is taken as a true model of the economy, the null hypothesis - with the performance of the auxiliary model when estimated from the actual data. If the structural model is correct then its predictions about the impulse responses, moments and time series properties of the data should statistically match those based on the actual data. The comparison is based on the distributions of the two sets of parameter estimates of the auxiliary model, or of functions of these estimates.

The testing procedure, thus, involves first constructing the errors implied by the previously calibrated/ estimated structural model and the data. These are called the structural errors and are backed out directly from the equations and the data.[14] These errors are then bootstrapped and used to generate for each bootstrap new data based on the structural

[14]Some equations may involve calculation of expectations. The method I use here is the robust instrumental variables estimation suggested by McCallum (1976) and Wickens (1982): I set the lagged endogenous data as instruments and calculate the fitted values from a VAR(1) - this also being the auxiliary model chosen in what follows.

model. An auxiliary time series model is then fitted to each set of data and the sampling distribution of the coefficients of the auxiliary time series model is obtained from these estimates of the auxiliary model. A Wald statistic is computed to determine whether functions of the parameters of the time series model estimated on the actual data lie in some confidence interval implied by this sampling distribution.

In the present model, the shocks are stationary such that I follow Le et al. (2012) in taking a VAR(1) as the auxiliary model.[15] Thus, the auxiliary model in practice is given by

$$Ax = B\left(L\right)x_{-1} + \epsilon \tag{3.48}$$

where A and $B\left(L\right)$ are, respectively, an n by n matrix of coefficients and polynomials in the lag operator, L, ϵ_t is an n by 1 vector of a mean zero, serially uncorrelated random structural disturbances such that $E\left(\epsilon, \epsilon^{'}\right) = \Sigma$ represents its finite diagonal variance-covariance matrix, and I treat $A^{-1}B\left(L\right)$ as the descriptors of the data the VAR coefficients on the endogenous variables, and $var[\epsilon]$ as the VAR error variances. The Wald statistic is computed from these. Thus, effectively I am testing whether the observed dynamics and volatility of the chosen variables are explained by the simulated joint distribution of these at a given confidence level. The Wald statistic is given by

$$(\Theta - \overline{\Theta})' \sum\nolimits_{(\Theta\Theta)}^{-1} (\Theta - \overline{\Theta}) \tag{3.49}$$

where Θ is the vector of VAR estimates of the chosen descriptors yielded in each simulation, with $\overline{\Theta}$ and $\sum_{(\Theta\Theta)}$ representing the corresponding sample means and variance-covariance matrix of these calculated across simulations, respectively.

The joint distribution of the Θ is obtained by bootstrapping the innovations implied

[15] See Canova (2005), Dave and DeJong (2007), Del Negro and Schorfheide (2004, 2006), and Del Negro et al. (2007a, b), and also the comments of Christiano (2007), Gallant (2007), Sims (2007), Faust (2007), and Kilian (2007). Further, I restrict the VAR lag to order one as high-order will only impose a more stringent overall test on the model, and will likely worsen the fit.

by the data and the theoretical model; it is, therefore, an estimate of the small sample distribution.[16] Such a distribution is generally more accurate for small samples than the asymptotic distribution; it is also shown to be consistent by Le et al. (2011) given that the Wald statistic is 'asymptotically pivotal'; they also showed it had quite good accuracy in small sample Monte Carlo experiments.[17]

This testing procedure is then applied to a set of structural parameters, which have been derived from calibration, estimation, or both, and put forward as the true ones; this is the null hypothesis: H_0. Regardless of how the parameters are obtained, the test then asks, "Could these coefficients within this model structure be the true numerical data generating process?" Of course only one true model with one set of coefficients is possible. Nevertheless, one may have chosen coefficients that are not exactly right numerically, so that the same model with other coefficient values could be correct. Only when one has examined the model with all coefficient values that are feasible within the model theory will one have properly tested it. For this reason I later extend the procedure by a further search algorithm, in which I seek other coefficient sets that could do better in the test.

Thus, I calculate the minimum-value Wald statistic for each period using a powerful algorithm based on Simulated Annealing (SA) in which search takes place over a wide range around the initial values, with optimising search accompanied by random jumps around the space.[18] In effect, this is estimation of the model by II; however, this estimation is being done here to find whether the model can be rejected *in itself* and not for the sake of finding the most satisfactory estimates of the model parameters. Nevertheless of course the method does this latter task as a by-product so that I can use the resulting *un*rejected model as representing the best available estimated version. The merit of this extended

[16] The bootstraps in the tests are all drawn as time vectors so contemporaneous correlations between the innovations are preserved.

[17] Specifically, they found on stationary data that the bias due to bootstrapping was just over 2% at the 95% confidence level and 0.6% at the 99% level. Meenagh et al. (2012) found even greater accuracy in Monte Carlo experiments on nonstationary data.

[18] I use a Simulated Annealing algorithm due to Ingber (1996). This 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 - this ensures 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. I find that this algorithm improves substantially here on a standard optimisation algorithm. My method used a standard testing method: I take a set of model parameters (excluding error processes), extract the resulting residuals from the data using the LIML method, find their implied autoregressive coefficients [$AR(1)$ here] and then bootstrap the implied innovations with this full set of parameters to find the implied Wald value. This is then minimised by the SA algorithm.

procedure is that one is able to compare the best possible versions of each model type when finally doing the comparison of model compatibility with the data.[19]

Data

Figure 3.3 displays the time paths for the data series that I make use of in the evaluation and estimation of the model. These are U.S. annual data covering the period 1949-2013, and are logarithmically transformed, real [using Bureau of Labour Statistics (BLS) series: consumer price index (CPI, 2009=100)] per capita [using Bureau of Labour Statistics (BLS) series: civilian non-institutionalised population over 16 years old] terms except for wage rate, interest rate, real exchange rate, relative prices, and capital utilisation rates. All series are filtered following Hodrick and Prescott (1981, 1997) procedure setting the smoothing parameter to 400. A detailed description of the data sources and construction of the 28 observables (empirical counterparts to the endogenous variables) are presented in the Supplementary Notes: Chapter 3.

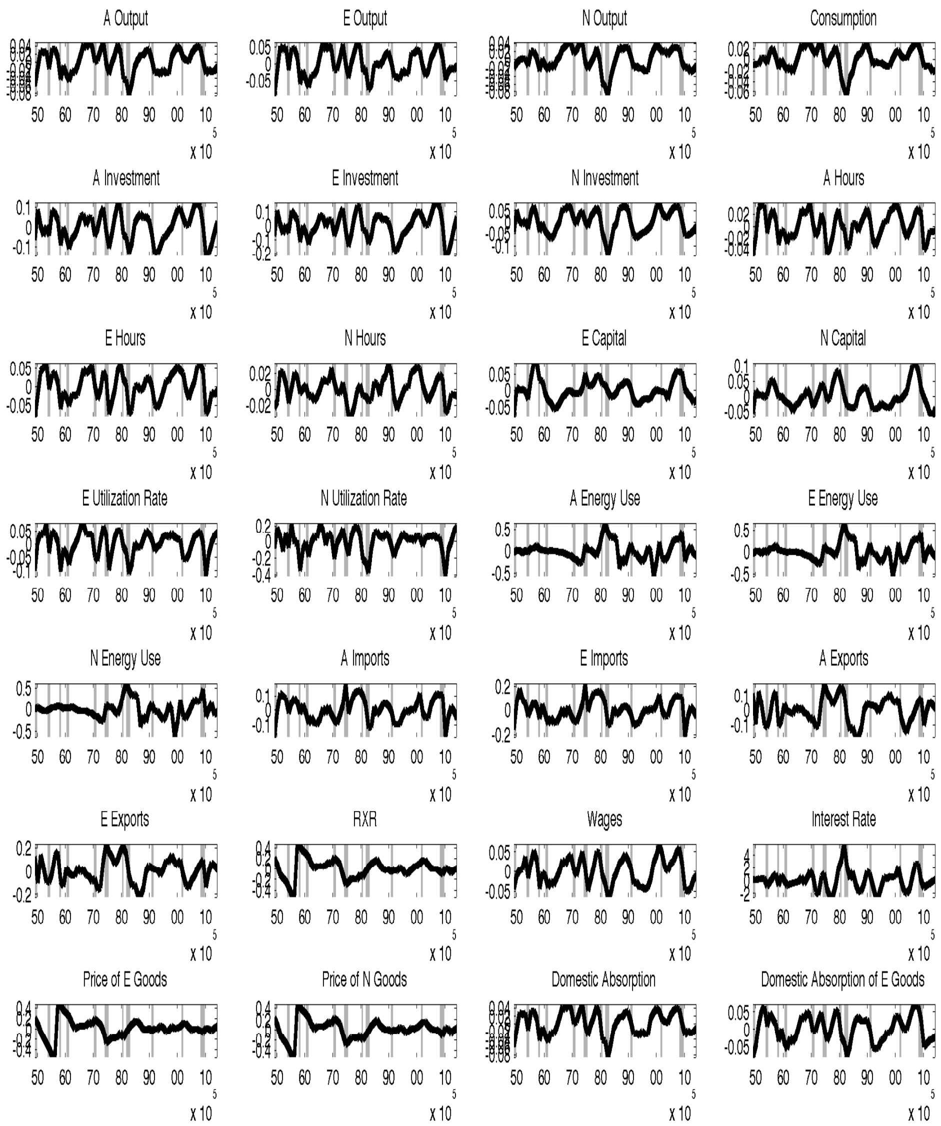
3.4 Results

The presentation of results in this section is divided into two parts: the calibrated version of the model is analysed in the first sub-section, and in the second sub-section, I summarise the results from the estimated version of the model.

Empirical Analysis 1

In this part, I discuss the simulation of the model, the choice of specific functional forms, the calibration of the model parameters, and quantitatively test the fit of the model to data for a number of key macroeconomic variables.

[19] See Le et al. (2013) for a discussion of the advantages of using II method.



Note: E denotes energy intensive; N denotes non-energy intensive.

Figure 3.2: HP-filtered data

Model Simulation Following Christiano (1988) and King et al. (1988a, b, 2001), I solve the model by first obtaining the equilibrium conditions based on the chosen functional forms, add the market-clearing conditions and the assumed laws of motion for the model's structural errors. Then, I derive the deterministic version of the model where all the standard deviations of innovations are identically equal to zero, and it is around these values that I express the decision variables of the model as a linear approximation using a Taylor-series expansion. This result gives a solution that permits a state-space representation of the model's endogenous variables in a way that allows for a possible matching of a set of observables.

Functional Forms Next, I choose functional forms for preferences, technologies, time-varying depreciation rates, capital adjustment costs, and the aggregator functions. The utility function is taken to be of the form

$$U\left(\frac{(C-\iota C_{-1})^{1-\epsilon}}{1-\epsilon}-\zeta\frac{H^{1+\omega}}{1+\omega}\right) \tag{3.50}$$

I assume that the sectoral production functions are Cobb-Douglas in labour hours and constant-elasticity-of-substitution (CES) in capital services and primary energy input

$$Y_e=\mathsf{A}_e\left(H_e\right)^{1-\alpha_e}\left(\theta_e\left(U_eK_{e,-1}\right)^{-\nu_e}+\left(1-\theta_e\right)\left(\mathsf{O}_eE_e\right)^{-\nu_e}\right)^{-\frac{\alpha_e}{\nu_e}} \tag{3.51}$$

$$Y_n=\mathsf{A}_n\left(H_n\right)^{1-\alpha_n}\left(\theta_n\left(U_nK_{n,-1}\right)^{-\nu_n}+\left(1-\theta_n\right)\left(\mathsf{O}_nE_n\right)^{-\nu_n}\right)^{-\frac{\alpha_n}{\nu_n}} \tag{3.52}$$

As in Basu and Kimball (1997), I define the time-varying rates of depreciation by

$$\delta\left(U_e\right)=\delta_{e0}+\frac{\delta_{e1}\left(U_e\right)^{\mu_e}}{\mu_e} \tag{3.53}$$

$$\delta\left(U_n\right)=\delta_{n0}+\frac{\delta_{n1}\left(U_n\right)^{\mu_n}}{\mu_n} \tag{3.54}$$

The adjustment cost functions adopted are standard

$$\Psi_e\left(\frac{K_e}{K_{e,-1}}\right)=\frac{\psi_e}{2}\left(\frac{K_e}{K_{e,-1}}-1\right)^2K_{e,-1} \tag{3.55}$$

$$\Psi_n\left(\frac{K_n}{K_{n,-1}}\right)=\frac{\psi_n}{2}\left(\frac{K_n}{K_{n,-1}}-1\right)^2K_{n,-1} \tag{3.56}$$

I take the aggregator functions $\boldsymbol{\kappa}$, Σ, Ξ, $\boldsymbol{\kappa}^w$, and Ξ^w as CES given, respectively, by

$$D=\left(\kappa^{\frac{1}{\phi}}\left(D^d\right)^{\frac{\phi-1}{\phi}}+\left(1-\kappa\right)^{\frac{1}{\phi}}\left(IM\right)^{\frac{\phi-1}{\phi}}\right)^{\frac{\phi}{\phi-1}} \tag{3.57}$$

$$D = \left(\sigma^{\frac{1}{\varsigma}} \left(D_e\right)^{\frac{\varsigma-1}{\varsigma}} + (1-\sigma)^{\frac{1}{\varsigma}} \left(D_n\right)^{\frac{\varsigma-1}{\varsigma}} \right)^{\frac{\varsigma}{\varsigma-1}} \tag{3.58}$$

$$IM = \left(\chi^{\frac{1}{\eta}} \left(IM_e\right)^{\frac{\eta-1}{\eta}} + (1-\chi)^{\frac{1}{\eta}} \left(IM_n\right)^{\frac{\eta-1}{\eta}} \right)^{\frac{\eta}{\eta-1}} \tag{3.59}$$

$$\mathsf{D}^w = \left(\kappa_w^{\frac{1}{\phi_w}} \left(D^f\right)^{\frac{\phi_w-1}{\phi_w}} + (1-\kappa_w)^{\frac{1}{\phi_w}} \left(EX\right)^{\frac{\phi_w-1}{\phi_w}} \right)^{\frac{\phi_w}{\phi_w-1}} \tag{3.60}$$

and

$$EX = \left(\chi_w^{\frac{1}{\eta_w}} \left(EX_e\right)^{\frac{\eta_w-1}{\eta_w}} + (1-\chi_w)^{\frac{1}{\eta_w}} \left(EX_n\right)^{\frac{\eta_w-1}{\eta_w}} \right)^{\frac{\eta_w}{\eta_w-1}} \tag{3.61}$$

I describe the parameters in the next sub-section.

Calibration The assessment of the quantitative workings of the model can only begin when one has chosen values for the model parameters such that one is able to simulate the model. In this sub-section, I discuss how to obtain these values. Table 3.1 documents the calibrated parameter values. Notably, I follow the procedure of Iacoviello et al. (2011) in providing parameters with numerical values.[20] Their approach requires that the parameters be divided into three groups, namely: (1) Parameters whose values are fixed throughout the exercise; (2) Parameters whose values are estimated but for which I must provide initial values as suggestions for the Simulated Annealing (SA) search algorithm during the estimation process;[21] and (3) Parameters whose values are derived given values of parameters in groups one and two, and the average values of some observed data ratios.

In the first group are the discount factor, β, which I fix at 0.96 suggesting that I have taken the annual real rate of interest to be 4%, which is consistent with the average post-WWII interest rate for the U.S., and the steady state of the depreciation functions for the two types of investment goods, δu^e and δu^n, which are set equal to the long-run average data values of investment-capital ratios for the energy and non-energy intensive goods. Then, all the 12 shocks are normalised to unity in steady state such that I can

[20] The classic references for calibration remains, of course, Kydland and Prescott (1982) and Prescott (1986).

[21] Note that, unlike Iacoviello et al. (2011) who estimated their model using Bayesian techniques, I have adopted the method of Indirect Inference discussed in the previous section. In a way, my initial parameters may be likened to Bayesian priors.

proceed to the second group.

Table 3.1: Calibration

Description	Symbol	Values
Discount factor	β	0.96
Inverse of Frisch elasticity of labour supply	ω	5
Consumption elasticity	ε	2
Habit formation parameter	ι	0.7
Energy intensive sector SoCE	α_e	0.43
Non-energy intensive sector SoCE	α_n	0.28
Energy intensive sector EoS btw capital services and energy	ν_e	0.7
Non-energy intensive sector EoS btw capital services and energy	ν_n	0.7
Energy intensive sector marginal CoCU	$\delta_{e1}u^{\mu_e}$	0.132
Energy intensive sector depreciation EoCU	μ_e	1.463
Non-energy intensive sector marginal CoCU	$\delta_{n1}u^{\mu_n}$	0.102
Non-energy intensive sector depreciation EoCU	μ_n	1.694
ACP for energy intensive goods	ψ_e	0.001
ACP for non-energy intensive goods	ψ_n	0.001
DC's EoS btw domestic and imported final goods	ϕ	1.5
FC's EoS btw foreign and exported final goods	ϕ_w	1.5
DC's EoS btw imported energy and non-energy goods	η	0.44
FC's EoS btw exported energy and non-energy goods	η_w	0.44
Bias for energy intensive goods in the DC	σ	0.55
Bias for domestically produced goods in the DC	κ	0.7
DC's EoS btw energy and non-energy intensive goods	ς	0.9
Steady state DF of energy intensive investment goods	δu^e	0.09
Steady state DF of non-energy intensive investment goods	δu^n	0.06
Weight on capital services of the energy intensive sector	θ_e	0.9903
Weight on capital services of the non-energy intensive sector	θ_n	0.9961

Note: SoCE: share of capital services and energy; EoS: elasticity of substitution; CoCU: cost of capital utilisation; EoCU: elasticity of capital utilisation; ACP: adjustment cost parameter; DF: depreciation function; DC: domestic country; FC: foreign country.

The second group is made up of 12 autocorrelation parameters, 12 standard deviations of innovations, and 20 deep structural parameters of the model. To calibrate the shocks, I assume that the twelve exogenous processes follow AR(1) stationary processes in logarithm. Further, by supposing that the innovations are serially uncorrelated, their 24 parameters can be calculated based on twelve derived series. More formally, eight behavioural errors: intertemporal preference, labour supply, two sectoral productivities, two investment-specific technologies, and two sectoral energy efficiencies; and four exogenous processes: energy price, government spending, world demand, and the price of imported energy intensive goods are calculated part-sequentially as[22]

$$\widehat{\mathsf{G}} = \frac{\widehat{Y} - (c/y)\,\widehat{C} - (i/y)\,\widehat{I}}{(g/y)}$$

$$\widehat{\zeta} = \widehat{W} - \omega \widehat{H} - \frac{\epsilon}{1-\iota}\left(\widehat{C} - \iota \widehat{C}_{-1}\right)$$

$$\widehat{\mathsf{P}}_e^{im} = \frac{\widehat{IM} - \widehat{IM}_e}{\eta}$$

$$\widehat{\mathsf{D}}^w = \widehat{EX} + \phi_w \widehat{P}$$

$$\widehat{\mathsf{Q}} = (pex/e)\left(\widehat{P} - \frac{(im/e)}{(pex/e)}\widehat{IM} - \frac{1}{(pex/e)}\widehat{E} + \widehat{EX}\right)$$

$$\widehat{\mathsf{O}}_e = \frac{\widehat{E}_e - \left[\widehat{P}_e + \widehat{Y}_e - \widehat{\mathsf{Q}} + \frac{\nu_e}{1+\frac{1-\theta_e}{\theta_e}\left(\frac{e_e}{k_e}\right)^{-\nu_e}}\left(\widehat{U}_e + \widehat{K}_{e,-1}\right)\right]}{\nu_e + 1 - \frac{\nu_e}{1+\frac{\theta_e}{1-\theta_e}\left(\frac{e_e}{k_e}\right)^{\nu_e}}} \frac{\nu_e + 1 - \frac{\nu_e}{1+\frac{\theta_e}{1-\theta_e}\left(\frac{e_e}{k_e}\right)^{\nu_e}}}{\frac{\nu_e}{1+\frac{\theta_e}{1-\theta_e}\left(\frac{e_e}{k_e}\right)^{\nu_e}} - \nu_e}$$

$$\widehat{\mathsf{O}}_n = \frac{\widehat{E}_n - \left[\widehat{P}_n + \widehat{Y}_n - \widehat{\mathsf{Q}} + \frac{\nu_n}{1+\frac{1-\theta_n}{\theta_n}\left(\frac{e_n}{k_n}\right)^{-\nu_n}}\left(\widehat{U}_n + \widehat{K}_{n,-1}\right)\right]}{\nu_n + 1 - \frac{\nu_n}{1+\frac{\theta_n}{1-\theta_n}\left(\frac{e_n}{k_n}\right)^{\nu_n}}} \frac{\nu_n + 1 - \frac{\nu_n}{1+\frac{\theta_n}{1-\theta_n}\left(\frac{e_n}{k_n}\right)^{\nu_n}}}{\frac{\nu_n}{1+\frac{\theta_n}{1-\theta_n}\left(\frac{e_n}{k_n}\right)^{\nu_n}} - \nu_n}$$

$$\begin{aligned}\widehat{\mathsf{A}}_e &= \widehat{Y}_e - (1-\alpha_e)\,\widehat{H}_e - \frac{\alpha_e}{1+\frac{1-\theta_e}{\theta_e}\left(\frac{e_e}{k_e}\right)^{-\nu_e}}\left(\widehat{U}_e + \widehat{K}_{e,-1}\right) \\ &\quad - \frac{\alpha_e}{1+\frac{\theta_e}{1-\theta_e}\left(\frac{e_e}{k_e}\right)^{\nu_e}}\left(\widehat{\mathsf{O}}_e + \widehat{E}_e\right)\end{aligned}$$

$$\begin{aligned}\widehat{\mathsf{A}}_n &= \widehat{Y}_n - (1-\alpha_n)\,\widehat{H}_n - \frac{\alpha_n}{1+\frac{1-\theta_n}{\theta_n}\left(\frac{e_n}{k_n}\right)^{-\nu_n}}\left(\widehat{U}_n + \widehat{K}_{n,-1}\right) \\ &\quad - \frac{\alpha_n}{1+\frac{\theta_n}{1-\theta_n}\left(\frac{e_n}{k_n}\right)^{\nu_n}}\left(\widehat{\mathsf{O}}_n + \widehat{E}_n\right)\end{aligned}$$

[22] I have followed Blankenau et al. (2001) who used "the observable endogenous variables and the orthogonality conditions implied by the Euler equations to recover the exogenous shocks ..." p. 874. The point to take from this is that this allows me to use the model equivalent of the four observed exogenous variables. This way, I have maintained one of the early open economy model assumptions in the lineage of Fleming (1962) and Mundell (1964) that treat current account transactions mainly as residuals. In the next chapter, I relax this manner of deriving the parameters of the observed shock processes making use of their corresponding actual observations, which follow the literature interpreting changes in the current account as emerging from planned behaviour of agents [see, for example, Sachs (1981), Aizenman (1983), Frenkel and Razin (1984), Razin (1984), and Dornbusch (1985) for earlier accounts].

$$\widehat{\tau} = \frac{\widehat{C} - \frac{1}{1+\iota}\widehat{C}' - \frac{\iota}{1+\iota}\widehat{C}_{-1} + \frac{1-\iota}{\epsilon(1+\iota)}\widehat{R}}{\frac{1-\iota}{\epsilon(1+\iota)}}$$

$$\widehat{\mathsf{Z}}_e = \left(\widehat{K}_e - \frac{\left[\frac{\epsilon}{1-\iota}\left(\widehat{C} - \iota\widehat{C}_{-1}\right) + \beta\delta_{e1}u^{\mu_e}\left(\mu_e - 1\right)\widehat{U}_e'\right.}{\psi_e\left(1+\beta\right)} \frac{\left.+\psi_e\left(\beta\widehat{K}_e' + \widehat{K}_{e,-1}\right) - \frac{\epsilon}{1-\iota}\left(\widehat{C}' - \iota\widehat{C}\right)\right]}{\psi_e\left(1+\beta\right)} \right) \psi_e\left(1+\beta\right)$$

$$\widehat{\mathsf{Z}}_n = \left(\widehat{K}_n - \frac{\left[\frac{\epsilon}{1-\iota}\left(\widehat{C} - \iota\widehat{C}_{-1}\right) + \beta\delta_{n1}u^{\mu_n}\left(\mu_n - 1\right)\widehat{U}_n'\right.}{\psi_n\left(1+\beta\right)} \frac{\left.+\psi_n\left(\beta\widehat{K}_n' + \widehat{K}_{n,-1}\right) - \frac{\epsilon}{1-\iota}\left(\widehat{C}' - \iota\widehat{C}\right)\right]}{\psi_n\left(1+\beta\right)} \right) \psi_n\left(1+\beta\right)$$

Nine of the above equations are without expectations such that the structural errors are backed out directly as residuals. For the last three (intertemporal preference, and energy and non-energy intensive investment-specific technology shocks) that are with expectations, the residuals are derived using the instrumental variable method recommended by McCallum (1976) and Wickens (1982), where the instruments are the lagged values of the endogenous variables. I then fit a univariate, AR(1), model to each of the calculated series for the shocks - Table 3.2 documents the results.

As for the remaining twenty parameters that are later on estimated, I calibrate their starting values here. I set the elasticity of labour supply, ω, equal to 5,[23] fix consumption elasticity, ϵ, at 2, and preserve the CES form of the production functions by setting the respective sector's elasticity of substitution between capital services and efficient energy use, ν_e and ν_n, equal to 0.7.[24] I suppose that there is some degree of habit formation

[23] A value of zero for ω implies perfect labour mobility between sectors. This type of perfect factor mobility is prevalent in the RBC literature especially as it relates to the labour market activities. However, suffice it to say that this is as much plausible as, for example, the degree of sector-specific skilled labour that is needed. Hence, as $\omega \to \infty$ so does the degree of sector-specificity. I am inclined to begin the analysis from a more Walrasian context such that I set ω closer to 0.

[24] Kim and Loungani (Table 2, p. 180) provide a justification for using this value. They also considered a value of 0.001 suggesting a Cobb-Douglas form and high elasticity of substitution between capital services and energy use. I, however, stick to the parameter value that preserves the general form of specification and leave the optimal choice of parameter value to the estimation stage later on.

for agents in this model setting the initial parameter value to 0.7, which is in line with previous estimates in the literature for a developed country such as the U.S. A very small value of 0.001 is chosen for the parameters that relate to the adjustment costs of capital, ψ_e and ψ_n, following a popular practice in the literature.

Table 3.2: Driving Processes

Shocks	ρ_s	σ_s
Energy intensive sector productivity, $\widehat{\mathsf{A}}_e$	0.4930	0.0203
Non-energy intensive sector productivity, $\widehat{\mathsf{A}}_n$	0.2594	0.0285
World demand, $\widehat{\mathsf{D}}^w$	0.6144	0.1968
Government spending, $\widehat{\mathsf{G}}$	0.4076	0.0572
Labour supply, $\widehat{\zeta}$	0.4888	0.1235
Energy intensive sector energy efficiency, $\widehat{\mathsf{O}}_e$	0.5881	0.5161
Non-energy intensive sector energy efficiency, $\widehat{\mathsf{O}}_n$	0.5873	0.5470
Price of imported energy intensive goods, $\widehat{\mathsf{P}}_e^{im}$	0.5572	0.0405
Energy price, $\widehat{\mathsf{Q}}$	0.5366	0.3127
Intertemporal preference, $\widehat{\tau}$	0.5760	1.1988
Energy intensive goods investment-specific technology, $\widehat{\mathsf{Z}}_e$	0.2996	0.0733
Non-energy intensive goods investment-specific technology, $\widehat{\mathsf{Z}}_n$	0.2990	0.0730

Note: ρ_s and σ_s are, respectively, the persistence parameters and the standard deviations of each shock, s.

Moving on to the component parameters of the two depreciation functions, the steady state implies that $\delta u^j = \delta_{j0} + \delta_{j1}\left(\mu_j\right)^{-1}(u^j)^{\mu_j}$ for $j = e, n$, for which I note that only four of their six parameters that needed identifying are δ_{e0}, δ_{n0}, μ_e and μ_n. So, conditional on the values of the discount factor and the real rental rates, I calibrate the parameters governing the elasticities of marginal depreciations with respect to capital utilisation rates using $\mu_e = \frac{\beta\delta_{e1}u^{\mu_e}}{\beta(1+\delta_{e1}u^{\mu_e})-1} = 1.463$ and $\mu_n = \frac{\beta\delta_{n1}u^{\mu_n}}{\beta(1+\delta_{n1}u^{\mu_n})-1} = 1.694$, which are reasonably located in the range found in the literature.[25] Moreover, with no loss of generality, I fix the

[25] Basu and Kimball (1997) suggested the upper bound of 2 based on a 95% confidence band. Further, to calibrate this parameter, I have gone for the more restricted form of the depreciation function by setting $\delta_{e0} = \delta_{n0} = 0$. Basu and Kimball (1995, 1997), though used the more general form in their empirical work and concluded that there is no statistical evidence in support of the non-zero value for the fixed component of the depreciation function as assumed by many other authors in the literature [see, for example, Greenwood et al. (1988) and Burnside and Eichenbaum (1996)]. I 'conclude' that my values are not far (not a statistical conclusion) from that usually employed in the literature [see, for example, Greenwood, et al. who used a value of 1.42, and Burnside and Eichenbaum using their factor-hoarding model and data on output and capital calibrated μ to be 1.56 ($\Delta = 0.56$)]. I must note that the specification for time-varying depreciation is less general in these other studies. Statistically, however, both values are not rejected by the data. This is done noting one of the concerns of Basu and Kimball (1997) that "...our method makes clear that Δ is a parameter that needs to be estimated, and in fact is not pinned down very precisely by the data because it has to be estimated as the reciprocal of a fairly small number. Thus, even the small standard error of the reduced-form parameter necessarily implies that there is large uncertainty about the structural parameter Δ. Consequently, economic modellers should conduct sensitivity analysis of their results using a wide range of values for this parameter." And also that "variable depreciation does not seem a significant source of error in the capital stock figures reported by the BEA." Specifically, they concluded that this issue "strikes us as second-order." This thus asks the question of sensitivity analysis regarding our results in response to various values that could be used for μ (Δ). Once I have assessed the performance of the model under this calibration approach,

values for δ_{e1} and δ_{n1} at unity.[26] The idea is that δ_{j1} and u^j are admitted into the model only jointly as $\delta_{j1}\left(u^j\right)^{\mu_j}$ such that $\delta_{j1}=1$ has a trivial implication that $\delta_{j1}\left(u^j\right)^{\mu_j}=\left(u^j\right)^{\mu_j}$. In addition, using household's optimality conditions with regards to capital utilisation rates conditioned on the values for the respective sector's rental rate of capital in the steady state, one can show that $\delta_{j1}\left(u^j\right)^{\mu_j}=r_j=1/\beta-\left(1-\delta\left(u^j\right)\right)$, which simplifies to give the values reported in the table for $\delta_{e1}u^{\mu_e}$ and $\delta_{n1}u^{\mu_n}$ of 0.132 and 0.102, respectively.

Parameters governing the elasticities of labour hours in the energy and non-energy intensive sectors, α_e and α_n, are found to be 0.43 and 0.28, respectively, being calibrated to match the respective sector's capital-output ratios. The values chosen for the elasticities of substitution parameters in the aggregator functions are all standard in the trade literature: $\phi=\phi_w=1.5$, $\eta=\eta_w=0.44$, and $\varsigma=0.99$ [see, for example, Stern and Schumacher (1976), Whalley (1985), and Shiells and Reinert (1993)].

Finally, the parameters in the third group (θ_e, θ_n) are calibrated given the fixed and/ or estimated parameters and an array of target steady state ratios of the model. These weight parameters are pinned down by the respective sector's average energy-capital ratio over the sample period, given values of some other underlying structural parameters using the expression, $\theta_j=\left[1+\frac{1}{\delta_{j1}u^{\mu_j}}\left(\frac{e_j}{k_j}\right)^{1+\nu_j}\right]^{-1}$. The values mainly change with the parameters ν_j. The initial values chosen for the bias parameters, σ and κ, are 0.55 and 0.7, respectively.[27]

Assessing the Fit of the Calibrated Model Now, I would like to know if the model can be fitted to the data for the macroeconomic variables I am most interested in. Davidson et al. (2010, 2011) showed that the more the number of variables included the more difficult it becomes for the model to fit the data, and also that the joint distribution of variables of interest depends more on the covariances between the VAR coefficients and

the above arguments make more important my next empirical exercise, which is to estimate the model's underlying structural parameters. In fact, a prior study by Basu and Kimball (1995) had put the value of μ at roughly 7 with a standard error of about 8. To this end, I impose a wider boundary of $[0,10]$ in the estimation exercise.

[26] See, for example, Burnside and Eichenbaum (1996), Boileau and Normandin (1999), King and Rebelo (2000), and Leduc and Sill (2004).

[27] I provide more interpretation for parameters and the implications of their values below when I discuss the estimated model.

not necessarily by the individual cross-correlation of variable coefficients.[28] Similar idea was put forth by Le et al. (2011) such that for the auxiliary VAR(1) model for which I present results, I have restricted the number of variable combinations and/ or lag order to a maximum of four - this is because a more rigorous pass criteria is set the higher the number of variables and/ or lags. The importance of this Directed Wald test is that it helps to narrow down the economic questions that can be addressed using the constructed economic model.

Hence, the primary goal is the result from the joint disstribution. Therefore, as a benchmark, I would particularly like to fit the model to the data on aggregate output, which serves as a measure of domestic country's total income, the real exchange rate, which serves as a measure of the domestic country's competitiveness against the rest of the world, energy use since this is an energy real business cycle (ERBC) model and because it is an indicator of inputs into the production process, and possibly consumption, which may serve as a measure of the agents welfare.

Now, one can assess Table 3.3 for the results on the model's predictions of individual and joint distributions of output, real exchange rate, energy use, and consumption. The model is rejected for the joint distribution test of the dynamics plus volatilities, and for separate tests on the dynamics and volatilities, where for the three auxiliary models, the Wald statistic is 100, and the respective transformed Mahalanobis distances are 40.14, 39.33, and 14.21. This can be expected as the model was only able to replicate the individual distribution of thirteen of the twenty VAR coefficients.

Particularly, it failed to capture the effects of lagged energy use on current real exchange rate, the effects of lagged consumption on current real exchange rate, and the effects of lagged consumption on current energy use. In two of the three instances, the model under-predicted the co-movements observed in the data, but under-predicted it in one. More interestingly, the dynamic coefficients that lie outside the 95% bounds relates to the cross-effects of consumption and real exchange rate with each appearing twice. Also, all the four data variances lie outside of the $95th$ percentile; specifically, the model

[28] This was already implied by Long and Plosser (1983, p. 39) in the introduction to Real Business Cycles when they wrote that the "... term business cycles refers to the joint time-series behaviour of a wide range of economic variables ...".

Table 3.3: VAR Results for the Calibrated Model

Coefficients	Actual	Lower Bound	Upper Bound	Mean
$\rho_{\widehat{Y},\widehat{Y}}$	0.4913	−0.2048	1.2775	0.5753
$\rho_{\widehat{P},\widehat{Y}}$	−0.0076	−0.8295	0.9103	0.0572
$\rho_{\widehat{E},\widehat{Y}}$	−0.0354	−0.1424	0.1600	0.0121
$\rho_{\widehat{C},\widehat{Y}}$	0.1080	−0.1121	0.1875	0.0255
$\rho_{\widehat{Y},\widehat{P}}$	0.0047	−0.6448	0.3742	−0.1102
$\rho_{\widehat{P},\widehat{P}}$	0.6797	−0.1720	0.9948	0.4269
$\rho_{\widehat{E},\widehat{P}}$	0.1341¶	−0.1331	0.0861	−0.0226
$\rho_{\widehat{C},\widehat{P}}$	0.4435¶	−0.1358	0.0862	−0.0207
$\rho_{\widehat{Y},\widehat{E}}$	0.4621	−1.6359	1.7728	0.1506
$\rho_{\widehat{P},\widehat{E}}$	−0.1641	−2.3913	1.9571	−0.0564
$\rho_{\widehat{E},\widehat{E}}$	0.4959	0.1970	0.8475	0.5445
$\rho_{\widehat{C},\widehat{E}}$	−1.2027¶	−0.3194	0.4214	0.0378
$\rho_{\widehat{Y},\widehat{C}}$	0.0697	−1.3391	0.7529	−0.2228
$\rho_{\widehat{P},\widehat{C}}$	0.0041	−1.3542	0.9729	−0.1666
$\rho_{\widehat{E},\widehat{C}}$	−0.0198	−0.1893	0.2235	0.0173
$\rho_{\widehat{C},\widehat{C}}$	0.5978	0.5854	0.9816	0.8255
$\sigma^2_{\widehat{Y}}$	0.0009♮	0.0139	0.0369	0.0241
$\sigma^2_{\widehat{P}}$	0.0314♮	0.0077	0.0199	0.0128
$\sigma^2_{\widehat{E}}$	0.0413♮	0.0778	0.2410	0.1514
$\sigma^2_{\widehat{C}}$	0.0004♮	0.0485	0.2361	0.1230
	Dynamics+Volatilities	Dynamics	Volatilities	
Wald (%)	100	100	100	
TMD	40.14	39.33	14.21	

Note: $\rho_{i,j}$ denotes the VAR coefficient of a lagged variable i on a variable j; σ^2_j denotes the variance of variable j; $\widehat{Y}$ denotes aggregate output; $\widehat{P}$ denotes the real exchange rate; $\widehat{E}$ denotes aggregate energy use; $\widehat{C}$ denotes consumption; TMD denotes transformed Mahalanobis distance. ¶The VAR coefficients that lie outside of the 95% confidence bounds; ♮the data variances of the variables that lie outside of the 95% confidence bounds.

over-projects the volatilities of output, consumption, and energy use, but under-projects the variability in real exchange rate.

Empirical Analysis 2

Parameter Estimates I begin the discussion of the empirical results by considering the estimated parameters in Table 3.4 where the calibrated values from Table 3.1 serve as the initial values for the SA algorithm. Three of the parameters are kept fixed throughout the exercise: β, δu^e, and δu^n (the last two are indeed the steady state representations of the depreciation functions), and two are derived from the calibrated/ estimated parameters: θ_e and θ_n. Some of the estimates have values that are not too far from the suggested initial values, while others have values that are quite far off.[29] In the first category are the values for ω, ε, ι, α_e, α_n, $\delta_{e1}u^{\mu_e}$, $\delta_{n1}u^{\mu_n}$, μ_e, μ_n, ψ_e, ψ_n, ϕ_w, η, η_w, κ, and σ, whose values changed by less than 100 percent in absolute terms relative to the initial values; in the second category are ν_e, ν_n, ϕ, and ς, whose values changed by more than 100 percent in absolute terms relative to the starting values.

Consumption elasticity is one of the highly difficult parameters to pin down in economics. The estimate of its inverse is 5.59, which is arguably within the range of estimates found in many DSGE models [Hall (1988) and Smets and Wouters (2003, 2005)]. Consumption elasticity of 0.18 found here implies that households are less willing to smooth consumption across time in response to a change in the real interest rate.[30] Compared to the initial value, the estimated value of the habit formation parameter interestingly is suggesting that household's utility in period t is less dependent on past consumption. Specifically, the estimated value of roughly 0.4 reduces the level of consumption inertia to transitory shocks; this should perhaps remove the hump-shape nature of consumption impulse response functions [see Fuhrer (2000)]. Theoretically, there is no judgement against this result, but quantitatively, it is too low relative to evidence of past estimates for a developed country [see Boldrin et al. (2001), Smets and Wouters (2004), Juilliard et al. (2004), and Christiano et al. (2005); however, low habit persistence has mainly been found in studies relating to emerging countries - see Uribe and Yue (2006)].

The high value for Frisch elasticity ($\omega^{-1} = 0.12$) says that labour hours react more to changes in the real wage. The estimated values for the share of capital services and energy in production in both sectors are a bit low but not unreasonable. $1 + \nu_e$ $(1 + \nu_n)$ is a measure of the inverse elasticity of substitution between capital services and primary energy use in the energy (non-energy) intensive sector such that the values of $\nu_e = 0.12$ and $\nu_n = 0.07$ imply that the two production functions are more Cobb-Douglas than the assumed general CES form, particularly in the non-energy intensive sector. Both

[29] This is no concern so far they are permitted by economic theory this much freedom/ flexibility, e.g. the elasticity parameters.

[30] This implies that agents would respond less to substitution effect than to wealth effect. A value of between zero and one is uncontroversial in the literature [see, for example, Kocherlakota (1988) advocated for a value close to zero]. Meanwhile, Campbell (1992) 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 (2002), Bergin (2003), and Cromb and Fernandez-Corugedo (2004).

Table 3.4: Estimation

Description	Symbol	Initial Values♯	Estimation
Discount factor✠	β	0.96	0.96
Inverse of Frisch elasticity of labour supply	ω	5	8.64
Consumption elasticity	ε	2	5.59
Habit formation parameter	ι	0.7	0.38
Energy intensive sector SoCE	α_e	0.43	0.43
Non-energy intensive sector SoCE	α_n	0.28	0.39
Energy intensive sector EoS btw capital services and energy	ν_e	0.7	0.12
Non-energy intensive sector EoS btw capital services and energy	ν_n	0.7	0.07
Energy intensive sector marginal CoCU	$\delta_{e1}u^{\mu_e}$	0.132	0.32
Energy intensive sector depreciation EoCU	μ_e	1.463	5.51
Non-energy intensive sector marginal CoCU	$\delta_{n1}u^{\mu_n}$	0.102	0.44
Non-energy intensive sector depreciation EoCU	μ_n	1.694	4.32
ACP for energy intensive goods	ψ_e	0.001	0.003
ACP for non-energy intensive goods	ψ_n	0.001	0.002
DC's EoS btw domestic and imported final goods	ϕ	1.5	0.16
FC's EoS btw foreign and exported final goods	ϕ_w	1.5	34.8
DC's EoS btw imported energy and non-energy goods	η	0.44	0.51
FC's EoS btw exported energy and non-energy goods	η_w	0.44	2.12
Bias for energy intensive goods in the DC	σ	0.55	0.48
Bias for domestically produced goods in the DC	κ	0.7	0.68
DC's EoS btw energy and non-energy intensive goods	ς	0.9	0.27
Steady state DF of energy intensive investment goods✠	δu^e	0.09	0.09
Steady state DF of non-energy intensive investment goods✠	δu^n	0.06	0.06
Weight on capital services of the energy intensive sector¶	θ_e	0.9902	0.9631
Weight on capital services of the non-energy intensive sector¶	θ_n	0.9961	0.9833

Note: SoCE: share of capital services and energy; EoS: elasticity of substitution; CoCU: cost of capital utilisation; EoCU: elasticity of capital utilisation; ACP: adjustment cost parameter; DF: depreciation function; DC: domestic country; FC: foreign country. ♯Calibrated values are used to initialise the simulated annealing search algorithm; ✠parameters that are fixed throughout the exercise; ¶parameters that are derived based on fixed and estimated parameters.

estimates for the adjustment cost parameters are close to zero though they have different quantitative impacts on the model. As it is, the value of 0.003 for the energy intensive capital adjustment cost parameter compared to the 0.002 for the equivalent non-energy intensive parameter means that the marginal user cost in the energy intensive sector responds by 50% more to changes in interest rate than does the marginal user cost in the accumulation of non-energy intensive capital goods.

Further, the estimate of the marginal costs of capital utilisation is 32% in the energy intensive sector while it is 44% in the non-energy intensive sector. These different estimates simply indicate that return to investment/ marginal product of capital services in the non-energy intensive sector is higher. Greenwood et al. (1988) and related literature [see, for example, Finn (1991, 1996), Burnside and Eichenbaum (1995), Baxter and Farr (2002), and Leduc and Sill (2004)] suggest that there is yet to be an empirical guide on the choice of a value (magnitude) for the elasticity of capital utilisation rate with Basu and Kimball (1995) admitting that it is a problematic parameter to correctly value. My estimates here are 5.51 and 4.32, respectively, for the energy and non-energy elasticities of capital utilisation rates. Lastly, all the elasticity of substitution parameters in the aggregator functions are sensibly in the ballpark of other estimates found in the literature.

Error Properties of the Estimated Model Using the parameter estimates reported in Table 3.4, the functional forms provided in the previous section, the relevant log-linearized equilibrium conditions, and the actual time series shown in Figure 3.3, I extract for the twelve exogenous variables the structural errors from the model. The estimated AR(1) equations are given by

$$\widehat{\mathsf{A}}_e = 0.4641\widehat{\mathsf{A}}_{e,-1} + \varepsilon^{\mathsf{a}^e},\ \varepsilon^{\mathsf{a}_e} \overset{i.i.d.}{\backsim} N\left(0, 0.0174^2\right) \tag{3.62}$$

$$\widehat{\mathsf{A}}_n = 0.2171\widehat{\mathsf{A}}_{n,-1} + \varepsilon^{\mathsf{a}^n}, \varepsilon^{\mathsf{a}_e} \overset{i.i.d.}{\backsim} N\left(0, 0.0402^2\right) \tag{3.63}$$

$$\widehat{\mathsf{D}}^w = 0.6625\widehat{\mathsf{D}}^w_{-1} + \varepsilon^{\mathsf{d}^w},\ \varepsilon^{\mathsf{d}^w} \overset{i.i.d.}{\backsim} N\left(0, 4.6214^2\right) \tag{3.64}$$

$$\widehat{\mathsf{G}} = 0.4076\widehat{\mathsf{G}}_{-1} + \varepsilon^{\mathsf{g}},\ \varepsilon^{\mathsf{g}} \overset{i.i.d.}{\backsim} N\left(0, 0.0572^2\right) \tag{3.65}$$

$$\widehat{\zeta} = 0.5750\widehat{\zeta}_{-1} + \varepsilon^{\zeta},\ \varepsilon^{\zeta} \overset{i.i.d.}{\backsim} N\left(0, 0.2157^2\right) \tag{3.66}$$

$$\widehat{\mathsf{O}}_e = 0.6009\widehat{\mathsf{O}}_{e,-1} + \varepsilon^{\mathsf{o}_e},\ \varepsilon^{\mathsf{o}_e} \overset{i.i.d.}{\backsim} N\left(0, 2.0775^2\right) \tag{3.67}$$

$$\widehat{\mathsf{O}}_n = 0.6025\widehat{\mathsf{O}}_{n,-1} + \varepsilon^{\mathsf{o}_n},\ \varepsilon^{\mathsf{o}_n} \overset{i.i.d.}{\backsim} N\left(0, 3.9343^2\right) \tag{3.68}$$

$$\widehat{\mathsf{P}}_e^{im} = 0.5572\widehat{\mathsf{P}}^{im}_{e,-1} + \varepsilon^{\mathsf{p}_e^{im}},\ \varepsilon^{\mathsf{p}_e^{im}} \overset{i.i.d.}{\backsim} N\left(0, 0.0353^2\right) \tag{3.69}$$

$$\widehat{\mathsf{Q}} = 0.4353\widehat{\mathsf{Q}}_{-1} + \varepsilon^{\mathsf{q}},\ \varepsilon^{\mathsf{q}} \overset{i.i.d.}{\backsim} N\left(0, 0.2959^2\right) \tag{3.70}$$

$$\widehat{\tau} = 0.5759\widehat{\tau}_{-1} + \varepsilon^{\tau},\ \varepsilon^{\tau} \overset{i.i.d.}{\backsim} N\left(0, 1.2076^2\right) \tag{3.71}$$

$$\widehat{\mathsf{Z}}_e = 0.4585\widehat{\mathsf{Z}}_{e,-1} + \varepsilon^{\mathsf{z}_e},\ \varepsilon^{\mathsf{z}_e} \overset{i.i.d.}{\backsim} N\left(0, 0.0875^2\right) \tag{3.72}$$

$$\widehat{\mathsf{Z}}_n = 0.5708\widehat{\mathsf{Z}}_{n,-1} + \varepsilon^{\mathsf{z}_n},\ \varepsilon^{\mathsf{z}_n} \overset{i.i.d.}{\backsim} N\left(0, 0.1074^2\right) \tag{3.73}$$

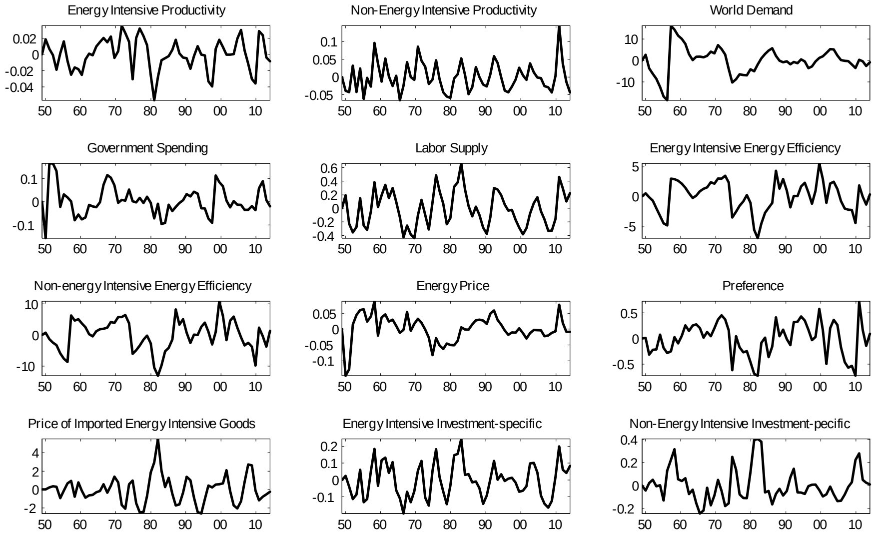


Figure 3.3: Shocks of the estimated model.

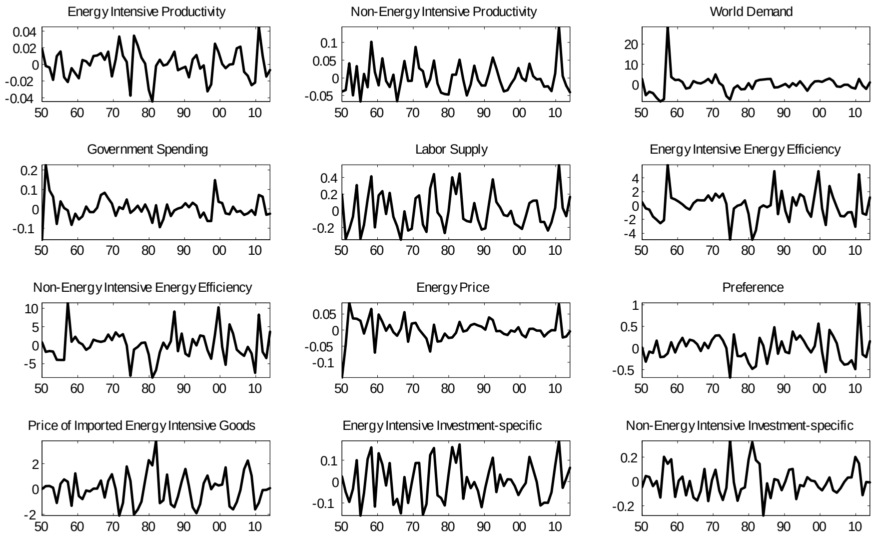


Figure 3.4: Innovations of the estimated model.

Figures 3.3 and 3.4 plot the shocks and innovations respectively of the estimated model. I observe that all the shocks are mildly persistent with the highest AR coefficient being that of the world demand shock and the lowest that of non-energy intensive sector productivity shock. It is also observed that world demand, labour supply, energy intensive sector energy efficiency, non-energy intensive sector energy efficiency, energy price, and intertemporal preference shocks are the most volatile.

Assessing the Fit of the Estimated Model Table 3.5 documents the estimates of the VAR coefficients given the estimated structural errors. Compared to the results reported in Table 3.3 for calibrated parameter values, the present results are a big improvement for the tests of individual and joint distributions of the model vis-à-vis the data, but especially regarding their joint distribution. More specifically, evaluating the estimated model against the data for output, real exchange rate, energy use, and consumption, the model fits the data jointly well having acceptance at roughly 93% level when both the dynamics and volatilities of the four variables are included. The transformed Mahalanobis distance (TMD) is 1.46. The dynamic fit of the model to the data passes slightly better the Wald test at the 91.7% level with an associated TMD of 1.3. This is suggesting a strong causality between the four VAR components. However, the model continues to fail massively in capturing the data variances both for the individual and joint distributions; there is evidence that the model's predictions of these variables have a deteriorating effect on the model fit. Evidently, the model is predicting wrongly the size of the joint data variances.

Figure 3.5 lends support to these findings. The estimated model matches well the persistence of each of the four macroeconomic variables - plotted on the diagonal. Only real exchange rate, at lags $6-7$, failed to fall within the 95% bound. I plot the cross-correlations of the four variables on the off-diagonal points of the graph. This replicates qualitatively the quantitative results discussed above that the model is unable to match the individual cross-correlations found in the data. The model appears to capture well the negative and positive cross-effects at lags and leads of 2 with the best fits involving real exchange rate correlations. On all occasions, the simulated and actual data depart on contemporaneous cross-effects between these variables.

Regarding the individual distributions of the VAR coefficients, all but one of the sixteen dynamic VAR parameters measuring autocorrelations and cross-correlations lie within the 95% confidence bounds, which is also an improvement over the results obtained for the calibrated parameter values. The only cross-effects that lies outside of the 95% confidence bounds being that from consumption to energy use. Meanwhile, all four data variances are now over-predicted by the model. In particular, the calibrated and estimated model

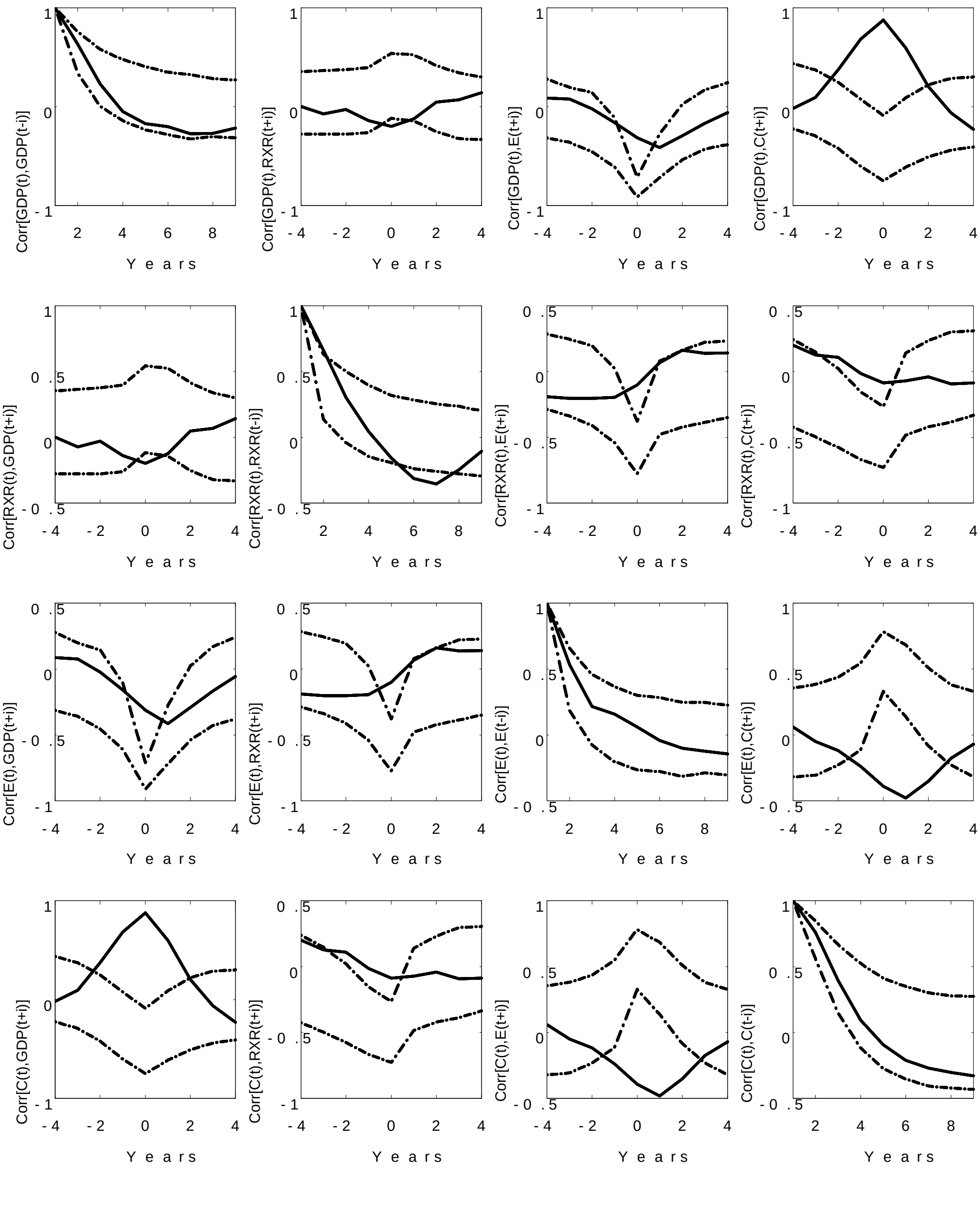


Figure 3.5: Cross-correlations: data vs. estimated model.

Table 3.5: VAR Results for Estimated Model

Coefficients	Actual	Lower Bound	Upper Bound	Mean
$\rho_{\widehat{Y},\widehat{Y}}$	0.4913	0.0316	1.0204	0.5756
$\rho_{\widehat{P},\widehat{Y}}$	−0.0076	−0.0628	0.0982	0.0132
$\rho_{\widehat{E},\widehat{Y}}$	−0.0354	−0.0720	0.0646	−0.0039
$\rho_{\widehat{C},\widehat{Y}}$	0.1080	−0.0767	0.1086	0.0107
$\rho_{\widehat{Y},\widehat{P}}$	0.0047	−2.2335	3.3631	0.5176
$\rho_{\widehat{P},\widehat{P}}$	0.6797	0.0987	0.8771	0.5107
$\rho_{\widehat{E},\widehat{P}}$	0.1341	−0.3020	0.4652	0.0780
$\rho_{\widehat{C},\widehat{P}}$	0.4435	−0.4135	0.5990	0.0769
$\rho_{\widehat{Y},\widehat{E}}$	0.4621	−5.1792	4.1954	−0.6893
$\rho_{\widehat{P},\widehat{E}}$	−0.1641	−0.8366	0.6663	−0.0840
$\rho_{\widehat{E},\widehat{E}}$	0.4959	−0.2948	1.0473	0.3765
$\rho_{\widehat{C},\widehat{E}}$	−1.2027¶	−1.0638	0.7703	−0.0884
$\rho_{\widehat{Y},\widehat{C}}$	0.0697	−0.6549	1.8098	0.5547
$\rho_{\widehat{P},\widehat{C}}$	0.0041	−0.2242	0.1765	−0.0225
$\rho_{\widehat{E},\widehat{C}}$	−0.0198	−0.1247	0.2351	0.0556
$\rho_{\widehat{C},\widehat{C}}$	0.5978	0.4833	0.9146	0.7138
$\sigma^2_{\widehat{Y}}$	0.0009♮	0.0019	0.0068	0.0040
$\sigma^2_{\widehat{P}}$	0.0314♮	0.0364	0.2030	0.0971
$\sigma^2_{\widehat{E}}$	0.0413♮	0.1614	0.4604	0.2851
$\sigma^2_{\widehat{C}}$	0.0004♮	0.0198	0.0633	0.0374
	Dynamics+Volatilities	Dynamics	Volatilities	
Wald (%)	93.1	91.7	98.1	
TMD	1.46	1.30	2.61	

Note: $\rho_{i,j}$ denotes the VAR coefficient of a lagged variable i on a variable j; σ^2_j denotes the variance of variable j; $\widehat{Y}$ denotes aggregate output; $\widehat{P}$ denotes the real exchange rate; $\widehat{E}$ denotes aggregate energy use; $\widehat{C}$ denotes consumption; TMD denotes transformed Mahalanobis distance. ¶The VAR coefficients that lie outside of the 95% confidence bounds; ♮the data variances of the variables that lie outside of the 95% confidence bounds.

differ in their predictions of the variances of the real exchange rate with the data variance for real exchange rate closer to the lower bound of acceptance interval for the estimated model. The result is opposite for the calibrated model.

Turning next to the VAR impulse response functions of output, real exchange rate, energy use, and consumption to the twelve shocks as a way to gleaning more intuition regarding the dynamic behaviour of the estimated model economy. These are shown in Figures 3.6-3.17, where the VAR shocks have been identified using the structural model. There appears to be congruence in the responses of both the model and the data to all the shocks for output, real exchange rate, and energy use, with their responses placed inside the 95% bounds both in the short- and the long-term. This is an interesting result yielding confidence on possible usability of the model for policy-related work by adapting

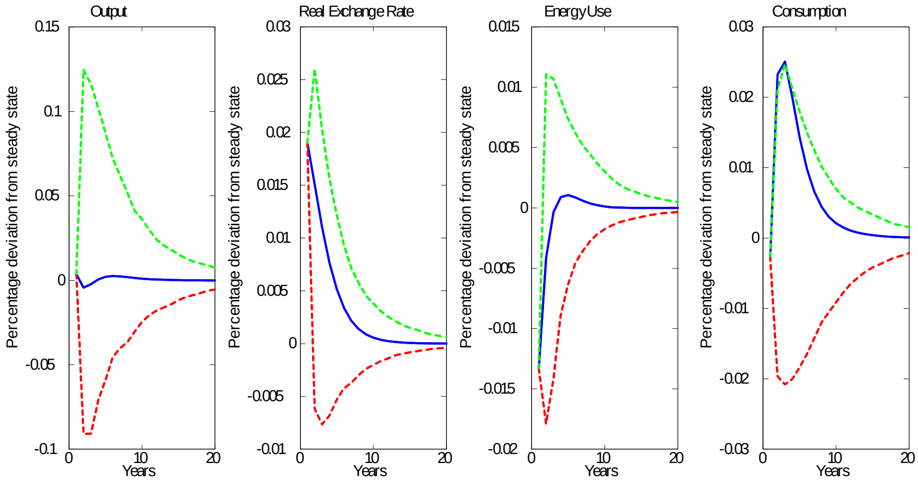


Figure 3.6: VAR IRFs of a_t^e.

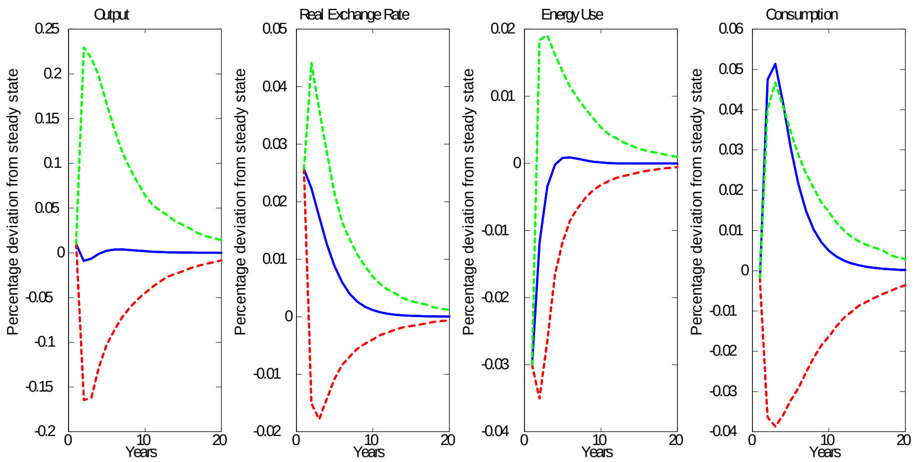


Figure 3.7: VAR IRFs of a_t^n.

the structural impulse response functions to determine the influences of shocks and in creating appropriate policy responses [see Christiano et al. (2005)].

Nevertheless, I cannot say the same for consumption as there is a consistent short-run differences between the model and the data, especially for non-energy intensive sector productivity, energy intensive sector energy efficiency, non-energy intensive sector energy efficiency, imported price of energy intensive goods, and energy price shocks. I have not included all the other shocks notably the energy intensive sector productivity, labour supply, and non-energy intensive investment-specific technology shocks chiefly because there is little difference between borderline non-rejection/ rejection given the very stringent econometric procedure I have applied [see Davidson et al. (2010)].

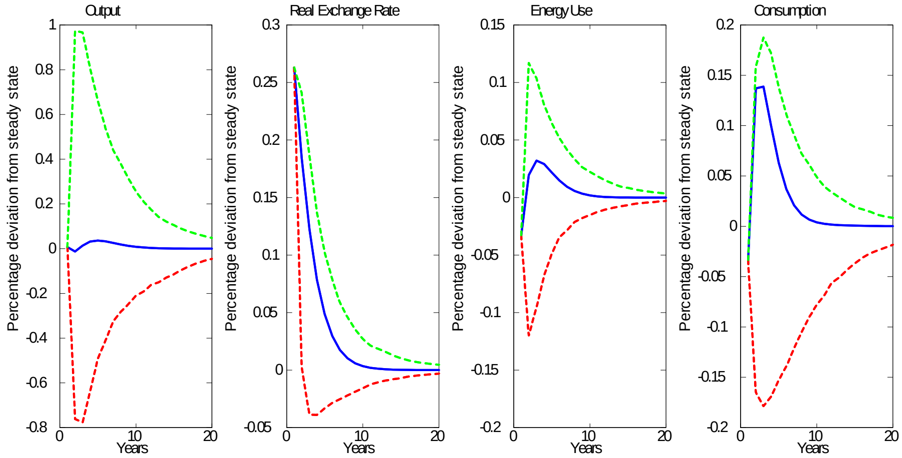


Figure 3.8: VAR IRFs of d_t^w.

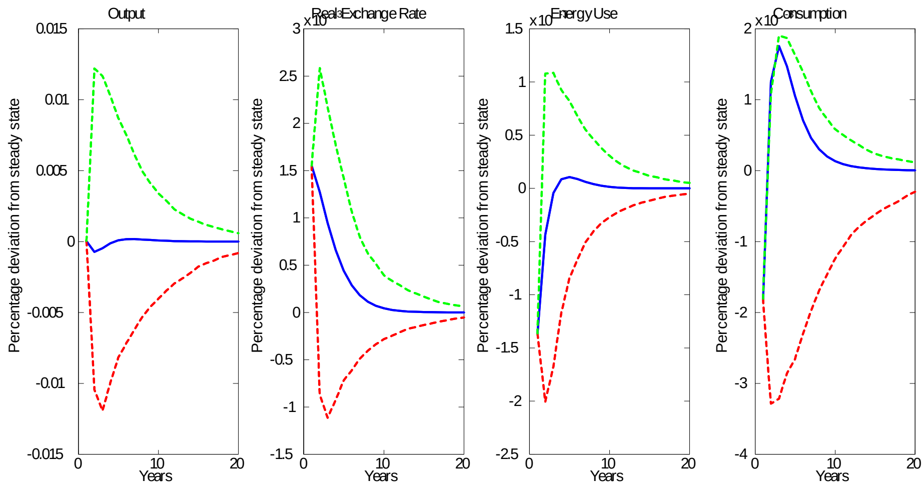


Figure 3.9: VAR IRFs of g_t.

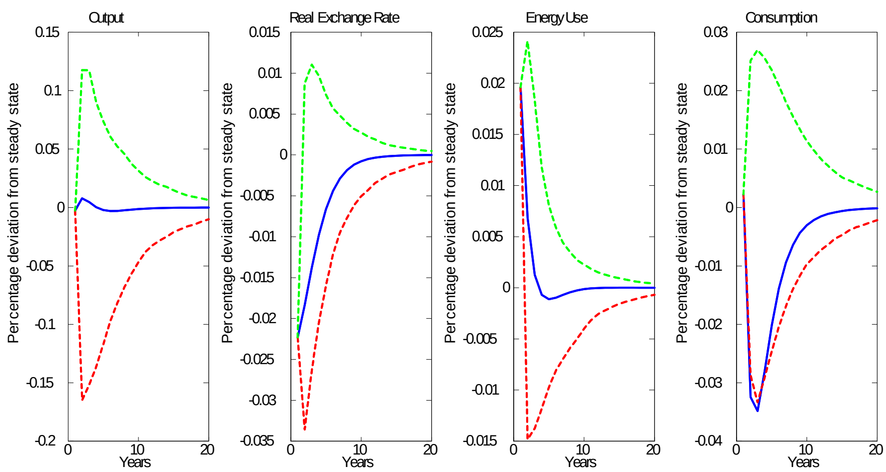


Figure 3.10: VAR IRFs of ζ_t.

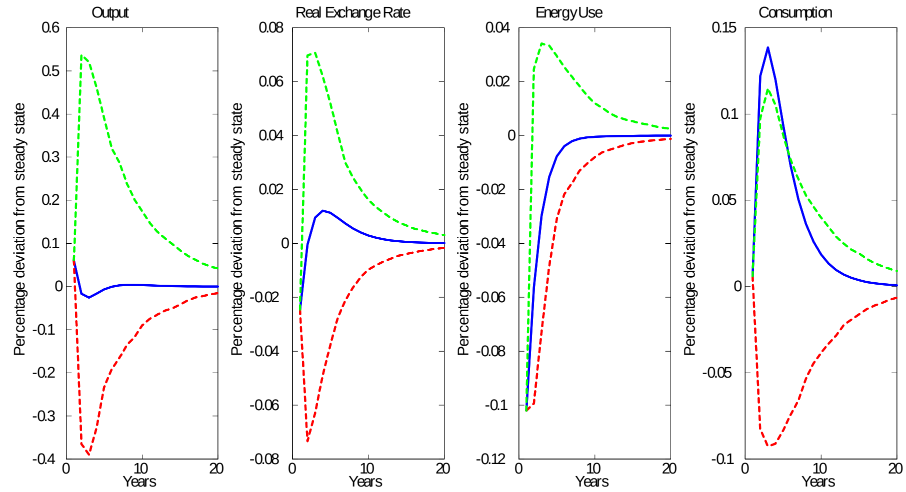


Figure 3.11: VAR IRFs of o_t^e.

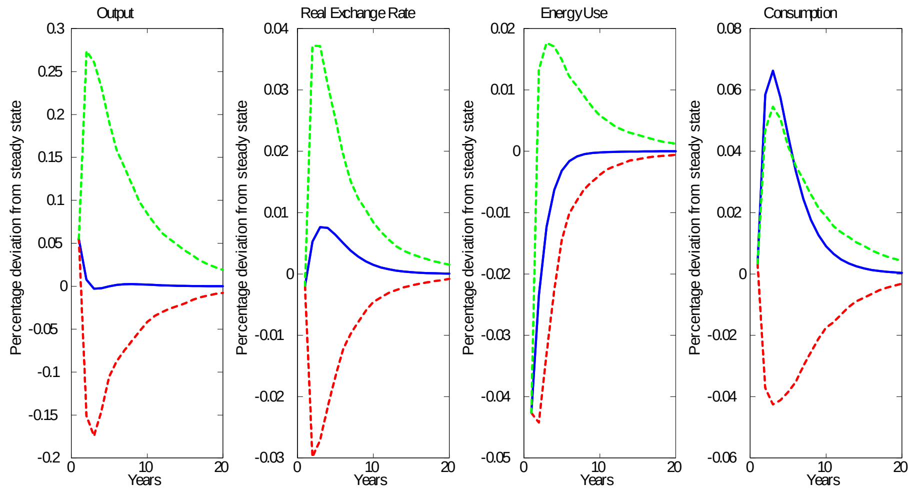


Figure 3.12: VAR IRFs of o_t^n.

Accounting for the U.S. Business Cycles Post-WW II To further study the business cycle implications of the estimated model, I report the standard deviations of real exchange rate, energy use, and consumption relative to that of output in Table 3.6, and plot the model's prediction of recession compared to that of the data in Figure 3.18. Given the identified recessions in both data and model, I conclude this sub-section by providing a ranking of the behaviour of the four macroeconomic time series included in the estimation following the realisation of the shock in Figure 3.19. Before generating the model statistics and the plots, I simulate 1000 artificial economies each with same length as the actual data observations. The model statistics and the plots are averages of the 1000 simulations.

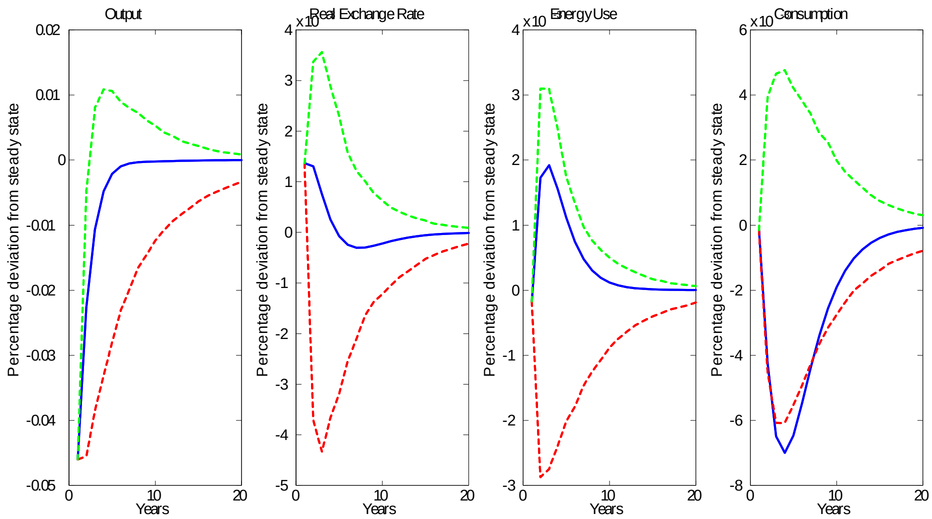


Figure 3.13: VAR IRFs of $\mathsf{p}^{im}_{e,t}$.

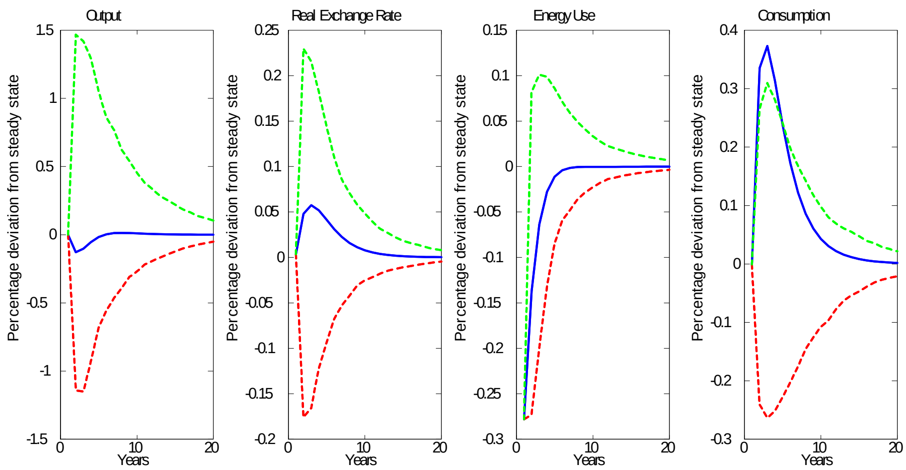


Figure 3.14: VAR IRFs of q_t.

It is reported in Table 3.6 that the model predicts values of the relative volatilities of real exchange rate and energy use that are quite similar to that found in the data. On the other hand, it failed to capture the relative volatility observed for consumption with massive over-prediction. All in all, the model generates higher volatilities for the four time series compared to the data. Further, the model matches very well the timing and persistence of recessions, but it is less successful in replicating the recovery rate. The economy is normally back to its pre-recession level of output 3 years after the shock according to the data. Whereas, the model requires a much longer time.

Overall, it can be seen in Figure 3.19 that the model is able to preserve the after-shock

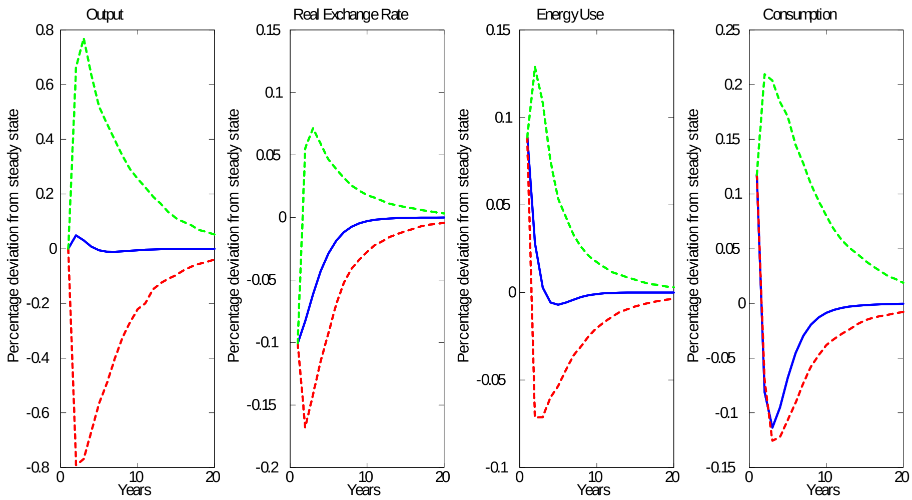


Figure 3.15: VAR IRFs of τ_t.

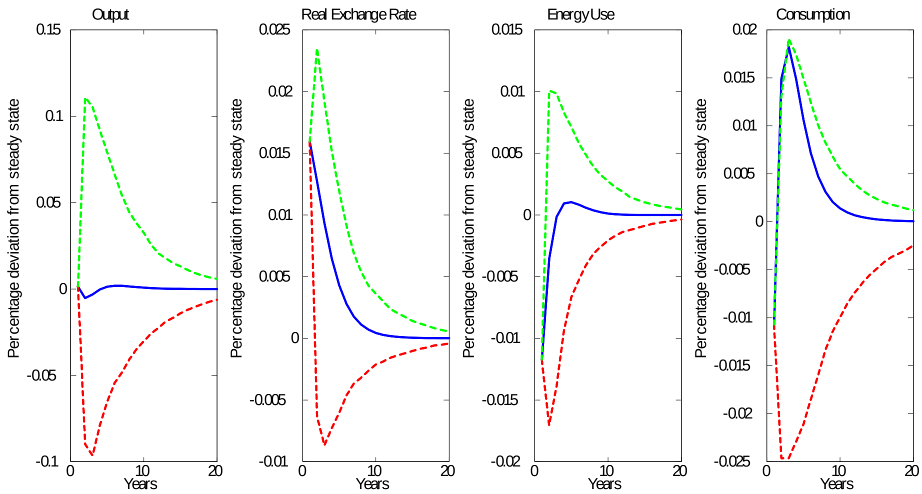


Figure 3.16: VAR IRFs of z_t^e.

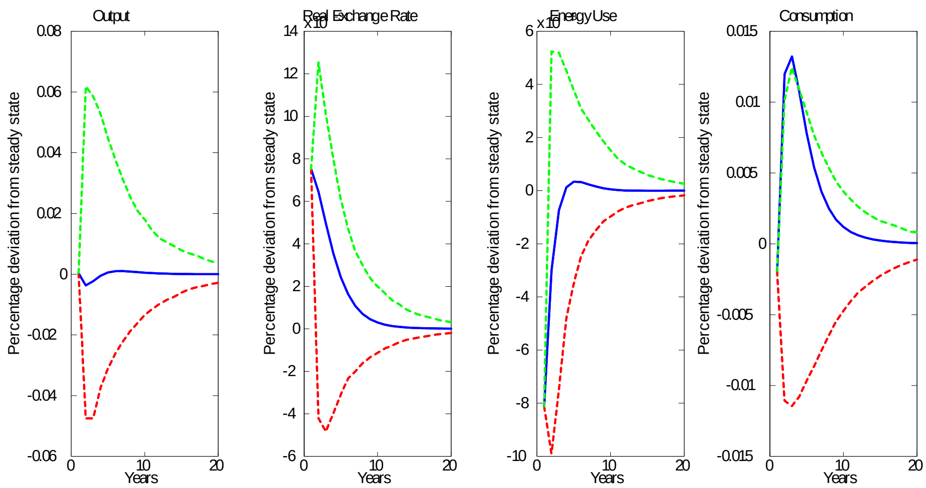


Figure 3.17: VAR IRFs of z_t^n.

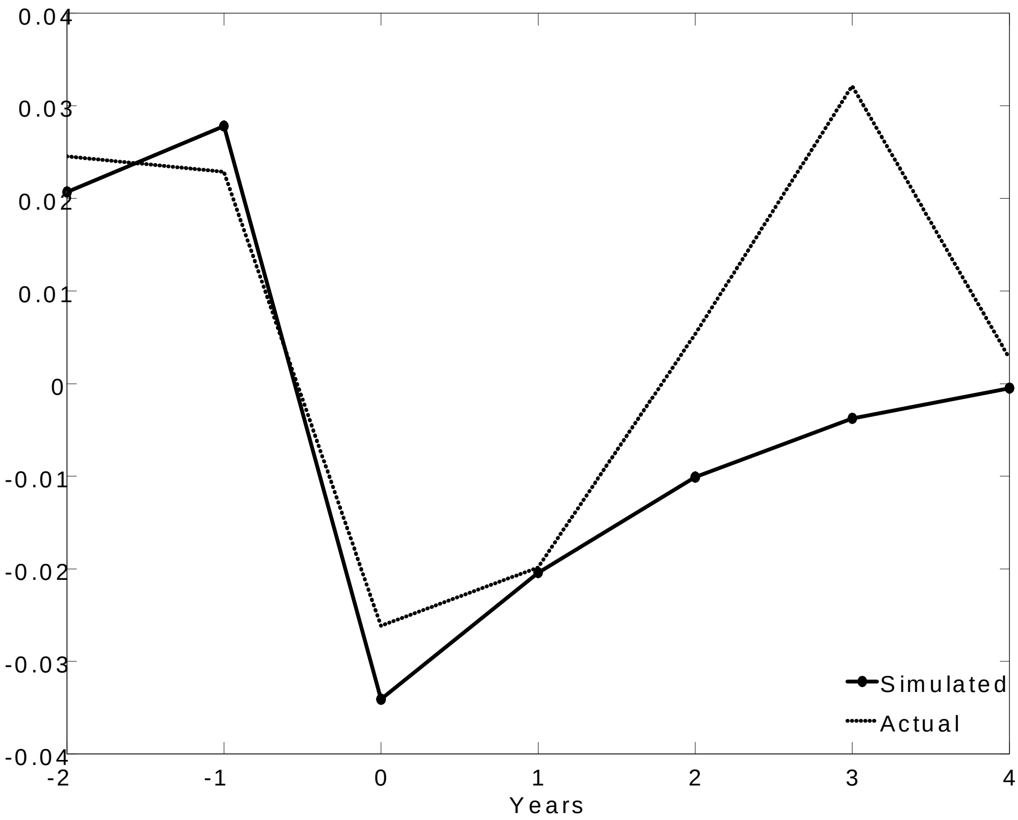


Figure 3.18: Prediction of recession by energy real business cycle model.

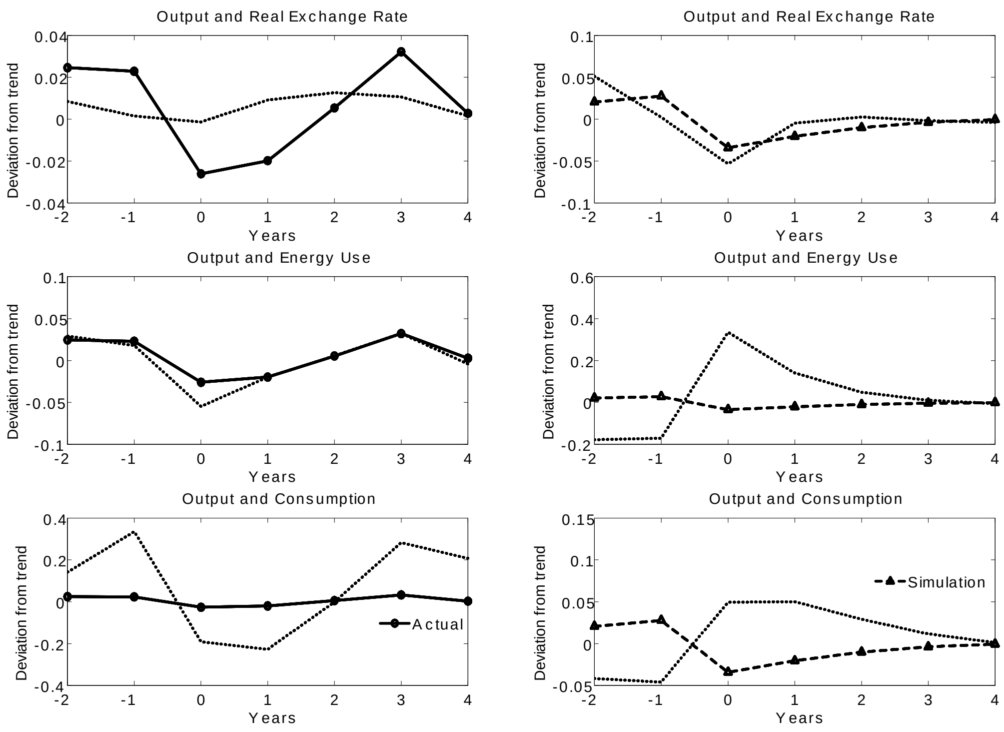


Figure 3.19: Business cycle ranking of data and model.

Table 3.6: Business Cycle Statistics

Statistic	$\frac{\sigma(Y)}{\sigma(Y)}$	$\frac{\sigma(RXR)}{\sigma(Y)}$	$\frac{\sigma(E)}{\sigma(Y)}$	$\frac{\sigma(C)}{\sigma(Y)}$
Data	1.00	5.86	6.72	0.65
Model	1.00	4.76	8.49	3.10
	$\frac{\sigma(Y_{DATA})}{\sigma(Y_{MODEL})}$	$\frac{\sigma(RXR_{DATA})}{\sigma(RXR_{MODEL})}$	$\frac{\sigma(E_{DATA})}{\sigma(E_{MODEL})}$	$\frac{\sigma(C_{DATA})}{\sigma(C_{MODEL})}$
$\frac{\sigma(*_{DATA})}{\sigma(*_{MODEL})}$	0.48	0.60	0.38	0.10

Note: $* = Y, RXR, E, C$ where RXR is real exchange rate, and σ denotes standard deviation.

business cycle behaviour of real exchange rate in relation to output, but not much that of energy use and consumption. In the data, energy use relative to output does not move much, but the model is picking up a decline in demand for energy given a rise in its price. Lastly, perhaps due to the lower consumption inertia estimated, there is little consumption smoothing in the model such that it drops instantly in response to the shock.

3.5 Conclusion

The model presented in this chapter has worked reasonably well both in fitting the model to data for my benchmark macroeconomic variables of output, real exchange rate, energy use, and consumption and also in capturing some salient facts regarding the macroeconomic-oil relationship. Clearly, the model was only able to explain my selected features leaving many questions unanswered. To investigate whether this is a model problem, or just a circumstance of the parameters in use, I carried out a further Directed Wald test. The main outcomes include that (1) *if* estimated using the SA algorithm, the model appear capable of fitting the data for several variable combinations, (2) when *any* parameter set (that fits the model to the data) for *certain* variable combination is used as a benchmark on which different variable combinations are evaluated, I find that the model can only explain along some lines and fails to fit the data for the rest suggesting that the parameters are not globally useful within the context of this model. What I take from this is a simple lesson on which a research endeavour must emanate from: that is, there must be a focused, definitive question of enquiry posed a priori. Given this, a model can then be applied to answer the proposed question.

Therefore, it is a matter for future research to extend this model to deal with economic issues along other dimensions and it is my hope that this model will be adjusted appropriately to answer many other macroeconomic questions particularly those that concern energy issues and their policy implications. To kick-start such an agenda, I motivate two particular possibilities in this concluding remark. First, the complete inter-country effects through (in)complete risk sharing and uncovered interest parity can be studied by allowing both the domestic and foreign residents investment opportunities in both the domestic and foreign bonds [see, for example, Gali and Monacelli (2005) and Corsetti et al. (2005)]. Having introduced capital accounts into the model, a second important and new effort could be to work with non-stationary data set. It is to these two exercises I now turn in Chapter 4.

Table 3.7: Oil Price Increases and Causes, 1947-2008

Oil Price Episode	Price Changes (%)	Principal Factors
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
2007-2008	145	Strong demand vs supply constraints

Source: Hamilton (1985, 2011).

Chapter 4

So, Do Energy Price Shocks Still Matter?

> A parameter that is valid for a model in one economic environment cannot be uncritically applied to a model embedded in a different economic environment. Martin Browning, Lars Peter Hansen, and James J. Heckman (Handbook of Macroeconomics, 1999, p. 546).

4.1 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. I take the U.S. as the example domestic country for this exercise. To put this into perspective, I display in Figure 4.1 the historical data on U.S. output (1929-2013) and its trend identified by using the Hodrick-Prescott (HP, 1981, 1997) filter with the smoothing parameter set to 400 in row 1, oil price-output (1949-2013) relationship in row 2, oil price-real exchange rate (1949-2013) relationship in row 3, and output-real exchange rate (1949-2013) relationship in row 4.

Row 1 shows two of the measures by which economic downturns can be represented. 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 shows that they often travel in opposite directions, especially during periods of radical upswing in prices (i.e., oil price shocks). Clearly, output is a lot less volatile than oil price. Oil price leads 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 price gets 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 chapter, I add to the significantly growing body of literature that is debating if energy price shocks still matter.[1] This issue is addressed 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 I am studying here being the pioneering works of Kim and Loungani (1992) and Finn (1991). In particular, I 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 - real price of oil - in influencing the U.S. business cycles and competitiveness vis-à-vis the rest of the world. My 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 assets across countries; (3) the model is augmented with an

[1] The background to this work encompasses many strands of the macro econometric 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, 1996, 2003, 2011), Hamilton and Herrara (2000), Herrera and Pesavento (2007), Hooker (1996, 1997, 2002), Hunt et. al. (2001), Kilian (2008), and Mork (1989), among others for empirical discussions; Blanchard and Gali (2010), Darby (1981), Dhawan and Jeske (2006, 2008), Dhawan et. al. (2010), Finn (1991, 1995, 2000), Gillingham et. al. (2009), Harris et. al. (2009), Kim and Loungani (1992), Loungani (1986), Rotemberg and Woodford (1996), Schmidt and Zimmermann (2005), among others for theoretical underpinnings; and policy related papers, see, for example, Barsky and Kilian (2002), Bernanke et. al. (1997), Blanchard and Simon (2001), Chakravorty (1997), Leduc and Sill (2004, 2006), and Stock and Watson (2003).

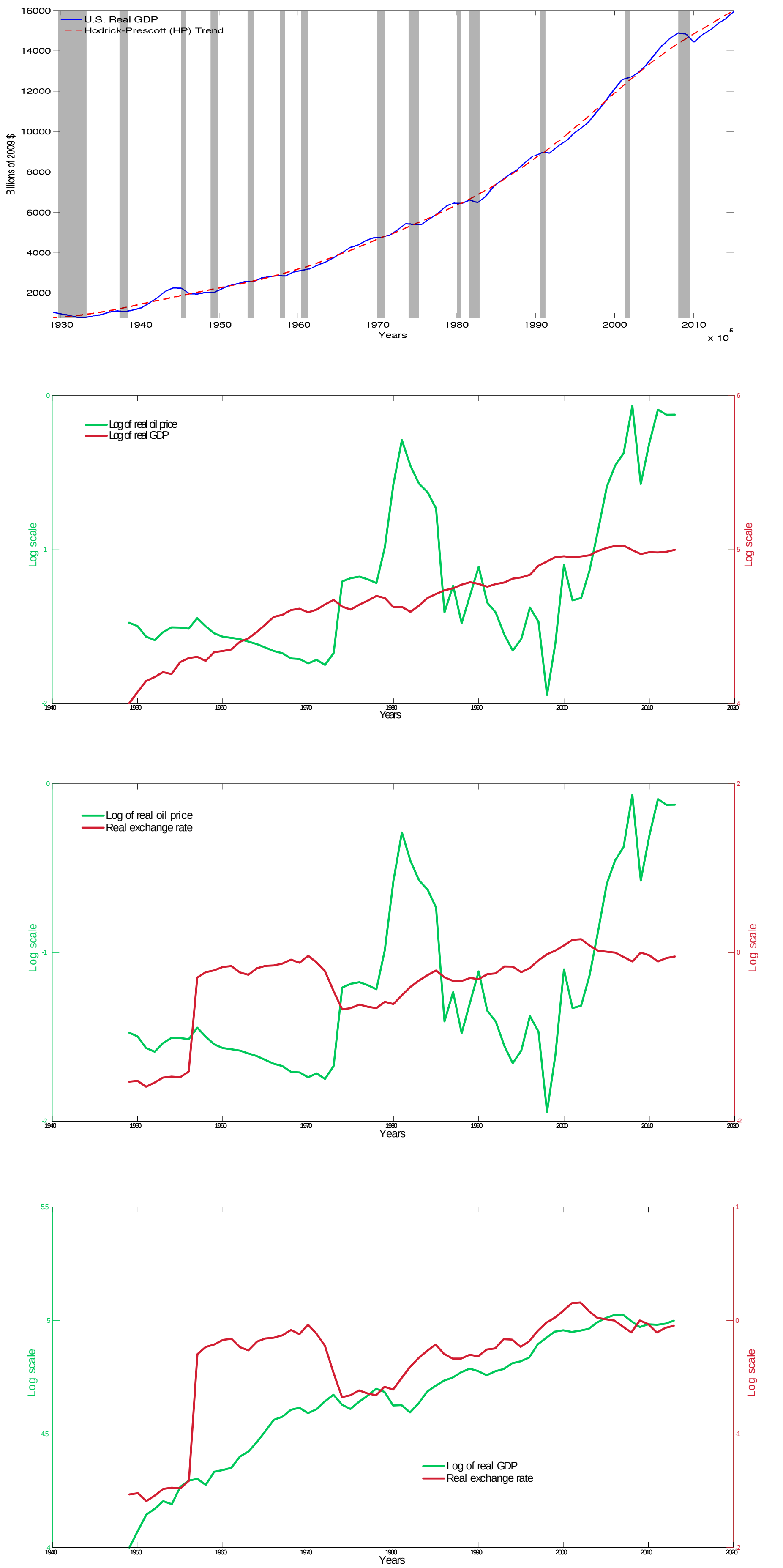


Figure 4.1: Output, oil price, and real exchange rate. U.S. Data 1929-2013

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

Thus, while it is a useful contribution that the model as it is spelt out in the next section as a two-sector energy and non-energy model is to my best knowledge a new and, as I will discuss later, an important set-up, I will like to draw attention to the fact that the model has been estimated on non-stationary data. In reality, most macroeconomic variables are non-stationary implying that we may be removing critical information when we filter them.[2] Therefore, it is useful whenever technically permissible to develop a model that can be used to describe unfiltered data. This is a major and novel contribution of this chapter 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."

The main finding is that energy price shocks is not able to directly generate the magnitude of economic downturn observed in the data. However, it possesses a strong indirect transmission link that endogenously spread its effect erroneously through the system. This leads me to conclude that previous results that attribute minimal importance to oil price shocks must be focusing on the energy cost share of gross domestic product. I also find that external shocks have been responsible for explaining the volatility in U.S. economic activities for a long time. This leads me to conclude that modelling the U.S. as a closed economy assumes away a sizeable set of very relevant factors.

The remainder of this chapter proceeds as follows. In Section 4.2, I describe the main features of the two-sector model in log-linearized form. In Section 4.3, I provide brief discussions of the econometric method of indirect inference (II) used in estimating the model, the non-stationary data serving as the empirical counterparts to model variables, and the initial parameter values used to initialise the starting points for the Simulated Annealling (SA) algorithm. I present the main findings in Section 4.4 and conclude with Section 4.5.

[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.

4.2 The Model

The model is described in this section. I am now more equipped to consider what I refer to as a complete model in the sense that the theoretical model being considered here is essentially that discussed in Chapter 3, but is being extended to include the capital account. I suppose that I have a complete model such that at the end of this section, I could be confident that I have developed an open economy model that incorporates many of the features of the national income account. Essentially, this introduces an additional first-order condition on the household's side: the uncovered interest parity (UIP) condition and both the balance of payment (BOP) account and the economy-wide resource constraint are extended to include the capital account. Further, note that more shocks are added and for this reason the first-order conditions on the firm and trader's side are also altered. Because of these changes, I re-present the model set-up.

Households

I begin with the characterisation of aggregate choices. Particularly, these are the consumer decisions. Hence, the stand-in consumer chooses consumption of goods, C_t, and labour hours, H_t, in order to maximise the utility function

$$\mathbb{E}_0 \sum_{t=0}^{\infty} \beta^t \tau_t U \left(\frac{(C_t - \iota C_{t-1})^{1-\epsilon}}{1-\epsilon} - \zeta_t \frac{H_t^{1+\omega}}{1+\omega} \right) \tag{4.1}$$

subject to the following sequential budget constraint

$$\begin{aligned} & B_t + \frac{F_t}{P_t} + C_t + T_t + \frac{K_t^e}{\mathsf{Z}_t^e} + \frac{K_t^n}{\mathsf{Z}_t^n} + 0.5\psi_e \left(\frac{K_t^e}{K_{t-1}^e} - 1 \right)^2 \frac{K_{t-1}^e}{\mathsf{Z}_t^e} \\ & +0.5\psi_n \left(\frac{K_t^n}{K_{t-1}^n} - 1 \right)^2 \frac{K_{t-1}^n}{\mathsf{Z}_t^n} + \frac{0.5\psi_f}{P_t} (F_t - f)^2 = (1 + r_{t-1}) B_{t-1} \\ & + \left(1 + \mathsf{r}_{t-1}^f\right) \frac{F_{t-1}}{P_t} + \left(R_t^e U_t^e + \frac{1 - \delta_{e0} - \delta_{e1} (U_t^e)^{\mu_e} / \mu_e}{\mathsf{Z}_t^e} \right) K_{t-1}^e \\ & +W_t H_t + \left(R_t^n U_t^n + \frac{1 - \delta_{n0} - \delta_{n1} (U_t^n)^{\mu_n} / \mu_n}{\mathsf{Z}_t^n} \right) K_{t-1}^n + \Pi_t \end{aligned} \tag{4.2}$$

In the utility function, $\mathbb{E}$ is the operator signifying mathematical expectations based on the information set available to the agents at period zero thereby introducing some elements of uncertainty into the model, $0 < \beta < 1$ is the discount factor, ι is the external habit formation parameter, ϵ is elasticity of consumption, ω is the inverse of Frisch elasticity of labour supply, and the exogenous stochastic variables are τ_t denoting intertemporal preference shock and ζ_t denoting labour supply shock. I describe the processes for these and subsequent shocks later and also, I assume that the utility function is continuously differentiable, increasing in its arguments, and concave.

In the budget constraint, ψ_e and ψ_n are the respective energy and non-energy intensive adjustment cost parameters, δ_{e0} and δ_{n0} are the respective constant portions of the steady state level of energy and non-energy intensive physical capital, δ_{e1} and δ_{n1} are the respective slopes of the energy and non-energy intensive depreciation functions, and μ_e and μ_n govern the respective energy and non-energy intensive elasticities of marginal depreciations with regards to capital utilisation rates. Moreso, the stand-in consumer invests in two types of assets: two types of physical capital (energy intensive, K_t^e, and non-energy intensive, K_t^n) and two types of financial assets (domestic bonds, B_t, and foreign bonds, F_t); W_t is the wage rate, R_t^e is the rental rate of energy intensive physical capital, R_t^n is the rental rate of non-energy intensive physical capital, U_t^e is energy intensive capital utilisation rate, U_t^n is non-energy intensive capital utilisation rate, r_t is the net return to domestic bonds, T_t is the lump-sum taxes/ transfers from the government, $\Pi_t = \Pi_t^e + \Pi_t^n$ defines the profit received by the stand-in consumer as lump-sum transfers from owning firms in the two production sectors of the economy, P_t is the real exchange rate, and the exogenous stochastic variables are Z_t^e denoting energy intensive investment-specific technology shock, Z_t^n denoting non-energy intensive investment-specific technology shock, and r_t^f denoting the exogenous net return to foreign bonds.

Also, I find it convenient to assume that consumers in the foreign bonds market face a quadratic portfolio adjustment or transaction cost similar to Schmitt-Grohe and Uribe

(2003),[3] Iacoviello and Minnetti (2006), and Fernandez-Villaverde et al. (2011).[4] In this formulation, f is the steady state value of the stock of foreign bonds and ψ_f is the adjustment cost parameter.

Further, indexing the two sectors by $j = e, n$, investments in the two stocks of physical capital by the stand-in consumer are given by

$$i_t^j = \mathsf{i}_1^j k_t^j - \mathsf{i}_2^j k_{t-1}^j + \mathsf{i}_3^j u_t^j - \mathsf{z}_t^j \tag{4.3}$$

where

$$\begin{aligned} \mathsf{i}_1^j &= 1/\delta u^j \\ \mathsf{i}_2^j &= \left(1 - \delta u^j\right)/\delta u^j \\ \mathsf{i}_3^j &= \delta_{j1} u^{\mu_j}/\delta u^j \end{aligned}$$

and as can be expected, current investment depends positively on currently installed physical capital stock, but negatively on lagged installed physical capital stock and investment/capital shock. Note that I assume that one period is sufficient to transform an investment good into a productive capital.

The stand-in consumer chooses the paths for C_t, H_t, B_t, F_t, K_t^e, and K_t^n, in order to maximise the utility function (4.1) subject to the constraints (4.2)-(4.3), and a no-Ponzi-game constraint of the form

$$\lim_{T\to\infty} \frac{F_T}{\prod_{t=0}^{T} \mathsf{r}_t^f} \leq 0 \tag{4.4}$$

taking as given the paths of prices, taxes, and profits P_t, W_t, R_t^e, R_t^n, r_t, T_t, and Π_t, the paths of the exogenous stochastic processes τ_t, ζ_t, r_t^f, z_t^e, and z_t^n, and the initial conditions

[3] They 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 foreign debt, following a unit root process. Further, Uribe and Yue (2006) provided a theoretical justification for the incorporation and use of portfolio adjustment cost in a model where a banking sector is implicit.

[4] See also Goodfriend and McCallum (2007), Aliaga-Diaz and Olivero (2010), Curdia and Woodford (2010), and Iacoviello (2014) for similar ideas.

C_{-1}, B_{-1}, F_{-1}, K^e_{-1}, and K^n_{-1}. The first-order conditions for the consumer's problem are equations (4.2)-(4.4) holding with equality, and

$$c_t = \mathsf{c}_1 \mathbb{E}_t c_{t+1} + \mathsf{c}_2 c_{t-1} + \mathsf{c}_3 \left(\tau_t - \mathbb{E}_t \tau_{t+1} - \mathsf{c}_4 r_t\right) \tag{4.5}$$

$$w_t = \omega h_t + \zeta_t + \mathsf{w}_1 \left(c_t - \iota c_{t-1}\right) \tag{4.6}$$

$$r_t = \mathsf{r}^f_t + p_t - \mathbb{E}_t p_{t+1} - \mathsf{r}_1 f_t \tag{4.7}$$

$$\begin{aligned} k^e_t &= \mathsf{k}^e_1 \left(c_t - \iota c_{t-1}\right) - \mathsf{k}^e_2 \left(\mathbb{E}_t c_{t+1} - \iota c_t\right) + \mathsf{k}^e_3 \left(\mathbb{E}_t \tau_{t+1}\right. \\ &\quad \left. - \tau_t - \mathbb{E}_t \mathsf{z}^e_{t+1} + \mathsf{z}^e_t\right) + \mathsf{k}^e_4 \mathbb{E}_t u^e_{t+1} + \mathsf{k}^e_5 \left(\beta \mathbb{E}_t k^e_{t+1} + k^e_{t-1}\right) \end{aligned} \tag{4.8}$$

$$\begin{aligned} k^n_t &= \mathsf{k}^n_1 \left(c_t - \iota c_{t-1}\right) - \mathsf{k}^n_2 \left(\mathbb{E}_t c_{t+1} - \iota c_t\right) + \mathsf{k}^n_3 \left(\mathbb{E}_t \tau_{t+1}\right. \\ &\quad \left. - \tau_t - \mathbb{E}_t \mathsf{z}^n_{t+1} + \mathsf{z}^n_t\right) + \mathsf{k}^n_4 \mathbb{E}_t u^n_{t+1} + \mathsf{k}^n_5 \left(\beta \mathbb{E}_t k^n_{t+1} + k^n_{t-1}\right) \end{aligned} \tag{4.9}$$

with

$$\begin{aligned} \mathsf{c}_1 &= \frac{1}{1+\iota}, \ \mathsf{c}_2 = \frac{\iota}{1+\iota}, \ \mathsf{c}_3 = \frac{1-\iota}{\epsilon\left(1+\iota\right)}, \ \mathsf{c}_4 = \beta r = 1-\beta; \\ \mathsf{w}_1 &= \frac{\epsilon}{1-\iota}; \ \mathsf{r}_1 = \psi_f f; \\ \mathsf{k}^j_1 &= \mathsf{k}^j_2 = \frac{\epsilon/\left(1-\iota\right)}{\psi_j\left(1+\beta\right)}, \ \mathsf{k}^j_3 = \frac{1}{\psi_j\left(1+\beta\right)}, \ \mathsf{k}^j_4 = \frac{\beta\delta_{j1} u^{\mu_j}\left(\mu_j - 1\right)}{\psi_j\left(1+\beta\right)}, \ \mathsf{k}^j_5 = \frac{1}{1+\beta} \text{ for } j = e, n; \end{aligned}$$

where I have substituted out the marginal utility of consumption, λ_t, and the sectoral rental rates of physical capital, R^e_t and R^n_t.[5] Consumption decision for goods by the consumer is intertemporal and is determined in equation (4.5): this equilibrium condition is a relatively standard forward-looking consumption Euler equation and states that current consumption is affected positively by future and lagged consumption because of the desire to smooth consumption over time, and the ratio of the current to future intertemporal

[5] λ_t is subbed out by combining relevant household's first-order conditions, while R^e_t and R^n_t are subbed out using relevant first-order conditions of the firms: the resulting expression for the rental/capital utilisation rates are provided along with the firms' first-order conditions in the next sub-section. See the Supplementary Notes: Chapter 4 for details.

preference shock, but negatively by the current net return to domestic bonds. The impact of the ratio $\tau_t/\mathbb{E}_t\tau_{t+1}$ being positive implies that a stand-in consumer weighs current consumption more than investment, and hence, future consumption, among other things, depends on the real return to domestic bonds. That is, a rise in the latter will lead to a decrease in current consumption and causing investment to go up contemporaneously. One can think of a similar impact on current consumption when there is a positive jump in financial investment, which incidentally is an expected outcome whenever, say, the system is hit by a positive interest rate shock.

Equilibrium condition (4.6), which determines how the stand-in consumer will supply their labour hours to the production sectors, or equivalently the level of equilibrium wage, says that equilibrium wage reacts positively to labour hours, current consumption, and labour supply shock, but negatively to lagged consumption. Equilibrium condition (4.7) summarises the uncovered interest parity condition stating that the net returns to domestic and foreign bonds will be the same except for when current and expected real exchange rates differ, and also domestic interest rate depends inversely on the volume of foreign bonds. Capital Euler equations yield the equilibrium conditions (4.8) and (4.9), which state that the respective physical capital is a positive function of current consumption, lagged capital stock, both the expected physical capital and capital utilisation rate, the ratio of future to current intertemporal preference shock, and the ratio of current to future investment/ capital shock, but a negative function of expected consumption. Again, the trade-off between consumption and investment is highlighted in how the stocks of the two physical capitals respond to the ratio of current-to-future intertemporal preference shocks.

Firms

I proceed with the characterisation of the disaggregate choices. Particularly, these begin with the decisions of the producers. There are two sectors indexed by j in this economy using a constant-elasticity-of-substitution (CES) production function, which is defined to be Cobb-Douglas in labour hours and a CES aggregate in capital services and energy services as

$$y_t^j = \mathsf{a}_t^j + \mathsf{y}_1^j h_t^j + \mathsf{y}_2^j \left(u_t^j + k_{t-1}^j\right) + \mathsf{y}_3^j \left(\mathsf{o}_t^j + e_t^j\right) \tag{4.10}$$

where

$$\mathsf{y}_1^j = 1 - \alpha_j,\ \mathsf{y}_2^j = \frac{\alpha_j}{1 + \frac{1-\theta_j}{\theta_j}\left(\frac{e^j}{k^j}\right)^{-\nu_j}},\ \mathsf{y}_3^j = \frac{\alpha_j}{1 + \frac{\theta_j}{1-\theta_j}\left(\frac{e^j}{k^j}\right)^{\nu_j}}$$

with $0 < 1 - \alpha_j < 1$ being the elasticity of output with respect to labour hours in sector j, $0 < \theta_j < 1$ being the weight of capital services in the CES production function for sector j, $0 < \nu_j < \infty$ is minus 1 plus the inverse of the elasticity of substitution between capital services and energy services in sector j, y_t^j is the output produced in sector j, h_t^j is the demand for labour hours of sector j, k_t^j is the capital demand of sector j, and e_t^j is the energy demand of sector j.[6] The exogenous stochastic variables are a_t^j denoting sector-specific neutral productivity shocks and o_t^j denoting sector-specific energy efficiency shocks.

Thus, the stand-in producers choose the paths for H_t^j, $U_t^j K_{t-1}^j$, and E_t^j in order to maximise

$$\begin{aligned} \Pi_t &= \textstyle\sum_{j=e,n} \Pi_t^j \\ &= \textstyle\sum_{j=e,n} \left[P_t^j Y_t^j - (W_t + \xi_t^j) H_t^j - (R_t^j + \vartheta_t^j) U_t^j K_{t-1}^j - \mathsf{Q}_t E_t^j\right] \end{aligned} \tag{4.11}$$

subject to production functions (4.10) taking as given the paths of prices, P_t^j and W_t, and the paths of the exogenous stochastic processes A_t^j, Q_t (the exogenous world price of energy), ξ_t^j (the exogenous sector-specific wage bill shifter), ϑ_t^j (the exogenous sector-specific capital cost shifter), and O_t^j. The first-order conditions of the producers' problem are the production functions (4.10), and

$$h_t^j = p_t^j + y_t^j - \mathsf{h}_1^j w_t - \mathsf{h}_2^j \xi_t^j \tag{4.12}$$

[6] Capital utilisation rates, u_t^j, have been discussed under households' problem.

$$u_t^j = \mathsf{u}_1^j \left(p_t^j + y_t^j + \mathsf{u}_2^j \mathsf{z}_t^j\right) + \mathsf{u}_3^j k_{t-1}^j + \mathsf{u}_4^j \left(\mathsf{o}_t^j + e_t^j\right) - \mathsf{u}_5^j \vartheta_t^j \tag{4.13}$$

$$e_t^j = \mathsf{e}_1^j \left(p_t^j + y_t^j - \mathsf{q}_t\right) + \mathsf{e}_2^j \left(u_t^j + k_{t-1}^j\right) - \mathsf{e}_3^j \mathsf{o}_t^j \tag{4.14}$$

where the coefficients are

$$\begin{aligned}
\mathsf{h}_1^j &= \frac{w}{1+w},\ \mathsf{h}_2^j = \frac{1}{1+w};\ \mathsf{u}_1^j = \frac{1}{\frac{\mu_j - 1}{1+\frac{1}{\delta_{j1} u^{\mu_j}}} + \nu_j + 1 - \frac{\nu_j}{1+\frac{1-\theta_j}{\theta_j}\left(\frac{e^j}{k^j}\right)^{-\nu_j}}},\\
\mathsf{u}_2^j &= \frac{1}{1+\frac{1}{\delta_{j1} u^{\mu_j}}},\ \mathsf{u}_3^j = \frac{\frac{\nu_j}{1+\frac{1-\theta_j}{\theta_j}\left(\frac{e^j}{k^j}\right)^{-\nu_j}} - \nu_j - 1}{\frac{\mu_j - 1}{1+\frac{1}{\delta_{j1} u^{\mu_j}}} + \nu_j + 1 - \frac{\nu_j}{1+\frac{1-\theta_j}{\theta_j}\left(\frac{e^j}{k^j}\right)^{-\nu_j}}},\\
\mathsf{u}_4^j &= \frac{\frac{\nu_j}{1+\frac{\theta_j}{1-\theta_j}\left(\frac{e^j}{k^j}\right)^{\nu_j}}}{\frac{\mu_j - 1}{1+\frac{1}{\delta_{j1} u^{\mu_j}}} + \nu_j + 1 - \frac{\nu_j}{1+\frac{1-\theta_j}{\theta_j}\left(\frac{e^j}{k^j}\right)^{-\nu_j}}},\ \mathsf{u}_5^j = \frac{\frac{1}{1+\delta_{j1} u^{\mu_j}}}{\frac{\mu_j - 1}{1+\frac{1}{\delta_{j1} u^{\mu_j}}} + \nu_j + 1 - \frac{\nu_j}{1+\frac{1-\theta_j}{\theta_j}\left(\frac{e^j}{k^j}\right)^{-\nu_j}}};\\
\mathsf{e}_1^j &= \frac{1}{\nu_j + 1 - \frac{\nu_j}{1+\frac{\theta_j}{1-\theta_j}\left(\frac{e^j}{k^j}\right)^{\nu_j}}},\ \mathsf{e}_2^j = \frac{\frac{\nu_j}{1+\frac{1-\theta_j}{\theta_j}\left(\frac{e^j}{k^j}\right)^{-\nu_j}}}{\nu_j + 1 - \frac{\nu_j}{1+\frac{\theta_j}{1-\theta_j}\left(\frac{e^j}{k^j}\right)^{\nu_j}}},\ \mathsf{e}_3^j = \frac{\nu_j - \frac{\nu_j}{1+\frac{\theta_j}{1-\theta_j}\left(\frac{e^j}{k^j}\right)^{\nu_j}}}{\nu_j + 1 - \frac{\nu_j}{1+\frac{\theta_j}{1-\theta_j}\left(\frac{e^j}{k^j}\right)^{\nu_j}}}.
\end{aligned}$$

The equilibrium condition (4.12) states that labour hours demanded in each sector j respond positively to both an increase in the price of own goods and sector's output, but negatively to both the wage rate and the exogenous wage bill shocks. Regarding the stand-in producers' usage of capital, equilibrium condition (4.13) shows that the demand for capital usage in each sector j depends positively on the price of own goods, sector's output, lagged physical capital stock, energy usage, and energy efficiency shock, but negatively on capital cost shock and investment/capital demand shock. The stand-in producers are allowed to also optimally choose the amount of energy input they buy on the world market. So, the sectoral energy demand is determined efficiently according to equilibrium condition (4.14), which implies that primary energy requirement depends negatively on the exogenous world price of energy and energy efficiency shock, but positively on the price of own goods, the supply or output of these goods, and capital services.

Government

The government is assumed to face the following budget constraint

$$\mathsf{G}_t = T_t + b_t - (1 + r_{t-1})\, b_{t-1} \tag{4.15}$$

which states that the exogenous government spending is financed by lump-sum taxes/transfers and the evolution of domestic bonds, and I have followed Correia et al. (1995), An and Schorfheide (2007), and Justiniano et al. (2009) in assuming that the fiscal stance of the government is fully Ricardian.

Trade in Goods with the Rest of the World

Moving on to the domestic country's choices regarding the components of the aggregate consumption and investment by the stand-in private consumers, and consumption and investment by the government. That is, the characterisation of the model equations that determine the import and export functions of this country noting that I have imposed Walras's law on the market clearing conditions for sectoral goods. More formally, the stand-in trader chooses the paths for D_t^e, IM_t, and IM_t^e in order to maximise

$$P_t \sum\nolimits_{z=g,l} D_t^z + IM_t - \left[P_t^d D_t^d + IM_t + P_t^e D_t^e + P_t^n D_t^n + \mathsf{P}_{e,t}^{im} IM_t^e + \mathsf{P}_{n,t}^{im} IM_t^n\right] \tag{4.16}$$

subject to the aggregator functions

$$D_t^l = \left(\kappa^{\frac{1}{\phi}} \left(D_t^d\right)^{\frac{\phi-1}{\phi}} + (1-\kappa)^{\frac{1}{\phi}} \varpi_t \left(IM_t\right)^{\frac{\phi-1}{\phi}}\right)^{\frac{\phi}{\phi-1}} \tag{4.17}$$

$$D_t^g = \left(\sigma^{\frac{1}{\varsigma}} \gamma_t \left(D_t^e\right)^{\frac{\varsigma-1}{\varsigma}} + (1-\sigma)^{\frac{1}{\varsigma}} \left(D_t^n\right)^{\frac{\varsigma-1}{\varsigma}}\right)^{\frac{\varsigma}{\varsigma-1}} \tag{4.18}$$

$$IM_t = \left(\chi^{\frac{1}{\eta}} \varphi_t \left(IM_t^e\right)^{\frac{\eta-1}{\eta}} + (1-\chi)^{\frac{1}{\eta}} \left(IM_t^n\right)^{\frac{\eta-1}{\eta}}\right)^{\frac{\eta}{\eta-1}} \tag{4.19}$$

and one can infer the paths for EX_t and EX_t^e chosen by the stand-in trader in the foreign country by maximising

$$\mathsf{D}_t^w + EX_t - \left[P_t^f D_t^f + P_t EX_t + P_t^e EX_t^e + P_t^n EX_t^n\right] \tag{4.20}$$

subject to the aggregator functions

$$\mathsf{D}_t^w = \left(\kappa_w^{\frac{1}{\phi_w}} \left(D_t^f\right)^{\frac{\phi_w - 1}{\phi_w}} + (1-\kappa_w)^{\frac{1}{\phi_w}} \varpi_t^w \left(EX_t\right)^{\frac{\phi_w - 1}{\phi_w}}\right)^{\frac{\phi_w}{\phi_w - 1}} \tag{4.21}$$

$$EX_t = \left(\chi_w^{\frac{1}{\eta_w}} \varphi_t^w \left(EX_t^e\right)^{\frac{\eta_w - 1}{\eta_w}} + (1-\chi_w)^{\frac{1}{\eta_w}} \left(EX_t^n\right)^{\frac{\eta_w - 1}{\eta_w}}\right)^{\frac{\eta_w}{\eta_w - 1}} \tag{4.22}$$

taking as given the paths of prices P_t, P_t^e, P_t^n, P_t^d, and P_t^f and the paths of the exogenous stochastic processes ϖ_t (preference for aggregate imported goods in the domestic country), ϖ_t^w (preference for aggregate imported goods in the foreign country), γ_t (preference for energy intensive goods in the domestic country), φ_t (preference for imported energy intensive goods in the domestic country), φ_t^w (preference for imported energy intensive goods in the foreign country), D_t^w (exogenous world demand), $\mathsf{P}_{e,t}^{im}$ (exogenous price of imported energy intensive goods), and $\mathsf{P}_{n,t}^{im}$ (exogenous price of imported non-energy intensive goods). In the above problem, $0 \leq \kappa, \sigma, \chi, \kappa_w, \chi_w \leq 1$ are, respectively, the share of domestically produced goods, D_t^d, in total domestic demand of goods by location of production, D_t^l, the share of energy intensive goods, D_t^e, in total domestic demand of goods by type of production, D_t^g, the share of imported energy intensive goods, IM_t^e, in the domestic country's total imports, IM_t, the share of foreign-produced goods, D_t^f, in total foreign demand, D_t^w, and the share of exported energy intensive goods, EX_t^e, in the domestic country's total exports, EX_t; $\phi, \varsigma, \eta, \phi_w, \eta_w > 0$ are measures of the elasticity of substitution between domestically produced and imported goods in total domestic demand of goods by location of production, the elasticity of substitution between domestic demand of energy and non-energy intensive goods in total domestic demand of goods by type of production, the elasticity of substitution between imported energy and non-energy intensive goods in domestic country's total imports, the elasticity of substitution between foreign-produced and exported goods in total world demand by location of production, and the elasticity of substitution between exported energy and non-energy intensive goods in total domestic country's exports, respectively. I treat the price of composite import, P_t^{im}, as the numeraire, P_t^d is the price index for the bundle of domestically produced demand, and P_t^f is the price index for the bundle of foreign-produced demand.[7]

The first-order conditions of the trader's problem are

$$d_t^e = \varsigma\gamma_t + \varsigma\left(p_t - p_t^e\right) + d_t \tag{4.23}$$

$$im_t = \phi\varpi_t + \phi p_t + d_t \tag{4.24}$$

$$im_t^e = \eta\varphi_t - \eta\mathsf{p}_{e,t}^{im} + im_t \tag{4.25}$$

$$ex_t = \phi_w\varpi_t^w - \phi_w p_t + \mathsf{d}_t^w \tag{4.26}$$

$$ex_t^e = \eta_w\varphi_t^w + \eta_w\left(p_t - p_t^e\right) + ex_t \tag{4.27}$$

where equilibrium conditions (4.23)-(4.27) describe the total demand for energy intensive goods, total domestic imports, imports of energy intensive goods, total domestic exports, and exports of energy intensive goods, respectively. (4.23) says that the demand for energy intensive goods depends positively on the real exchange rate, total domestic demand, and the preference shock for energy intensive goods in the domestic country, but negatively on own price of energy intensive goods.

(4.24) says that total import depends positively on the real exchange rate, total domestic demand, and the preference shock for the aggregate imported goods in the domestic country. (4.25) says that the imports of energy intensive goods is a negative function of the exogenous price of energy intensive goods produced in the rest of the world, but a positive function of both the total domestic demand for imports and the preference shock for imported energy intensive goods in the domestic country. (4.26) says that total exports is negatively related to the real exchange rate, but positively related to both the total world

[7] I treat D_t^l and D_t^g identically as D_t. This distinction is only used here to formalise the problem. See the Supplementary Notes: Chapter 4 for details. Also, P_t^d, P_t^f, and $\mathsf{P}_{n,t}^{im}$ do not enter the equations used for simulation of the model.

demand and the preference shock for the aggregate imported goods in the foreign country.

Finally, (4.27) says that the exports of energy intensive goods is a negative function of the price of energy intensive goods and a positive function of the real exchange rate, total world demand for exports, and the preference shock for imported energy intensive goods in the foreign country. What is quite interesting about these expressions is the effect of the relative price of the goods. A stand-in consumer will clearly be more favourable to buying the type of consumption goods that is cheaper assuming one abstracts from any other distinguishing attributes of these goods. Hence, an increase in the price of domestic goods will likely reduce the competitiveness of exporters of the domestic goods and also increase the share of imported goods.

Market Clearing and Equilibrium

The model is closed by defining the relevant aggregate and market clearing conditions. In particular, the general price level, aggregate labour hours, aggregate investment, aggregate capital, aggregate energy, aggregate output, sectoral goods market clearing condition, total domestic absorption, GDP/ economy-wide resource constraint, and the evolution of foreign bonds, in that order, are given by

$$p_t = \mathsf{p}_1 \left(\varsigma \gamma_t + p_t^e\right) + \mathsf{p}_2 p_t^n \tag{4.28}$$

$$h_t = \left(h^e/h\right) h_t^e + \left(h^n/h\right) h_t^n \tag{4.29}$$

$$i_t = \left(i^e/i\right) i_t^e + \left(i^n/i\right) i_t^n \tag{4.30}$$

$$k_t = \left(k^e/k\right) k_t^e + \left(k^n/k\right) k_t^n \tag{4.31}$$

$$e_t = \left(e^e/e\right) e_t^e + \left(e^n/e\right) e_t^n \tag{4.32}$$

$$y_t = \left(y^e/y\right) y_t^e + \left(y^n/y\right) y_t^n \tag{4.33}$$

$$y_t^e = \left(d^e/y^e\right) d_t^e + \left(ex^e/y^e\right) ex_t^e - \left(im^e/y^e\right) im_t^e \tag{4.34}$$

$$d_t = (c/d)\, c_t + (i/d)\, i_t + (\mathsf{g}/d)\, \mathsf{g}_t \tag{4.35}$$

$$y_t = (c/y)\, c_t + (i/y)\, i_t + (\mathsf{g}/y)\, \mathsf{g}_t + (ex/y)\, ex_t - (im/y)\, im_t - (e/y)\, (\mathsf{q}_t + e_t) \tag{4.36}$$

and

$$f_t = \left(1 + \mathsf{r}^f_{t-1}\right) f_{t-1} + (ex/y)\, (p_t + ex_t) - (im/y)\, im_t - (e/y)\, (\mathsf{q}_t + e_t) \tag{4.37}$$

where $\mathsf{p}_1 = \sigma\gamma^{\varsigma}\, (p^e/p)^{1-\varsigma}$ and $\mathsf{p}_2 = (1-\sigma)\, (p^n/p)^{1-\varsigma}$.

I am now able to round up this section by providing the definition of a competitive equilibrium for the model.

Definition 2 ***Competitive equilibrium.*** *Taking as given prices* (p_t, p^e_t, p^n_t, w_t, r_t), *shocks* (a^e_t, a^n_t, d^w_t, φ_t, φ^w_t, γ_t, g_t, ζ_t, o^e_t, o^n_t, $\mathsf{p}^{im}_{e,t}$, q_t, r^f_t, τ_t, ϑ^e_t, ϑ^n_t, ϖ_t, ϖ^w_t, ξ^e_t, ξ^n_t, z^e_t, z^n_t), *and the initial conditions for consumption, bonds, and capital* (c_{-1}, b_{-1}, f_{-1}, k^e_{-1}, k^n_{-1}), *a competitive equilibrium is characterised by a set of endogenous stochastic processes* (c_t, h_t, h^e_t, h^n_t, f_t, i_t, i^e_t, i^n_t, u^e_t, u^n_t, k^e_t, k^n_t, y_t, y^e_t, y^n_t, e_t, e^e_t, e^n_t, d_t, d^e_t, im_t, im^e_t, ex_t, ex^e_t, w_t, r_t, p_t, p^e_t, p^n_t) *satisfied by the solutions to the stand-in consumer, producer, and trader's problems, and the bond, labour, capital, energy, and good markets clear.*

4.3 Econometric Methodology

In this section, I discuss the methodology used to choose parameter values - this consists of the standard calibration approach and estimation using indirect inference approach. I then provide a brief description of the data used for estimation.

Calibration

I know that the assessment of the quantitative workings of the model can only begin when one has chosen values for the model parameters of preference and technology functions, and hence, is able to simulate the model. This I have done by a combination of

Table 4.1: Calibration

Description	Symbol	Value♯
Discount factor✠	β	0.96
Inverse of Frisch elasticity of labour supply	ω	5
Consumption elasticity	ε	2
Habit formation parameter	ι	0.7
Energy intensive sector SoCE	α_e	0.43
Non-energy intensive sector SoCE	α_n	0.28
Energy intensive sector EoS btw capital services and energy	ν_e	0.7
Non-energy intensive sector EoS btw capital services and energy	ν_n	0.7
Energy intensive sector marginal CoCU	$\delta_{e1}u^{\mu_e}$	0.132
Energy intensive sector depreciation EoCU	μ_e	1.463
Non-energy intensive sector marginal CoCU	$\delta_{n1}u^{\mu_n}$	0.102
Non-energy intensive sector depreciation EoCU	μ_n	1.694
ACP for energy intensive goods	ψ_e	0.001
ACP for non-energy intensive goods	ψ_n	0.001
ACP for foreign bonds	ψ_f	0.001
DC's EoS btw domestic and imported final goods	ϕ	1.5
FC's EoS btw foreign and exported final goods	ϕ_w	1.5
DC's EoS btw imported energy and non-energy goods	η	0.44
FC's EoS btw exported energy and non-energy goods	η_w	0.44
Share of energy intensive goods in the DC	σ	0.55
DC's EoS btw energy and non-energy intensive goods	ς	0.90
Steady state DF of energy intensive investment goods✠	δu^e	0.09
Steady state DF of non-energy intensive investment goods✠	δu^n	0.06
Weight on capital services of the energy intensive sector¶	θ_e	0.9966
Weight on capital services of the non-energy intensive sector¶	θ_n	0.9931

Note: SoCE: share of capital services and energy; EoS: elasticity of substitution; CoCU: cost of capital utilisation; EoCU: elasticity of capital utilisation; ACP: adjustment cost parameter; DF: depreciation function; DC: domestic country; FC: foreign country. ♯Calibrated values are used to initialise the simulated annealing search algorithm; ✠parameters that are fixed throughout the exercise; ¶parameters that are derived based on calibrated (later estimated) and fixed parameters.

calibration and indirect inference estimation techniques. Going forth, I divide the structural parameters into three groups. In the first group are β, δu^e, δu^n, θ_e, and θ_n. Table 4.1 reports the values for these parameters - I fix the values of the first three parameters throughout the exercise: the discount factor, β, at 0.96 suggesting that I have taken the annual real rate of interest to be about 4%, which is consistent with the average post-WWII interest rate for the U.S. and the values used by Kydland and Prescott (1982) and Prescott (1986); also, the steady state of the depreciation functions for the two types of investment goods, δu^e and δu^n, which are set equal to the long-run average data values of investment-capital ratios for the energy and non-energy intensive goods. The share parameters for capital services in the two sectors, θ_e and θ_n, are pinned down by the respective sector's average energy-capital ratio over the sample period, given values of some other underlying structural parameters using the expressions, $\frac{1}{1+\frac{q}{\delta_{e1}u^{\mu_e}}\left(\frac{e^e}{k^e}\right)^{1+\nu_e}}$ and $\frac{1}{1+\frac{q}{\delta_{n1}u^{\mu_n}}\left(\frac{e^n}{k^n}\right)^{1+\nu_n}}$.[8]

[8] The values yielded by these expressions will only alter to the extent that estimated elasticity parameters, ν_e and ν_n, change during the Simulated Annealing searching.

In the second group are the steady state parameters/ ratios which values are determined directly from the data except for the exogenous world price of energy and wage rate, which are normalised to unity in steady state: see Table 4.5 for the calibrated values. There is not much to say about the parameters in the first two groups, but that their values are kept fixed throughout the econometric exercise except for the sectoral capital services share parameters.

In the third group are the model parameters I intend to estimate: ω, ε, ι, α_e, α_n, ν_e, ν_n, $\delta_{e1}u^{\mu_e}$, $\delta_{n1}u^{\mu_n}$, μ_e, μ_n, ψ_e, ψ_n, ψ_f, ϕ, ϕ_w, η, η_w, σ, and ς. Table 4.1 provides the initial values serving as a guide to the Simulated Annealing (SA) algorithm (details below) to find a more optimal values. Hence, as a starting point, I set the elasticity of labour supply equal to 5, fix consumption elasticity at 2, and preserve the CES form of the production functions by setting the respective sector's elasticity of substitution between capital services and efficient energy use, ν_e and ν_n, equal to 0.7.[9] Elasticities of labour hours in the energy and non-energy intensive sectors, $1-\alpha_e$ and $1-\alpha_n$, are calibrated to be 0.57 and 0.72, respectively. I also suppose that there is some degree of habit formation for agents in this model setting the initial parameter value to 0.7.

Next, I turn to calibrate the component parameters of the two depreciation functions. In the steady state, these are given by $\delta U^e = \delta_{e0} + \delta_{e1}\left(\mu_e\right)^{-1}\left(U^e\right)^{\mu_e}$ and $\delta U^n = \delta_{n0} + \delta_{n1}\left(\mu_n\right)^{-1}\left(U^n\right)^{\mu_n}$ for which I note that only four of the six parameters needed identifying are δ_{e0}, δ_{n0}, μ_e and μ_n. Thus, with no loss of generality, I fix the values for δ_{e1} and δ_{n1} at unity.[10] The idea is that, for $j = e, n$, δ_{j1} and U^j are admitted into the model only jointly as $\delta_{j1}\left(U^j\right)^{\mu_j}$ such that $\delta_{j1} = 1$ has a trivial implication that $\delta_{j1}\left(U^j\right)^{\mu_j} = \left(U^j\right)^{\mu_j}$. Then, using household's optimality conditions with regards to capital utilisation rates conditioned on the values for the respective sector's real rental rate of capital in the steady state, I have that $\delta_{j1}\left(U^j\right)^{\mu_j} = R^j = 1/\beta - \left(1 - \delta\left(U^j\right)\right)$, where I have already calibrated $\delta\left(U^j\right)$. The previous expression then simplifies to give the values reported in the table for $\delta_{e1}u^{\mu_e}$ and $\delta_{n1}u^{\mu_n}$ of 0.132 and 0.102, respectively.

[9] Kim and Loungani (Table 2, p. 180) provide a justification for using this value. They also considered a value of 0.001 suggesting a Cobb-Douglas form and high elasticity of substitution between capital services and energy use. I, however, stick to the parameter value that preserves the general form of specification and leave the optimal choice of parameter value to the estimation stage later on.

[10] See, for example, Burnside and Eichenbaum (1996), Boileau and Normandin (1999), King and Rebelo (2000), and Leduc and Sill (2004).

Conditional on the values of the discount factor and the real rental rates, I calibrate the parameters governing the elasticities of marginal depreciations with respect to capital utilisation rates as $\mu_e = \frac{\delta_{e1}(U^e)^{\mu_e}}{1+\delta_{e1}(U^e)^{\mu_e}-1/\beta} = 1.463$ and $\mu_n = \frac{\delta_{n1}(U^n)^{\mu_n}}{1+\delta_{n1}(U^n)^{\mu_n}-1/\beta} = 1.694$, which are reasonably located in the range found in the literature.[11] For me, the point of adding adjustment costs is mainly technical rather than for imposing a prori a very high friction into the model. Thus, I have set the parameters that relate to the adjustment costs of capital and foreign bonds, ψ_e, ψ_n, and ψ_f to a very small value of 0.001 to follow a standard practice in the literature. This way I am permitting the model to inform me when it has been estimated whether there is more or less real rigidity in the system. The values chosen for the shares and elasticities of substitution parameters in the aggregator functions are all standard in the literature.

Indirect Inference

The next task was to test how good my choices of parameters were by taking the model to the data. If they fit each other, my job was done; otherwise, I would need to proceed to estimating the twenty parameters in group three above. Now, I briefly give an overview of the method of indirect inference (II), which has increasingly been shown in the literature to be statistically powerful in helping to evaluate models and in estimating a model's structural parameters to improve its performance. I am mainly concerned with

[11] Basu and Kimball (1997) suggested the upper bound of 2 based on a 95% confidence band. Further, to calibrate this parameter, I have gone for the more restricted form of the depreciation function by setting $\delta_{e0} = \delta_{n0} = 0$. Basu and Kimball (1995, 1997), though used the more general form in their empirical work and concluded that there is no statistical evidence in support of the non-zero value for the fixed component of the depreciation function as assumed by many other authors in the literature [see, for example, Greenwood et al. (1988) and Burnside and Eichenbaum (1996)]. I 'conclude' that my values are not far (not a statistical conclusion) from that usually employed in the literature [see, for example, Greenwood, et al. who used a value of 1.42, and Burnside and Eichenbaum using their factor-hoarding model and data on output and capital calibrated μ to be 1.56 ($\Delta = 0.56$)]. I must note that the specification for time-varying depreciation is less general in these other studies. Statistically, however, both values are not rejected by the data. This is done noting one of the concerns of Basu and Kimball (1997) that "...our method makes clear that Δ is a parameter that needs to be estimated, and in fact is not pinned down very precisely by the data because it has to be estimated as the reciprocal of a fairly small number. Thus, even the small standard error of the reduced-form parameter necessarily implies that there is large uncertainty about the structural parameter Δ. Consequently, economic modellers should conduct sensitivity analysis of their results using a wide range of values for this parameter." And also that "variable depreciation does not seem a significant source of error in the capital stock figures reported by the BEA." Specifically, they concluded that this issue "strikes us as second-order." This thus asks the question of sensitivity analysis regarding our results in response to various values that could be used for μ (Δ). Once I have assessed the performance of the model under this calibration approach, the above arguments make more important my next empirical exercise, which is to estimate the model's underlying structural parameters. In fact, a prior study by Basu and Kimball (1995) had put the value of μ at roughly 7 with a standard error of about 8. To this end, I impose a wider boundary of $[0, 10]$ in the estimation exercise.

using the method for estimation in this chapter, but given how the procedure works I have discussed both how it is used for evaluation and estimation purposes here.

Minford et al. (2009) originally proposed the use of II for evaluating a model's capacity in fitting the data, and subsequently with a number of refinements by Le et al. (2011) who evaluate the method using Monte Carlo experiments. The approach employs an auxiliary model that is completely independent of the theoretical one to produce a description of the data against which the performance of the theory is evaluated indirectly. Such a description can be summarised either by the estimated parameters of the auxiliary model or by functions of these; I will call these the descriptors of the data. While these are treated as the 'reality', the theoretical model being evaluated is simulated to find its implied values for them.

II has been widely used in the estimation of structural models [see, for example, Smith (1993), Gregory and Smith (1991, 1993), Gourieroux et al. (1993), Gourieroux and Monfort (1995), and Canova (2005)]. Here, my approach is two-fold - one is estimation and the second is making a further use of II to evaluate structural model. The common element is the use of an auxiliary time series model. In estimation the parameters of the structural model are chosen such that when this model is simulated it generates estimates of the auxiliary model similar to those obtained from the actual data. The optimal choices of parameters for the structural model are those that minimise the distance between a given functions of the two sets of estimated coefficients of the auxiliary model. Common choices of this function are the actual coefficients, the scores or the impulse response functions. In model evaluation the parameters of the structural model are taken as given. The aim is to compare the performance of the auxiliary model estimated on simulated data derived from the given estimates of a structural model - which is taken as a true model of the economy, the null hypothesis - with the performance of the auxiliary model when estimated from the actual data. If the structural model is correct then its predictions about the impulse responses, moments and time series properties of the data should statistically match those based on the actual data. The comparison is based on the distributions of the two sets of parameter estimates of the auxiliary model, or of functions of these estimates.

The testing procedure thus involves first constructing the errors implied by the previously estimated/ calibrated structural model and the data. These are called the structural errors and are backed out directly from the equations and the data.[12] These errors are then bootstrapped and used to generate for each bootstrap new data based on the structural model. An auxiliary time series model is then fitted to each set of data and the sampling distribution of the coefficients of the auxiliary time series model is obtained from these estimates of the auxiliary model. A Wald statistic is computed to determine whether functions of the parameters of the time series model estimated on the actual data lie in some confidence interval implied by this sampling distribution.

Following Meenagh et al. (2012) I use as the auxiliary model a VECM which I re-express as a VAR(1) for the macroeconomic variables of interest with a time trend and with some residuals entered as exogenous non-stationary processes (these two elements having the effect of achieving cointegration).[13] Thus, the auxiliary model, unlike in the previous chapter where the model/ data is stationary, in practice is given by

$$y_t = [I - K]y_{t-1} + \gamma\overline{x}_{t-1} + gt + v_t \tag{4.38}$$

where $\overline{x}_{t-1}$ is the stochastic trend in productivity, gt are the deterministic trends, and v_t are the VECM innovations. I treat as the descriptors of the data the VAR coefficients (on the endogenous variables only, $I - K$) and the VAR error variances ($var[v]$). The Wald statistic is computed from these.[14] Thus, effectively I am testing whether the observed dynamics and volatility of the chosen variables are explained by the simulated joint

[12] Some equations may involve calculation of expectations. The method I use here is the robust instrumental variables estimation suggested by McCallum (1976) and Wickens (1982): I set the lagged endogenous data as instruments and calculate the fitted values from a VAR(1) - this also being the auxiliary model chosen in what follows. Given that I am working with non-stationary data, the actual auxiliary model chosen is a VECM that got re-written as a VAR(1).

[13] See Le et al. (2013).

[14] I do not attempt to match the time trends and the coefficients on non-stationary trend productivity; I assume that the model coefficients yielding these balanced growth paths and effects of trend non-stationary shocks on the steady state are chosen accurately. However, I am not interested, for the exercise here, in any effects on the balanced growth path, as this is fixed. As for the effects of the non-stationary shocks on the steady state I assume that any inaccuracy in this will not importantly affect the business cycle analysis I am carrying out - any inaccuracy would be important in assessing the effect on the steady state, but this is not my focus. Thus, m assessment of the model is as if I was filtering the data into stationary form by regressing it on the time trends and trend productivity.

distribution of these at a given confidence level. The Wald statistic is given by

$$(\Theta - \overline{\Theta})' \sum\nolimits_{(\Theta\Theta)}^{-1} (\Theta - \overline{\Theta}) \tag{4.39}$$

where Θ is the vector of VAR estimates of the chosen descriptors yielded in each simulation, with $\overline{\Theta}$ and $\sum_{(\Theta\Theta)}$ representing the corresponding sample means and variance-covariance matrix of these calculated across simulations, respectively. The joint distribution of the Θ is obtained by bootstrapping the innovations implied by the data and the theoretical model; it is therefore an estimate of the small sample distribution.[15] Such a distribution is generally more accurate for small samples than the asymptotic distribution; it is also shown to be consistent by Le et al. (2011) given that the Wald statistic is 'asymptotically pivotal'; they also showed it had quite good accuracy in small sample Monte Carlo experiments.[16]

This testing procedure is applied to a set of (structural) parameters put forward as the true ones (H_0, the null hypothesis); they can be derived from calibration, estimation, or both. However derived, the test then asks: could these coefficients within this model structure be the true (numerical) model generating the data? Of course only one true model with one set of coefficients is possible. Nevertheless one may have chosen coefficients that are not exactly right numerically, so that the same model with other coefficient values could be correct. Only when one has examined the model with all coefficient values that are feasible within the model theory will one have properly tested it. For this reason I later extend the procedure by a further search algorithm, in which I seek other parameter sets that could do better in the test.

Thus, I calculate the minimum-value full Wald statistic for each period using a powerful algorithm based on SA in which search takes place over a wide range around the initial values, with optimising search accompanied by random jumps around the space.[17] In

[15] The bootstraps in the tests are all drawn as time vectors so contemporaneous correlations between the innovations are preserved.

[16] Specifically, they found on stationary data that the bias due to bootstrapping was just over 2% at the 95% confidence level and 0.6% at the 99% level. Meenagh et al. (2012) found even greater accuracy in Monte Carlo experiments on non-stationary data.

[17] I use a Simulated Annealing algorithm due to Ingber (1996). This 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—this 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. I find that this algorithm improves substantially here on a standard optimisation algorithm. The method used follows

effect this is Indirect Inference estimation of the model; however here this estimation is being done to find whether the model can be rejected *in itself* and not for the sake of finding the most satisfactory estimates of the model parameters. Nevertheless of course the method does this latter task as a by-product so that I can use the resulting unrejected model as representing the best available estimated version. The merit of this extended procedure is that I can then compare the best possible versions of each model type when finally doing my comparison of model compatibility with the data.

Data

Figures 4.2-4.3 display the time paths for the data series that are used in the calibration, estimation, and evaluation of the model. These are unfiltered U.S. annual data covering the period 1949-2013, and are logarithmically transformed, real [using Bureau of Labour Statistics (BLS) series: consumer price index (CPI, 2009=100)] per capita [using Bureau of Labour Statistics (BLS) series: civilian non-institutionalised population over 16 years old] terms except for wage rate, interest rate, real exchange rate, and capital utilisation rates.[18] Meanwhile, just as the U.S. variables are deflated by the U.S. CPI, world CPI is used to deflate world series, especially world demand and is also the numeraire.

4.4 Results

In this section, which I organise into two sub-sections, the main findings of the exercise are discussed. Firstly, I examine the estimated parameter values. Secondly, I look at the properties of the estimated model by considering some qualitative and quantitative outcomes. While doing these, I emphasise at every opportunity the main focus of this chapter, which is to determine how well this energy model of open economy can reproduce the business cycle implications of output and real exchange rate of the U.S.

a standard testing method: I take a set of model parameters (excluding error processes), extract the resulting residuals from the data using the LIML method, find their implied autoregressive coefficients ($AR(1)$ here) and then bootstrap the implied innovations with this full set of parameters to find the implied Wald value. This is then minimised by the SA algorithm.

[18] A detailed description of the data sources and construction of the observables are presented in the Appendix.

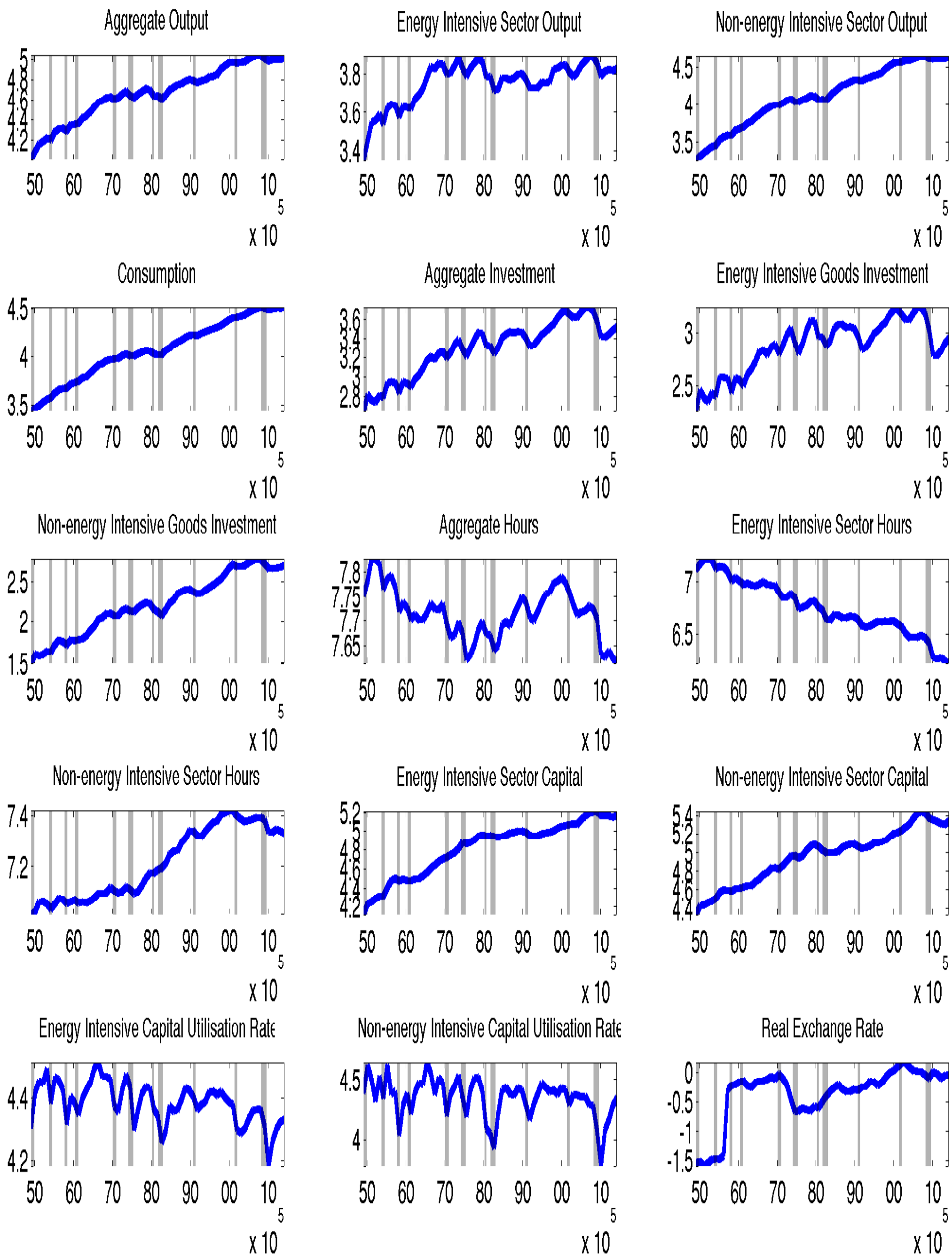


Figure 4.2: Data used for estimation.

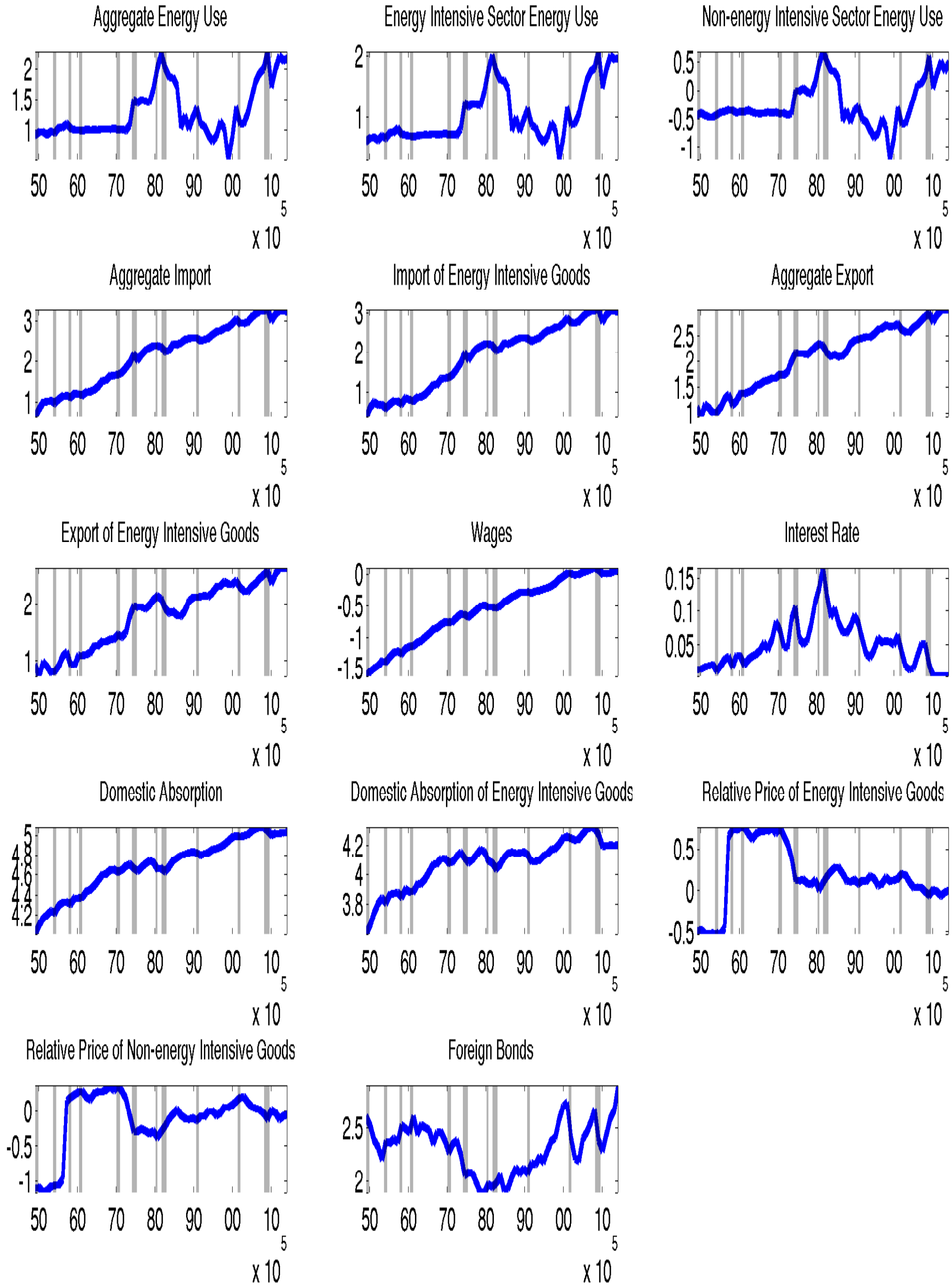


Figure 4.3: Data used for estimation (contd.).

Parameter Estimates

Structural Parameters Estimates of the model parameters are summarised in the upper panel of Table 4.2. Consumption elasticity, ε, is one of the highly difficult parameters to pin down in economics. The estimate of its inverse is 1.24, which is arguably within the range of estimates found in many DSGE models [Hall (1988) and Smets and Wouters (2003, 2005)]. 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.[19] Compared to the initial value, the estimated value of the habit formation parameter interestingly is suggesting that household's utility in period t is less dependent on past consumption. Specifically, the estimated value of 0.3 reduces any forms of consumption inertia to transitory shocks; hence, the hump of consumption impulse response functions becomes more sharpened - see Fuhrer (2000). Theoretically, there is no judgement against this result as the focus of the research is not that of 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 (2004) who reported a value of 0.55; 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) estimated this to be 0.2 using a panel data for emerging countries.

Labour elasticities in the two sectors are 0.75 and 0.63 for the energy and non-energy intensive sector, respectively. The high value for Frisch elasticity ($\omega^{-1} = 0.17$) says that labour hours react more to changes in the real wage. $1 + \nu_e$ $(1 + \nu_n)$ is a measure of the inverse elasticity of substitution between capital services and primary energy use in the energy (non-energy) intensive sector such that the values of $\nu_e = 0.29$ and $\nu_n = 0.27$ implies that there are high elasticities of substitution between the two factors in both sectors. All estimates for the adjustment cost parameters are close to zero: the values of 0.0001, 0.0007, and 0.0001 for ψ_e, ψ_n, and ψ_f, respectively, which are all smaller than the initial values by at least 30% justifies my decision to assume that the cost of adjusting all

[19] This implies that agents would respond more to substitution effect than to 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 (2002), Bergin (2003), and Cromb and Fernandez-Corugedo (2004).

Table 4.2: Structural parameters and Wald statistics

a. Γ_1		
Discount factor	β	0.96
e investment-capital ratio	δu^e	0.09
n investment-capital ratio	δu^n	0.06
b. Γ_{2a}		
Frisch elasticity	ω	6.03
Consumption elasticity	ε	1.24
Habit formation	ι	0.30
e share of capital and energy	α_e	0.25
n share of capital and energy	α_n	0.37
e elasticity of substitution between capital and energy	ν_e	0.29
n elasticity of substitution between capital and energy	ν_n	0.27
e marginal cost of capital utilisation	$\delta_{e1} u^{\mu_e}$	0.03
e depreciation elasticity of capital utilisation	μ_e	1.90
n marginal cost of capital utilisation	$\delta_{n1} u^{\mu_n}$	0.06
n depreciation elasticity of capital utilisation	μ_n	4.72
e adjustment cost parameter	ψ_e	0.0001
n adjustment cost parameter	ψ_n	0.0007
Adjustment cost parameter for foreign bonds	ψ_f	0.0001
Substitution elasticity, $d_t^d - im_t$ goods	ϕ	0.97
Substitution elasticity, $d_t^f - ex_t$ goods	ϕ_w	0.43
Substitution elasticity, $im_t^e - im_t^n$ goods	η	0.07
Substitution elasticity, $ex_t^e - ex_t^n$ goods	η_w	0.04
Weight of d_t^e goods	σ	0.26
Substitution elasticity, $d_t^e - d_t^n$ goods	ς	0.44
e weight on capital services	θ_e	0.997
n weight on capital services	θ_n	0.993
c. Γ_3 [Estimated on output and real exchange rate]	Wald	TMD
Initial values	100	49.64
Estimated model	89.2	1.04

Note: e is energy intensive, n is non-energy intensive; TMD: transformed Mahalanobis distance; see notes to Table 4.1 for the description of the parameters.

types of investments from period to period may be small relatively. Further, the estimate of the marginal costs 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 return to investment/ marginal product of capital services in the non-energy intensive sector is higher. Greenwood et al. (1988) and related literature [see, for example, Finn (1991, 1996), Burnside and Eichenbaum (1995), Baxter and Farr (2002), Leduc and Sill (2004)] suggest that there is yet to be an empirical guide on the choice of a value (magnitude) for the elasticity of capital utilisation rates, μ_e and μ_n, with Basu and Kimball (1995) admitting that it is a problematic parameter to correctly value. My estimates here are 1.90 and 4.72, respectively, for the energy and non-energy elasticities of capital utilisation rates. Lastly, all the elasticity of substitution parameters are sensibly in the ballpark of other estimates found in the literature. Without putting too much emphasis, the implied coefficients for the way the model was written in Section 3.2 are reported in Table 4.7.

Driving Processes There are 22 exogenous stochastic processes in the model: 17 behavioural shocks and 5 exogenous variables. Figures 4.4-4.5 plot the 22 shocks both for calibrated (in blue lines) and estimated (in dashed red lines) models - these errors are either extracted directly from the model first-order conditions as in the cases of the behavioural shocks, or observed directly in the data as in the cases of the exogenous variables. 14 of the relevant equations are without expectations such that the structural errors are backed out directly as residuals; for the remaining 3: intertemporal preference, and energy and non-energy intensive investment-specific technology shocks that are with expectations, the residuals are derived using the instrumental variable method recommended by McCallum (1976) and Wickens (1982), where the instruments are the lagged values of the endogenous variables. The accompanying estimated innovations for these shocks are shown in Figures 4.6-4.7.

Meanwhile, until now I have been silent about the processes that these shocks follow. Given that I am working with unfiltered data, one cannot arbitrarily impose a first-order autoregressive process on them all. Table 4.6 reports the unit root tests carried out for each of the shocks (based on calibrated values) showing the conclusions I reached. For now, the econometric procedures were carried out for 11 $I(1)$ shocks modelled as ARIMA(1, 1, 0) processes and 11 $I(0)$ shocks modelled as ARIMA(1, 0, 0). More specifically, I 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.

The results for the persistence parameters and the standard deviations of innovations are shown in Table 4.3. Observe 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.

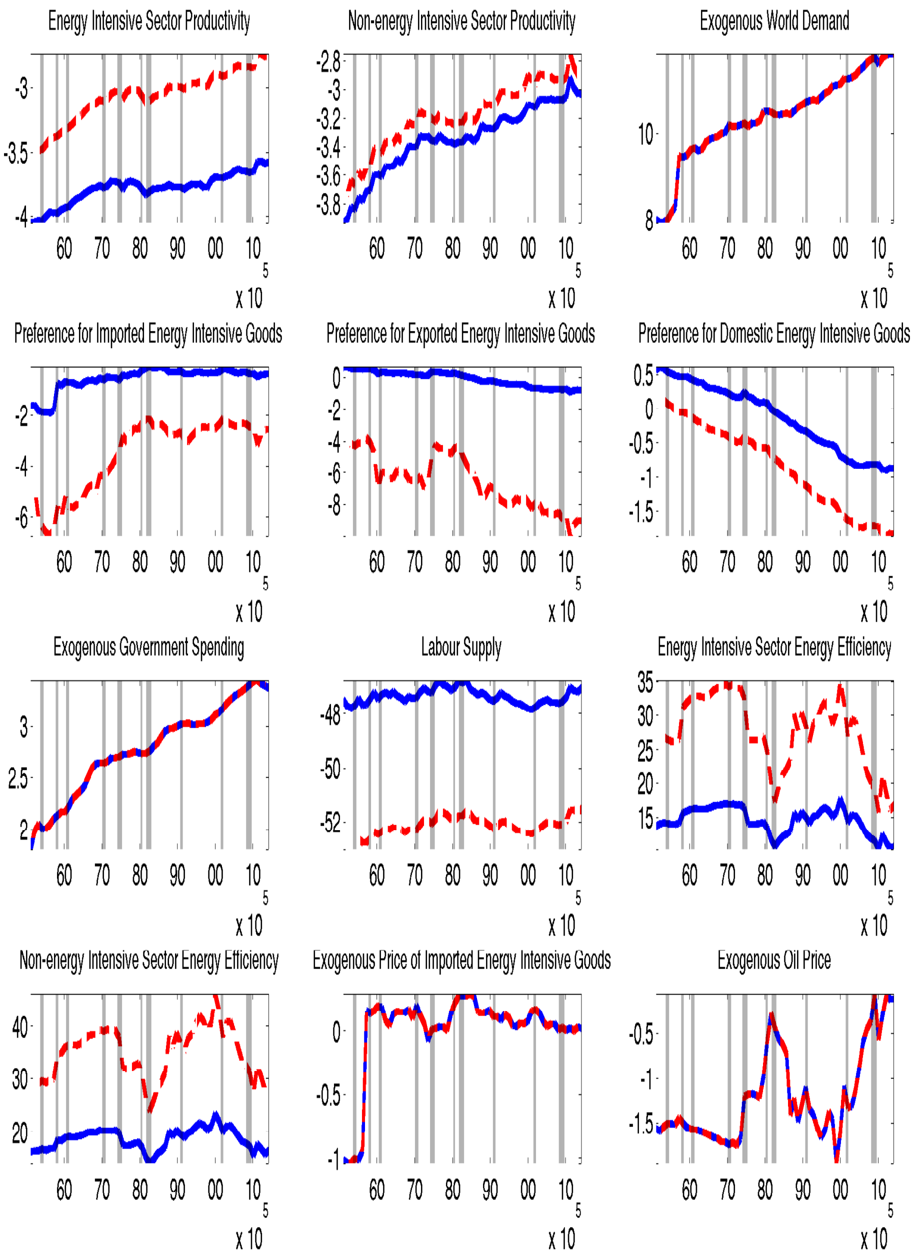


Figure 4.4: Shocks.

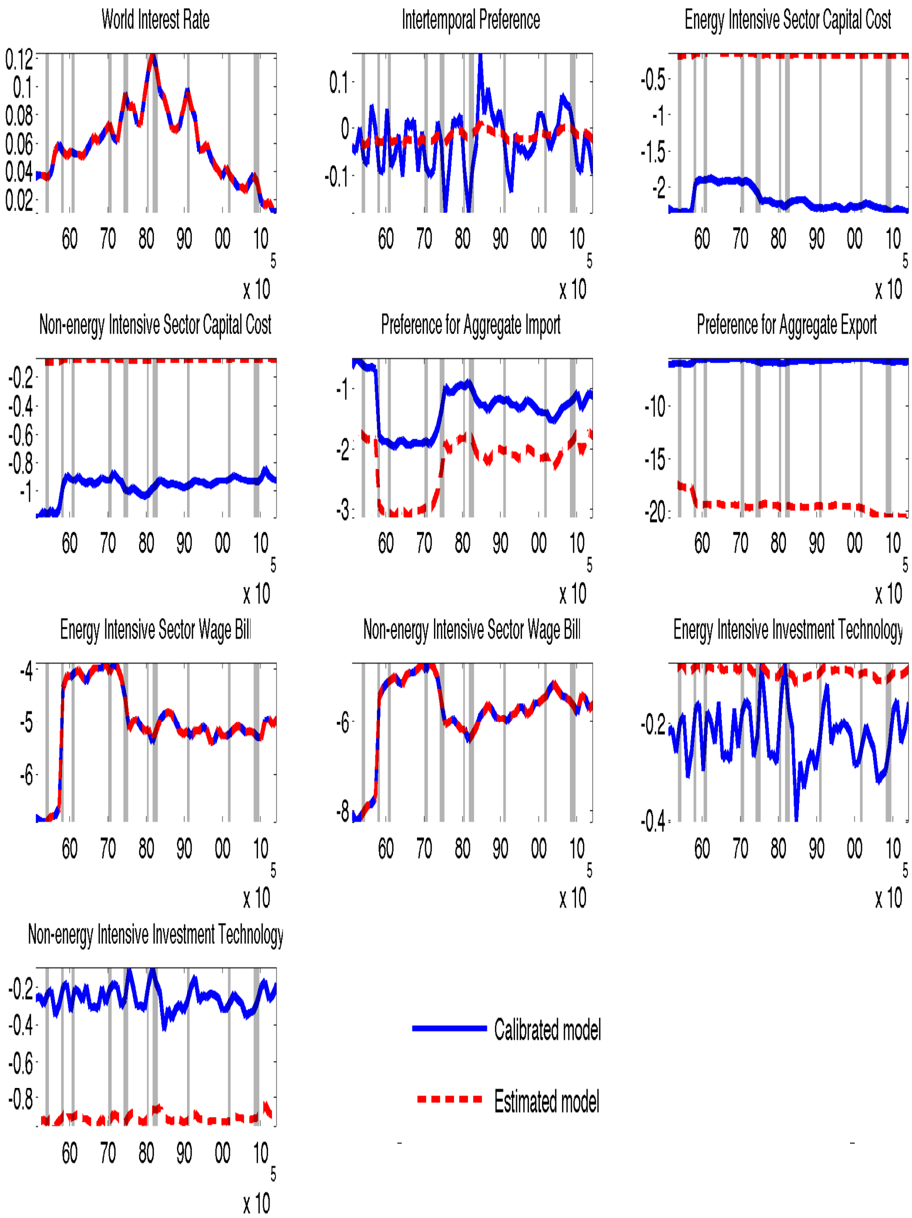


Figure 4.5: Shocks (contd.).

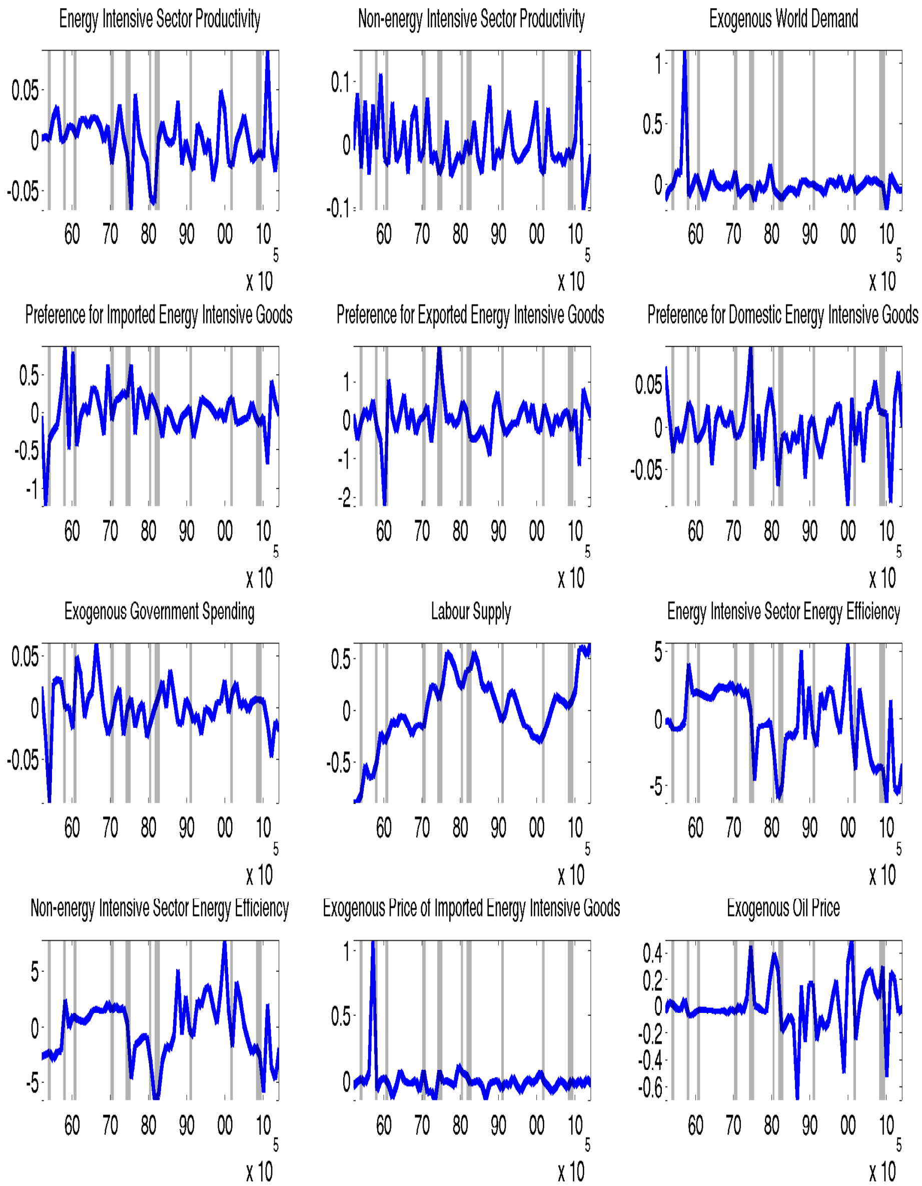


Figure 4.6: Innovations.

Properties of the Estimated Model

One of the main agenda in this section is to interrogate the estimated model about the role of energy price shocks in causing the U.S. business cycles and especially in an economic environment littered with a host of other shocks chief among which are the 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 I provide a the-

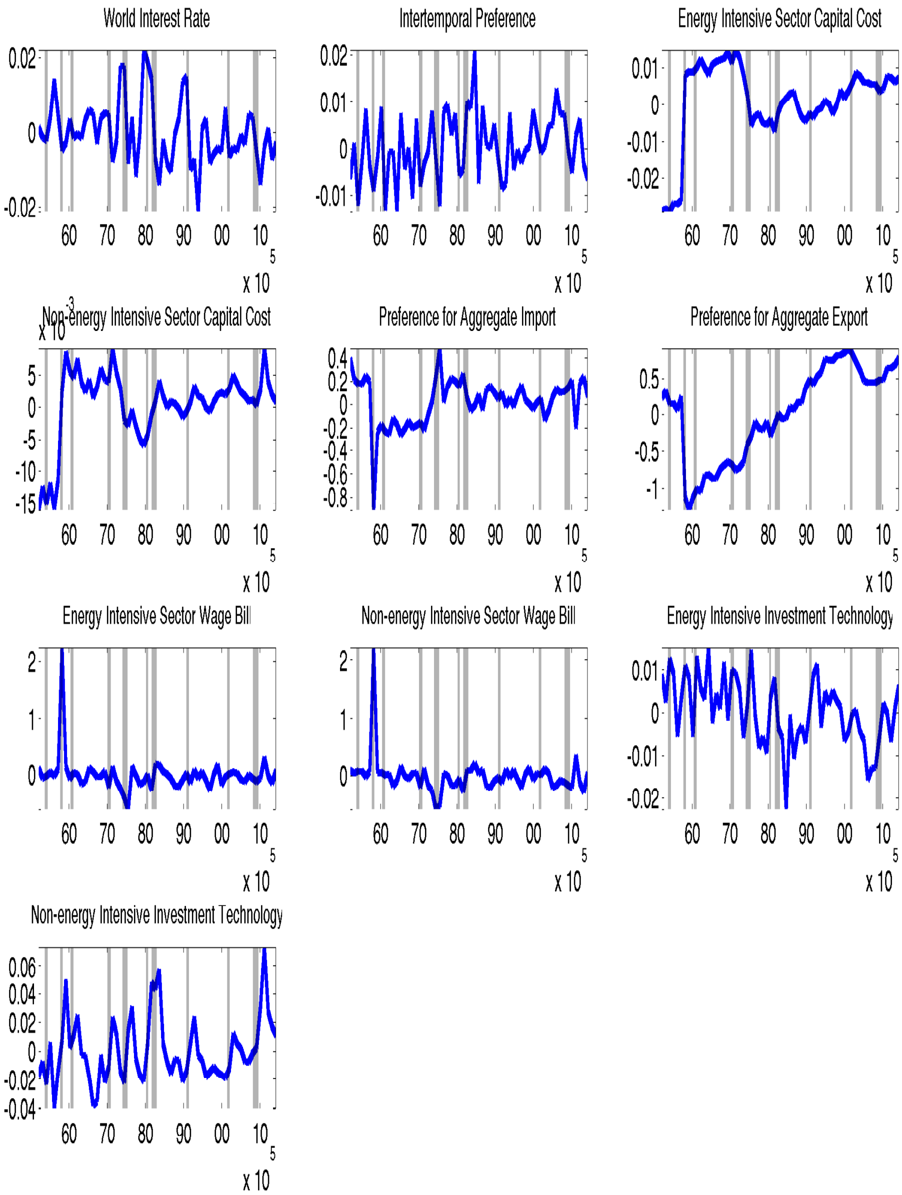


Figure 4.7: Innovations (contd.).

Table 4.3: Estimated Parameters and Driving Processes

Shocks	a_t^e	a_t^n	d_t^w	φ_t	φ_t^w	γ_t	g_t	ζ_t	o_t^e	o_t^n	$\mathsf{p}_{e,t}^{im}$
ρ_s	−0.004	−0.006	0.0051	0.0453	−0.062	0.2459	0.5057	−0.010	0.6601	0.5678	0.0371
σ_s	0.0263	0.0470	0.1555	0.3094	0.5527	0.0347	0.0230	0.3584	2.7803	2.7600	0.1470

Shocks	q_t	r_t^f	τ_t	ϑ_t^e	ϑ_t^n	ϖ_t	ϖ_t^w	ξ_t^e	ξ_t^n	z_t^e	z_t^n
ρ_s	−0.006	0.9601	0.6453	0.0936	0.0364	0.6785	0.0666	0.0297	0.0395	0.3407	−0.003
σ_s	0.2086	0.0086	0.0072	0.0099	0.0057	0.2038	0.6232	0.3234	0.3241	0.0077	0.0231

Note: ρ_s and σ_s are, respectively, the persistence parameter and the standard deviation of each shock, s.

oretical explanation to account for the empirical outcome. I start with the theoretical interpretation of the results.

The Propagation Mechanism of Energy Price Shocks I 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 the model. I focus the exposition on two markets, namely labour and capital markets with references to how these effects translate into the goods market, and ultimately, affecting the imports-exports 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, I make two propositions.

Proposition 3 *Impact effect: oil price increases depress the economic system intratemporally by working through the labour-consumption channel.*

Proof.

The analysis is illustrated in Figure 4.8. Working with the general forms of the model described in Section 3.2 and abstracting from other shocks and real frictions (like habit formation and adjustment costs), household's decision in the labour market is 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 yield: $-U_H(C_t, H_t)/\beta U_C(C_{t+1}, H_{t+1}) = (1 + r_t) W_t$, 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 household's 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 4.8). 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 $F_H(H_t, K_t, E_t)/F_E(H_t, K_t, E_t) = W_t/\mathsf{Q}_t$, where the relative productivities on the left-hand determines the schedule for labour demand (this is represented by the downward sloping curve in Figure 4.8). For a required level of crude oil, a positive shock to its price, ceteris 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 suppose that the required quantity of energy is fixed, the labour quantity demanded falls.[20] Moreover, without assuming 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.[21] Bringing the consumers and the producers together, equilibrium in the labour market is given by: $-U_H(C_t, H_t)/\beta U_C(C_{t+1}, H_{t+1}) = (1 + r_t) W_t = W_t/\mathsf{Q}_t = F_H(H_t, K_t, E_t)/F_E(H_t, K_t, E_t)$ which I find useful broken up into prices $(1 + r_t) W_t = W_t/\mathsf{Q}_t$ implying that $\mathsf{Q}_t = 1/\beta(1 + r_t)$ 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 of the connection to investment implying that when Q_t goes up, r_t must fall to maintain equilibrium since the discount factor is constant.[22] All things being equal, the resource drain effect can be shown to be given by: $\left.\frac{dY_t}{d\mathsf{Q}_t}\right|_{H,K} = \Psi(\cdot) \leq 0$ where Ψ always takes a negative value for an oil-importing country like the U.S. and $(\cdot)$ include energy use and structural

[20] As is standard in the literature when analysing short-run production function that 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 $\mathsf{Q} = \frac{W_t}{F_H(H_t,K_t,E_t)/F_E(H_t,K_t,E_t)}$. Obviously, as Q rises the numerator and/ or the denominator of the right-hand side must change appropriately to ensure equality.

[21] Formally, we assume that $E \in [\underline{E}, \overline{E}]$ indicating that there is a minimum level of energy required, $\underline{E}$, for firms to be operational and a maximum level, $\overline{E}$, that the firms would import depending either on cost or production possibility frontier. Further, note that the effects of oil price shocks in this model are not direct on the 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]. But to the extent that the profits of the firms are affected will the return to household's investment be. This is one of the channels by which the negative spiral of this shock permeates the system.

[22] 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 $U_C(C_t, H_t) W_t = -U_H(C_t, H_t)$.

model parameters (e.g., share of energy use in production and elasticity of substitution parameter).[23] As drawn, the demand for labour is that which achieves point B in panel a of Figure 4.8 with a corresponding lower output level Y_{H_1,K_0,E_0} in panel b. ■

The above result appears rooted in the notion that the model is able to generate intertemporal labour-consumption substitution, which in itself is not a new idea, but to my best knowledge this particular re-interpretation in relation to the *impact effect* on aggregate and sectoral macroeconomic variables is novel.[24]

Proposition 4 *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* transfers it to the households in the form of job losses, possible lower wage rate, and lower return to last period's investment (end-of-period t profit declines). All told, this implies that the household's 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 next period is reduced creating the link to probable further output decreases in period $t + 1$. We illustrate this outcome in Figure 4.8 shown by point C in panel a and output level Y_{H_2,K_1,E_1} in panel b. ■

I round this sub-section up by looking at the sectoral output fluctuations to which the above results are tied and show how this impacts on aggregate output. Specifically, when the price of imported energy goes up, this takes resources from the domestic country transferring 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

[23] 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)].

[24] See Lucas (1972a, 1972b, 1973) for the theoretical development of labour smoothing. Meanwhile, a closely related interpretation brought to my attention after this analysis was put forth is that of factor-price frontier done for an aggregate economy by Blanchard and Gali (2010) 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.

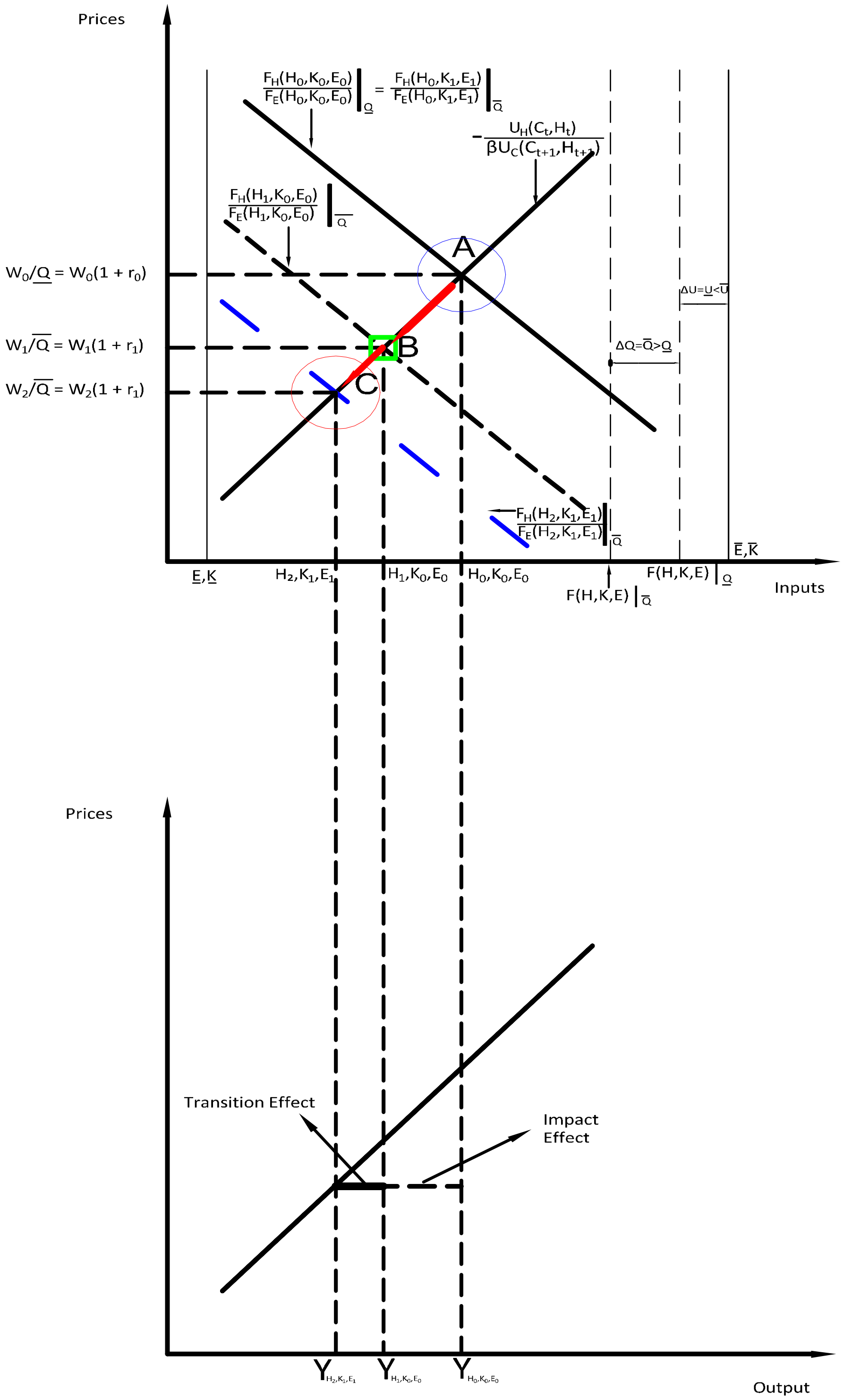


Figure 4.8: Propagation mechanism of oil price shock.

exporter buys at least an equivalent amount of goods from the domestic country. I abstract from this possibility and explain the complementary outcome to the above propositions in relation to international trade and competitiveness of the domestic country. Additionally, an increase in the price of energy means that the price of 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, both prices of energy and non-energy intensive goods in the domestic country are derived endogenous, but of importance is 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. My focus is on the latter and Figure 4.9 is used to illustrate this mechanism. Note that the vertical axes on both panels a and b 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 to a fall in P_t^n. Thus, output falls and the demand for both types of goods fall to reduce net exports as consumers are poorer. The effect on real exchange rate is actually ambiguous as it depends on a host of other factors.[25]

Accounting for Two Recessions Using the U.S. data over the sample period, I 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, I define recession as any negative change in output. For both growth and recession, I take as one episode every successive occurrence. I then seek to understand these *excessive* U.S. business cycles. To undertake this study, I adopt the dating of the U.S. recessions by the National Bureau of Economic Research (NBER) and the dating (and causes) of oil crises and recession provided in Table 4.12, which is based on Hamilton's (1985, 2011) calculations.

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

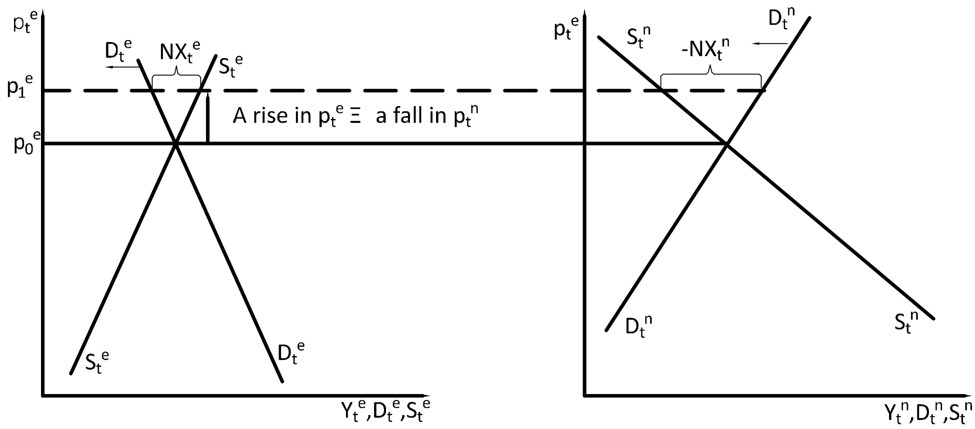


Figure 4.9: Sectoral propagation mechanism of oil price shock.

Then, I carry out the following experiments: (1) for output and real exchange rate for which I have fitted the model to data and working with two selected sub-samples,[26] I decompose each growth and recession/ depression according to the model based on the twelve structural shocks - I depict the results in Figures 4.10-4.13; (2) I consider the role played by each shock over these periods by examining the accumulated shocks for each episode of abnormal growth and recession as shown in Figures 4.17-4.20; and (3) I generate a pseudo data for 62,000 years using Monte Carlo techniques and use it to guess oil price-macroeconomic relationship over my sample period - I then compare these predictions to actual data as presented in Table 4.13 and Figure 4.21.

To investigate the effects of energy related shocks on the historical macroeconomic experiences of the U.S. in a model buffeted by numerous supply-side and demand-side shocks, I construct the time paths for output and real exchange rate for the two sub-periods opting for an orthogonalisation scheme that 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. I extend this approach down the line till I reached the last shock, which according to my ordering is the non-energy intensive investment-specific technology shock.

Further, the shock decompositions for the variables are analysed in groups, viz: productivity shocks, which include the energy and non-energy intensive sectors' neutral productivities (a_t^e and a_t^n), energy and non-energy intensive sectors' energy efficiencies (o_t^e and o_t^n), and energy and non-energy intensive goods' investment-specific technologies (z_t^e and z_t^n); preference shocks, which include the intertemporal preference (τ_t), labour supply (ζ_t), preference for imported energy intensive goods (φ_t), preference for exported energy intensive goods (φ_t^w), preference for energy intensive goods (γ_t), preference for aggregate imported goods (ϖ_t), and preference for aggregate exported goods (ϖ_t^w); cost-push shocks, which include energy and non-energy intensive capital cost shifters (ϑ_t^e and ϑ_t^n), energy

[26] The two chosen sub-samples are 1967-1984 and 1995-2012 and are of equal lengths. The former period is characterised by strike, reduction in Libyan supply, bursting of the Trans-Arabian pipeline, Iranian revolution, and the Iran-Iraq War; the latter period is characterised by the Second Gulf War, Venezuela unrest, and the overshooting of demand over supply.

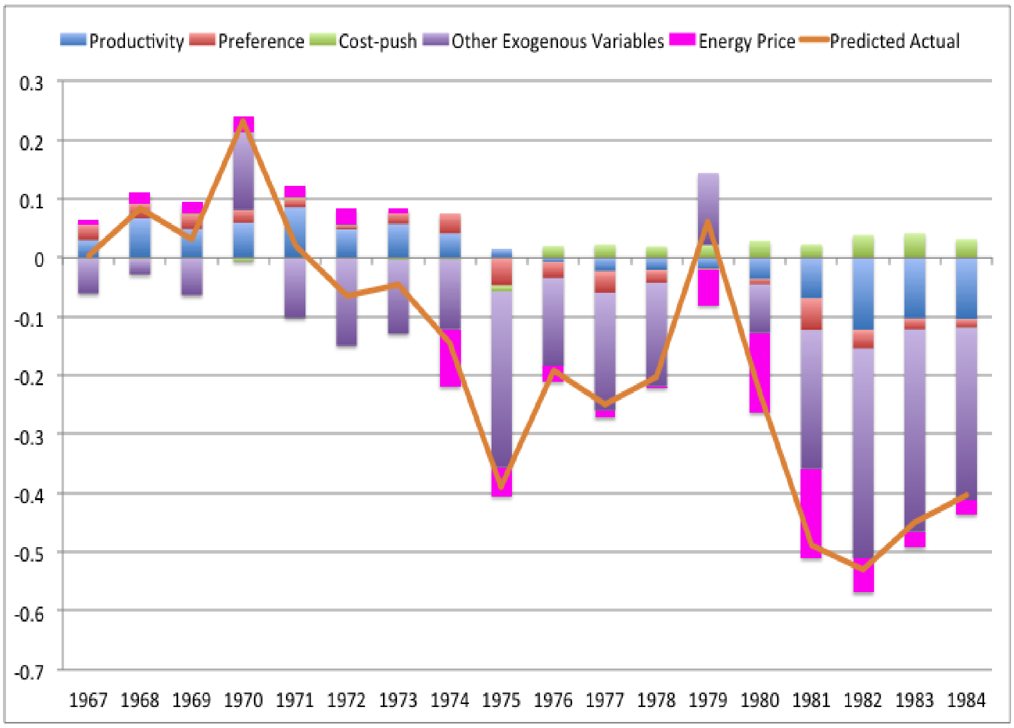


Figure 4.10: Shock decomposition for output.

and non-energy intensive sectors' wage bill shifters (ξ_t^e and ξ_t^n); energy price shock (q_t); and the exogenous variables, which include world demand (d_t^w), government spending (g_t), the price of imported energy intensive goods ($\mathsf{p}_{e,t}^{im}$), and foreign interest rate (r_t^f).[27]

Considering the prediction of the model for output over the two sub-periods first, I show in Figures 4.10 and 4.12 that other exogenous variables generally drive output, albeit more in the earlier sub-period; these are again very important in 2009 when the U.S. output dropped massively. My model was able to correctly predict the year-on-year direction of output changes over the two sub-periods, and more importantly I show in Figure 4.12 that the model's predicted time path for output in the last Great Recession preserved the ranking of changes observed in the actual data. A similar story can be told for productivity shocks though 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 - Figure 4.10.

[27] 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. Detailed variance decomposition with the effects of each shock shown individually are also included.

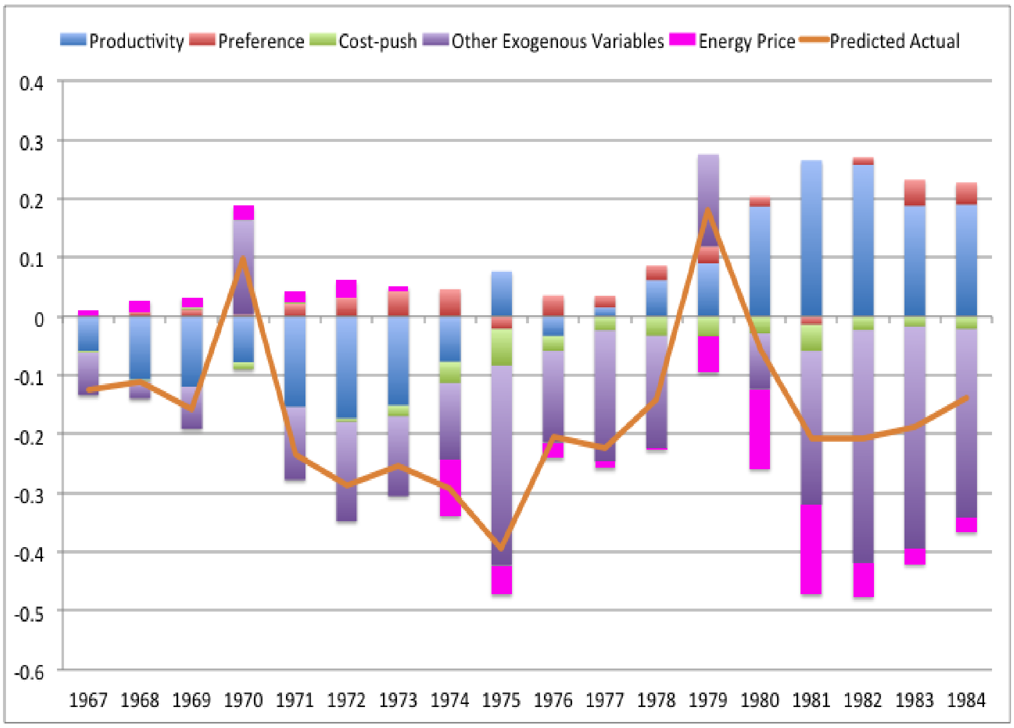


Figure 4.11: Shock decomposition for real exchange rate.

On the other hand, 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 2007-12, which all correspond to specific times when energy price experienced a hike - see Table 4.12. You can see an exception with the predicted response of output to energy price rise in 1999-2000, which was mainly caused by demand overshooting supply.

Then, in Figures 4.11-4.13 for the real exchange rate, the exogenous variables and energy price shocks continue to dominate the other shocks 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 real exchange rate positive. For the latter sub-sample, energy price and exogenous variables move the real exchange rate in the same direction and usually opposite that of the productivity shocks, but for a few exceptions.

Finally, my assessment of the bootstrap simulated data reveals a few interesting facts of which I emphasise two: the first is the frequency of occurrence of the two events (ab-

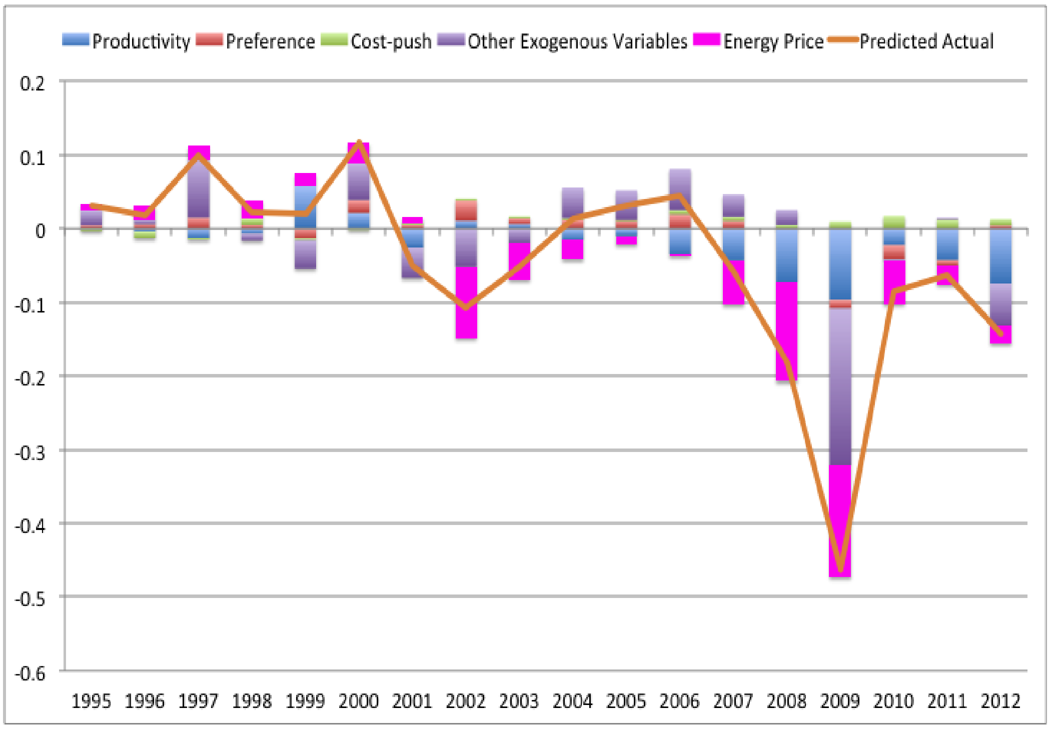


Figure 4.12: Shock decomposition for output.

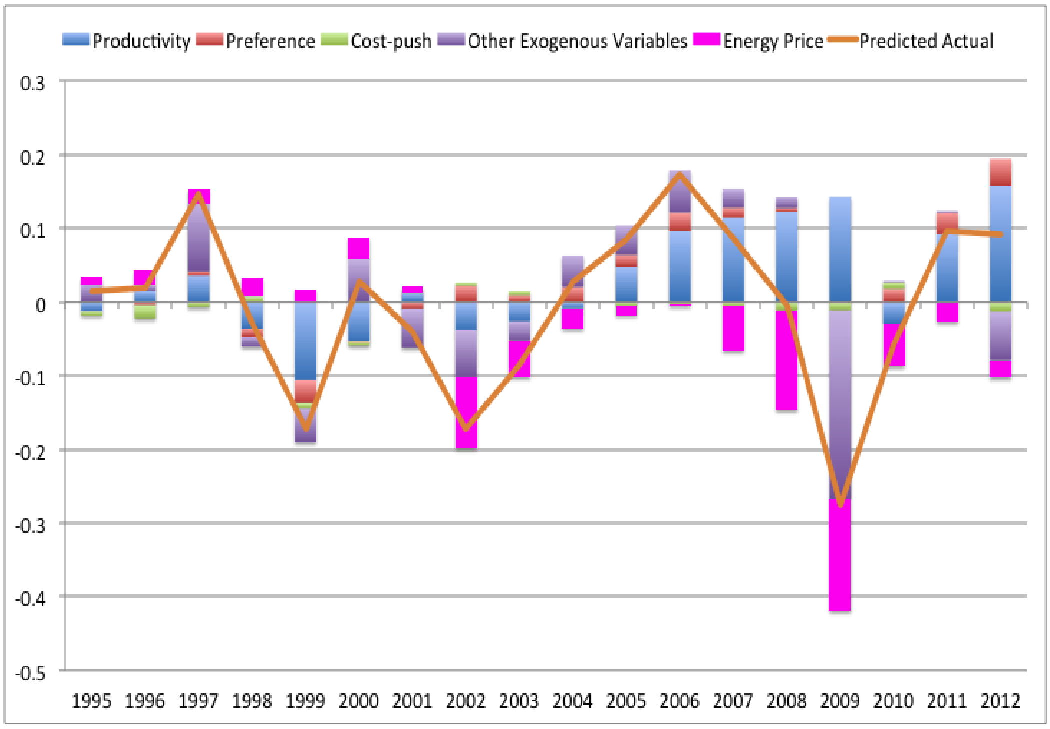


Figure 4.13: Shock decomposition for real exchange rate.

normal growth and recession) in tango with oil price changes (down and up); the second is the percentage of events involving oil price changes. I have shown by the results that the adopted definitions of growth and recession are integral to the business cycle experiences of the U.S. and that this would be the benchmark against which to judge every other experience. More specifically, I find that of the times when there has been an abnormal growth (a recession), about 17 (16) percent involve oil price decreases (increases). Unfortunately, I am 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 attributes of oil price changes. In addition, 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. I split the sample period into two periods (pre-1980 and post-1980) and find that the results remain similar across time.

Impulse Response Functions I now turn to a discussion of some of the impulse response functions to grasp the dynamics implied by the model shocks. I mainly study the effects of a one-off standard deviation positive shock to some of the key exogenous variables on selected variables focusing especially on output and real exchange rate (Figures 4.14-4.16).[28] Suffice it to say that most of the variables have expected responses to each shock; for when this is not so because of any feature(s) of my model, I underlined this in the explanation that follows. Note that I have used the actual values of the shocks as either extracted from the model or observed in the data, and have scaled the vertical axis of the plots by 100 to make it easier for presentation.

I begin with the productivity shocks by first looking at the sectoral Solow residuals - see rows 1 and 2 of Figure 4.14. Next, let us consider the productivity shocks starting with the sectoral Solow residuals where it is obvious that the impact effects generated by sectoral productivity shocks in the energy intensive sector are different to that of sectoral productivity shocks of the non-energy intensive sector. Given that there are positive shocks to both sectoral productivities, A_t^e and A_t^n, respectively, (that is, $\sigma_{a^e}, \sigma_{a^n} >$

[28] See Figures 4.22-4.43 for the impulse responses of all the variables to all the exogenous variables.

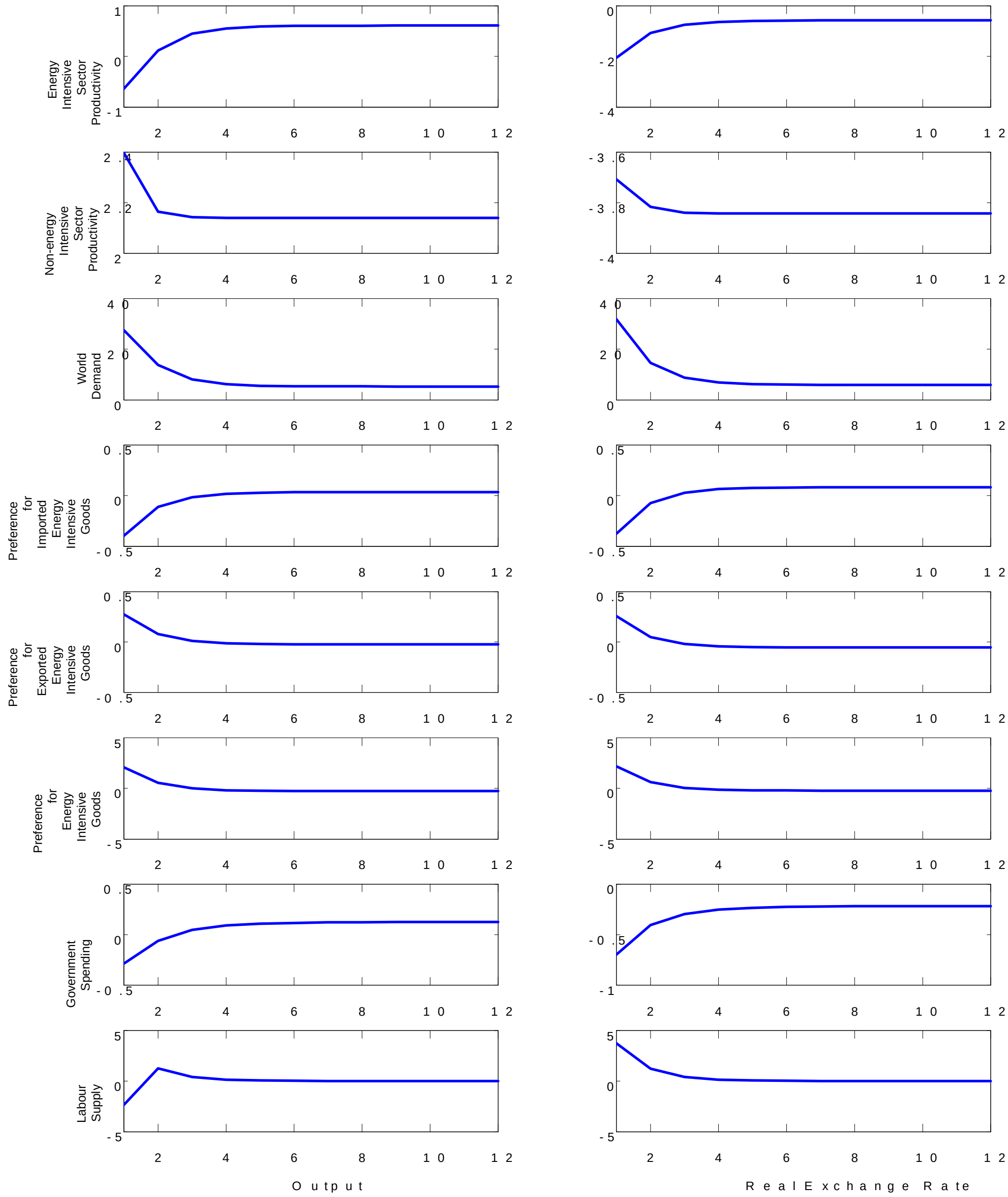


Figure 4.14: Impulse response functions.

0), one would expect the outputs of both sectors to increase, causing an increase in factor demand accompanied by increased factor prices and a falling relative prices for each sector's goods. My model did not particularly lead to these standard outcomes, which are mainly generalisations of expected results in aggregate, or one sector, economic models.

However, the transmission mechanisms at work in multi-sector models sometimes lead to contradicting dynamics as I see here. In fact, it is the case that permanent productivity shocks in the energy and non-energy intensive sectors affect some of the interesting model variables differently. For instance, productivity in the non-energy intensive sector lead to standard results in output (aggregate and sectoral), consumption, wages, sectoral relative prices, real exchange rate, and components of the BOP, but it is less so for productivity of the energy intensive sector. I surmise that what is going on here is a form re-structuring of resources. More specifically, contrary to standard results where one may expect that a positive productivity shock would work by raising the productivity of factor inputs, and hence, all of sectoral hours, capital utilisation rates, capital, and energy use should increase, the model suggests that a positive productivity shock in the energy intensive sector will raise productivity and hence, output of the energy intensive sector, but the spill-over effects to the non-energy intensive sector is negative.

Given that the magnitude of the increased output of the energy intensive sector is far smaller than that of the fall in the non-energy intensive sector output, aggregate output declines after energy intensive sector productivity shock hits the system. Consequently, there is an accompanying fall in the demand for/ use of the factor inputs mainly because aggregate demand (of output and investment) dropped significantly more than the rise of consumption aggregate demand. While it is puzzling that a positive technology can end up depressing the economy, it is not for both 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 devise to encourage more aggregate economic activities. This negative response of hours to productivity shock has also been found in other studies [see, for example, Christiano et al. (2003)].[29] With regards to international trade, a fall in income implies that there is an immediate drop in imports and rise in exports since foreigners are relatively more well off. Real exchange rate depreciation occurs to aid in the re-balancing of balance of payments accounts and thus, imports and exports begin to gradually travel in opposite directions.

The remaining four productivity shocks in rows 1 and 2 of Figure 4.15 and rows 6 and

[29] However, the mechanism by which this contraction is effected in their model is different to that in mine. I put forth a story of structural/ sectoral re-allocation of resources, while they explore the notion of nominal rigidity of prices.

7 of Figure 4.16 show that the remaining productivity shocks all produce standard results for most of the key macroeconomic variables. I note the following exceptions. First, the energy efficiency shocks have the model implications of lowering the energy BTU input per unit of the volume of output. Hence, all energy (aggregate and sectoral) usage dropped in response to these shocks and because the amount of an input required has fallen, cost of production also fell such that sectoral prices of goods followed suit. Second, I point out the impact affects of energy and non-energy intensive investment-specific technology shocks on consumption - because these shocks move resources from consumption to investment, it can be seen how the time paths for consumption and investment are almost a perfect mirror image of each other.

Next, I investigate the impulse responses to the preference shocks beginning with the labour supply shock. A positive shock has a negative correlation with output - see row 8 of Figure 4.14. This result originates from the first-order condition (4.6), which implies that $\partial H_t/\partial \zeta_t < 0$. This indeed has both the intratemporal and intertemporal effects of drops in both the aggregate consumption and investment though the latter in the non-energy intensive sector still rose. Additionally, the substitution assumption between labour hours and the CES of capital services and energy use implies that capital utilisation rate, capital, and energy use all had to increase. This is what I observe except for capital demand in the energy intensive 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 the energy intensive sector. This contraction in labour supply and investment would lead to a rise in wages and interest rate. It is now costlier 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-à-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. The dynamics of the remaining preference shocks are quite interesting to look as depicted in rows 4 to 6 of Figure 4.14, row 6 of Figure 4.15, and rows 2 and 3 of Figure 4.16. What is particularly unique about these shocks, except the intertemporal preference shock, is that they act as

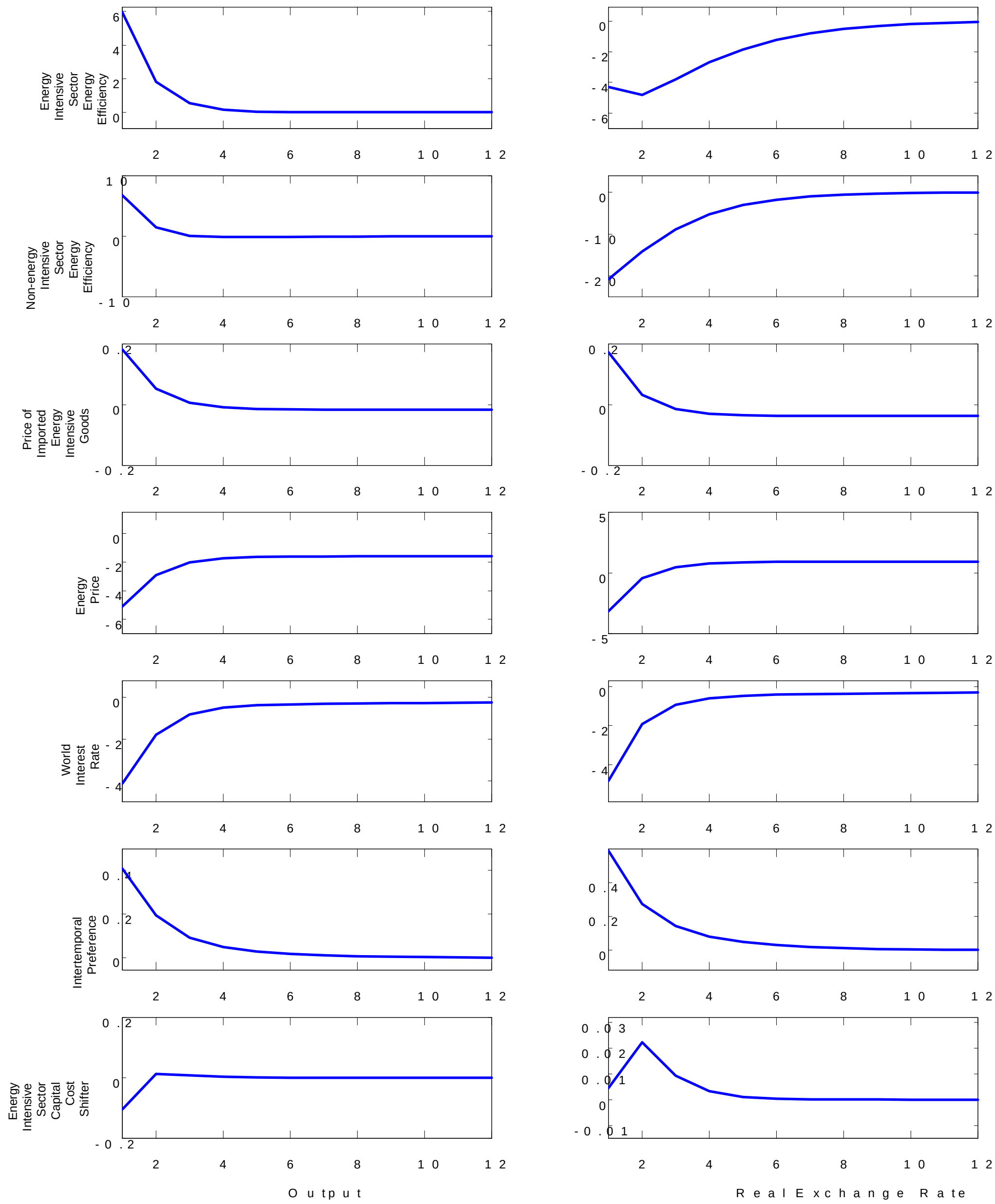


Figure 4.15: Impulse response functions (contd.).

a switcher of preferences between goods and/ or services intratemporally. For instance, a preference for energy intensive goods shocks changes household's preference away from non-energy intensive goods to energy intensive goods. Put simply, these are good-/ service-/ product-specific demand shocks.

Given this, I illustrate the remaining preference shocks with intertemporal preference shocks and shocks to the preference for energy intensive goods.[30] 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, output also jumps on impact. This will lead to higher factor demands and concurrently increases in factor prices to incentivise the households to supply. Higher costs of production mean 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 energy intensive goods are qualitatively similar to that of the intertemporal preference shocks, except for the effects on consumption and non-energy intensive output and inputs. These results can be due to: (1) the estimated weight of energy intensive goods in the aggregator function is 26%; (2) there is re-allocation of resources from the non-energy intensive sector to the energy intensive sector as demand increases for output of the latter.

Let us turn to the analysis of the impulse response functions to a positive standard deviation shock to the energy price in row 4 of Figure 4.15. Unlike the productivity shocks, an increase in the energy price worsens income. On the production side, the 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 is a 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 (wage rate falls), and investment falls in response to lower marginal product of capital (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 because of the complementarity with energy. Two things to note regarding trade with the rest of the world: first, I 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

[30] Other good-/ service-/ product-specific demand shocks can be interpreted from the shocks to the preference for energy intensive goods.

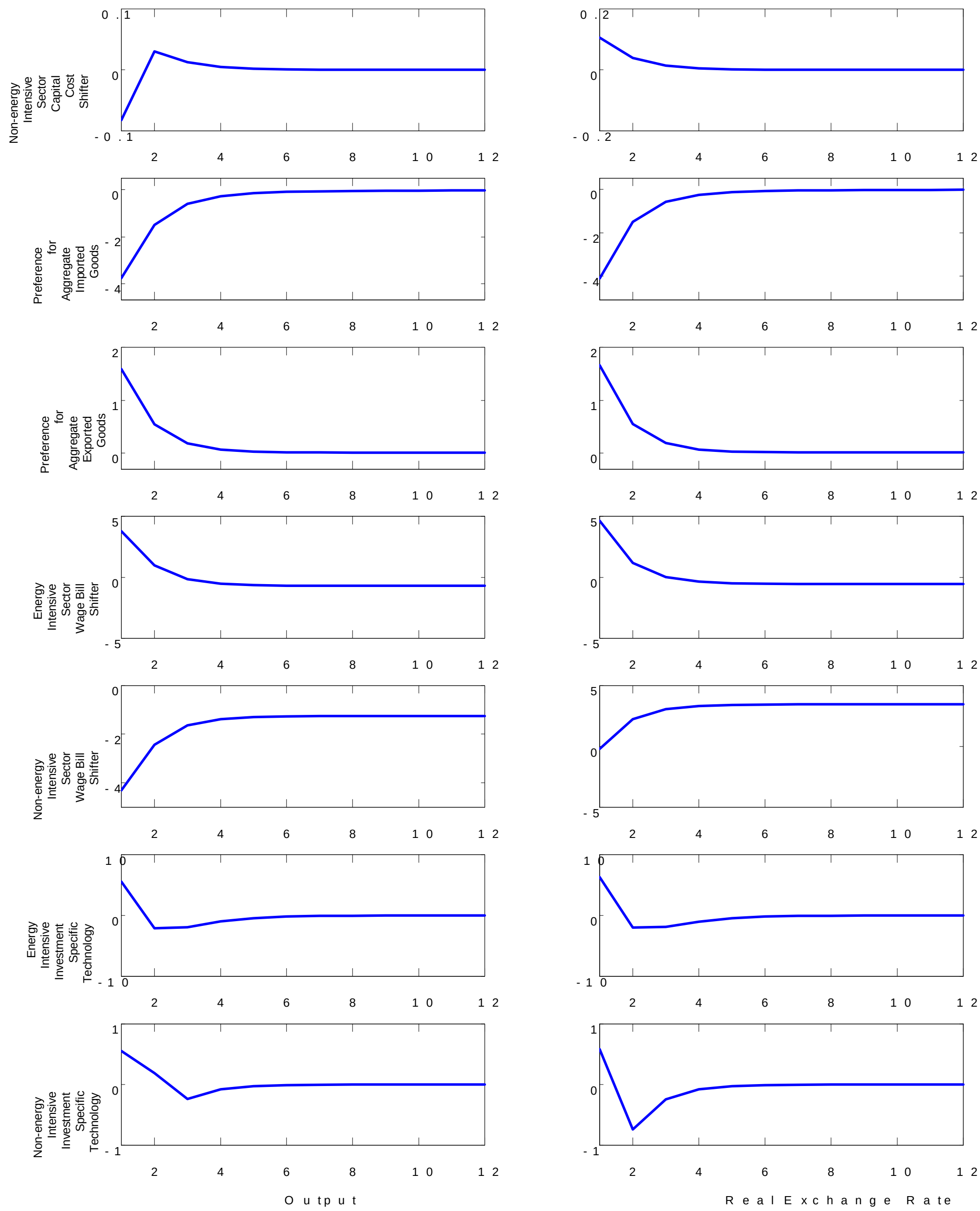


Figure 4.16: Impulse response functions (contd.).

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.

Now, I examine the effects of the group of shocks labelled cost-push in row 7 of Figure 4.15 and rows 1, 4, and 5 of Figure 4.16. One thing to note here is that these shocks are predominantly sector-specific and any impacts they generate on other variables are spill-over effects. Moreover, only energy intensive sector wage bill shifter generated non-standard results and so, I only discuss this shock under cost-push group and in relation basically to output. I conjecture that the fall in labour hours demanded by firms in the energy intensive sector because of wage bill hike does not lead to a fall in output of the energy intensive sector that is sufficient to lower aggregate output.

Finally, I consider the time paths of the endogenous variables to the observed exogenous variables beginning with the impulse response functions to a positive world demand shock - see row 3 of Figure 4.14. 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 energy intensive sector goods in cross-border trade is much larger such that 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 (see row 5 of Figure 4.15) 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 energy intensive goods in row 3 of Figure 4.15. Essentially, an increase in the imported price of energy intensive goods will lead to fall in the import of such goods and consumption falls for two reasons: first is that aggregate consumption is a composite involving imported energy intensive goods and second is that domestic sectoral prices have been driven up by positive imported price movement such that consumption goods are now more expensive. Lastly, the crowding out effects of government spending means that consumption and investment fell on impact, and because government spending is non-productive in the current model, it leads to a decrease in output, which particularly contradicts some findings in the literature [for example, Finn (1998) and Ravn et al. (2012)]. I see that the fall in consumption is trivial as households are able to smooth consumption overtime. A further effect is that both aggregate and sectoral labour hours increased on impact reflecting household's willingness to sacrifice some leisure during hard times. Consequently, wages fall as labour supply increases. This will cause output to start rising to lessen the adverse wealth effect accompanying the government spending shock.

Variance Decompositions To explain the percentage of variation in each variable that is due to the different shocks, one can examine Table 4.4, which documents the variance decomposition of the endogenous variables. It shows that every group is important to some degree, in most cases, to explaining the variations in all 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 my belief that energy price shock is (should be) a main covariate of macroeconomic variables. For example, energy price shock is only approximately 4.55% of the shocks in the model and accounts 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 movements in aggregate output. Proportionally and as would be expected, energy price shock is 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 I observe 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 though given that energy use is not modelled for the household and so there is a weak link between preference shocks and energy usage.

Perhaps, a look at Tables 4.8-4.9 can provide a better insight into which shocks are individually most (least) important. The key shocks are the permanent shocks accounting for well over 90% of movements in all variables considered with the other shocks appearing 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 4.4 as expanded in Tables 4.8-4.9. It is interesting to see that variability in imports (aggregate and energy intensive), exports (aggregate and energy intensive), and interest rate are dominated by

Table 4.4: Variance Decomposition

Variable, symbol	Shocks, 1949-2013				
	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 aborption 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, f_t	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 (a_t^e and a_t^n), energy and non-energy intensive investment-specific technologies (z_t^e and z_t^n), and energy and non-energy intensive energy efficiencies (o_t^e and o_t^n); preference shocks: sum of intertemporal preference (τ_t), labour supply (ζ_t), preference for imported energy intensive goods (φ_t), preference for exported energy intensive goods (φ_t^w), preference for energy intensive goods (γ_t), preference for aggregate imported goods (ϖ_t), and preference for aggregate exported goods (ϖ_t^w); energy price shock (q_t); exogenous variables: sum of world demand (d_t^w), government spending (g_t), the price of imported energy intensive goods ($p_{e,t}^{im}$), and foreign interest rate (r_t^f); cost-push shocks: sum of energy intensive sector capital cost shifter (ϑ_t^e), non-energy intensive sector capital cost shifter (ϑ_t^n), energy intensive sector wage bill shifter (ξ_t^e), non-energy intensive sector wage bill shifter (ξ_t^n)

world demand (66.5%, 69.7%, 38.3%, 42.3%, and 56.5%, respectively). It is, however, startling that volatility in the U.S. wage rate is explained 48.9% 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 effecting volatilities in any of the model variables. Regarding labour supply shock, my finding disagrees with Meenagh et al. (2010) who find that it contributed 25.34% and 28.11% to output and consumption, respectively. My 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 impacts 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 generate sufficiently large enough responses from model variables. Moreover, unlike Stockman and Tesar (1995) and Garcia-Cicco et al. (2010), I did not find introducing intertemporal preference shock to be adding anything to the variability of model variables.

4.5 Conclusion

I 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 work 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. I have shown qualitatively that output is affected both intratemporally - the *impact effect* - and intertemporally - the *transition effect* - and quantitatively assess these results in the estimated model. I find that the macroeconomic effects of oil price shock are still sizeable and that real exchange rate moves to account for these changes after each shock.

Meanwhile, it would be interesting to carry out the preceding exercises for a number of countries and study how output and their competitiveness measured in real exchange rate change with changes in the exogenous world price of crude oil. In doing this, it is perhaps necessary and preferable to extend this model to include an energy-producing sector if we were to fully grasp the effects of oil price increases on the general price level and the relative sectoral price. Further, it may be important to investigate more fully 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 to study also 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 I have used. Thus, it may be informative to have a version of this model augmented with measurement error estimated in a future research. Finally, in the current paper I have explained what happens to output and real exchange when there is an exogenous increase in the real price of oil without any particular offer of a plausible policy recommendation for accommodating such occurrences. Therefore, as a next step it will be interesting to incorporate a monetary and/ or fiscal channels by which there could be policy responses as already been done in the literature. However, I think such an exercise within this theoretical framework, when properly motivated, could lead to a more optimal plan of actions.

Table 4.5: Steady State Parameters

Parameter	q	$\frac{e^e}{k^e}$	$\frac{e^n}{k^n}$	$\frac{i^e}{k^e}$	$\frac{i^n}{k^n}$	$\frac{i^e}{i}$	$\frac{i^n}{i}$	$\frac{h^e}{h}$	$\frac{h^n}{h}$	$\frac{e^e}{e}$	$\frac{e^n}{e}$	$\frac{y^e}{y}$	$\frac{y^n}{y}$	$\frac{g}{d}$	$\frac{i}{d}$	$\frac{c}{d}$
Value/ expression	1	0.011	0.014	0.08	0.17	0.7	$1-\frac{i^e}{i}$	0.4	$1-\frac{h^e}{h}$	0.78	$1-\frac{e^e}{e}$	0.41	$1-\frac{y^e}{y}$	0.21	0.30	$1-\frac{g}{d}-\frac{i}{d}$

Parameter	$\frac{d^e}{y^e}$	$\frac{ex^e}{y^e}$	$\frac{im^e}{y^e}$	$\frac{d^e}{d}$	$\frac{i}{y}$	$\frac{g}{y}$	$\frac{e}{y}$	$\frac{ex}{y}$	$\frac{im}{y}$	$\frac{c}{y}$	f	r	w
Value/ expression	1.385	0.1573	0.205	0.370	0.308	0.215	0.037	0.080	0.092	$1-\frac{i}{y}-\frac{g}{y}-\frac{ex}{y}+\frac{im}{y}+\frac{e}{y}$	0.023	$\frac{1}{\beta}-1$	1

Table 4.6: Test for Stationarity of Shocks

Shocks	*ADF* Test Statistics			*PP* Test Statistics			*KPSS* Test Statistics			Conclusion
	LL	*WT*	*FD*	*LL*	*WT*	*FD*	*LL*	*WT*	*FD*	
a^e_t	−1.48 (0.54)	−2.04 (0.57)	−6.86 (0.00)	−1.48 (0.54)	−1.99 (0.60)	−6.80 (0.00)	0.8340	0.1387	0.1666	Non-stationary†
a^n_t	−2.48 (0.13)	−3.07 (0.12)	−6.77 (0.00)	−3.09 (0.03)	−2.97 (0.15)	−9.35 (0.00)	0.9517	0.1728	0.4504	Non-stationary‡
d^w_t	−2.13 (0.23)	−2.67 (0.25)	−7.66 (0.00)	−2.16 (0.22)	−2.66 (0.26)	−7.66 (0.00)	0.9461	0.1489	0.2304	Non-stationary‡
φ_t	−0.42 (0.90)	−1.57 (0.79)	−6.20 (0.00)	−0.64 (0.85)	−1.45 (0.84)	−6.42 (0.00)	0.8700	0.1550	0.1542	Non-stationary‡
φ^w_t	−0.51 (0.88)	−2.05 (0.57)	−8.04 (0.00)	−0.47 (0.89)	−2.08 (0.55)	−8.07 (0.00)	0.9616	0.1543	0.0858	Non-stationary‡
γ_t	0.11 (0.96)	−1.95 (0.62)	−7.25 (0.00)	0.08 (0.96)	−1.95 (0.62)	−7.25 (0.00)	0.9898	0.1733	0.1742	Non-stationary‡
g_t	−1.22 (0.66)	−1.35 (0.87)	−6.30 (0.00)	−3.30 (0.02)	−2.75 (0.22)	−6.30 (0.00)	0.9732	0.1687	0.4662	Non-stationary‡
ζ_t	−2.07 (0.26)	−2.04 (0.57)	−7.71 (0.00)	−2.02 (0.28)	−2.00 (0.59)	−7.84 (0.00)	0.1586	0.1705	0.1120	Stationary*
o^e_t	−1.86 (0.35)	−1.86 (0.66)	−7.98 (0.00)	−1.86 (0.35)	−1.89 (0.65)	−8.01 (0.00)	0.0915	0.0939	0.1560	Stationary*
o^n_t	−1.92 (0.32)	−1.76 (0.71)	−7.55 (0.00)	−1.97 (0.30)	−1.78 (0.71)	−7.55 (0.00)	0.4441	0.0902	0.1202	Stationary*
$\mathsf{p}^{im}_{e,t}$	−0.93 (0.77)	−1.43 (0.84)	−4.92 (0.00)	−0.66 (0.85)	−1.44 (0.84)	−4.93 (0.00)	0.8792	0.1526	0.1468	Non-stationary‡
q_t	−0.99 (0.75)	−1.84 (0.67)	−7.74 (0.00)	−1.03 (0.74)	−1.86 (0.67)	−7.74 (0.00)	0.4758	0.0793	0.1159	Non-stationary†
r^f_t	−1.47 (0.54)	−1.91 (0.64)	−5.58 (0.00)	−0.84 (0.80)	−1.17 (0.91)	−5.29 (0.00)	0.3284	0.2477	0.4658	Stationary*
τ_t	−2.27 (0.19)	−2.14 (0.51)	−8.95 (0.00)	−2.05 (0.27)	−1.85 (0.67)	−9.53 (0.00)	0.2566	0.2525	0.3534	Stationary*
ϑ^e_t	−0.10 (0.95)	−2.03 (0.58)	−7.63 (0.00)	−0.15 (0.94)	−2.19 (0.49)	−7.66 (0.00)	0.9145	0.1150	0.1406	Trend stationary*
ϑ^n_t	−1.27 (0.64)	−3.67 (0.03)	−6.55 (0.00)	−1.25 (0.65)	−3.67 (0.03)	−13.6 (0.00)	0.9949	0.1309	0.3379	Trend stationary*
ϖ_t	−0.53 (0.88)	−1.37 (0.86)	−7.58 (0.00)	−0.53 (0.88)	−1.50 (0.82)	−7.58 (0.00)	0.9714	0.1198	0.1553	Trend stationary*
ϖ^w_t	−0.40 (0.90)	−2.64 (0.26)	−6.35 (0.00)	−0.48 (0.89)	−1.99 (0.60)	−6.37 (0.00)	0.8085	0.1161	0.1842	Trend stationary*
ξ^e_t	−0.50 (0.88)	−1.69 (0.74)	−3.80 (0.01)	−0.56 (0.87)	−1.58 (0.79)	−6.90 (0.00)	0.9647	0.1645	0.1131	Non-stationary‡
ξ^n_t	−2.03 (0.28)	−0.15 (0.99)	−6.77 (0.00)	−1.84 (0.36)	−0.30 (0.99)	−6.54 (0.00)	0.9983	0.2075	0.4352	Non-stationary‡
z^e_t	−5.67 (0.00)	−5.62 (0.00)	−9.68 (0.00)	−5.34 (0.00)	−5.26 (0.00)	−23.6 (0.00)	0.0523	0.0362	0.3187	Stationary‡
z^n_t	−5.61 (0.00)	−5.55 (0.00)	−9.57 (0.00)	−5.26 (0.00)	−5.17 (0.00)	−23.7 (0.00)	0.0437	0.0361	0.3390	Stationary‡

Note: a^e_t: energy intensive sector productivity, a^n_t: non-energy intensive sector productivity, d^w_t: world demand, φ_t: preference for imported energy intensive goods, φ^w_t: preference for exported energy intensive goods, γ_t: preference for energy intensive goods, g_t: government-spending, ζ_t: labour supply, o^e_t: energy intensive sector energy efficiency, o^n_t: non-energy intensive sector energy efficiency, $\mathsf{p}^{im}_{e,t}$: price of imported energy intensive goods, q_t: energy price, r^f_t: foreign interest rate, τ_t: intertemporal preference, ϑ^e_t: energy intensive sector capital cost shifter, ϑ^n_t: non-energy intensive sector capital cost shifter, ϖ_t: preference for aggregate imported goods, ϖ^w_t: preference for aggregate exported goods, ξ^e_t: energy intensive sector wage bill shifter, ξ^n_t: non-energy intensive sector wage bill shifter, z^e_t: energy intensive investment-specific technology, and z^n_t: non-energy intensive investment-specific technology; *ADF*: Augmented Dickey-Fuller, *PP*: Phillips-Perron, *KPSS*: Kwiatkowski, Phillips, Schmidt, and Shin, *LL*: levels, *WT*: with trend, and *FD*: first difference. †I made a judgement supporting ADF and PP tests; *I made a judgement supporting KPSS test; ‡all three methods agree on the conclusion I reached; conclusions are based on 5% critical value.

Table 4.7: Value of Coefficients

Symbol	Definition	Value	Symbol	Definition	Value
i_1^e	$\frac{1}{\delta u^e}$	13.021	y_2^n	$\frac{\alpha_n}{1+\frac{1-\theta_n}{\theta_n}\left(\frac{e^n}{k^n}\right)^{-\nu_n}}$	0.3005
i_1^n	$\frac{1}{\delta u^n}$	5.7707	y_3^e	$\frac{\alpha_e}{1+\frac{\theta_e}{1-\theta_e}\left(\frac{e^e}{k^e}\right)^{\nu_e}}$	0.0699
i_2^e	$\frac{1-\delta u^e}{\delta u^e}$	12.021	y_3^n	$\frac{\alpha_n}{1+\frac{\theta_n}{1-\theta_n}\left(\frac{e^n}{k^n}\right)^{\nu_n}}$	0.0693
i_2^n	$\frac{1-\delta u^n}{\delta u^n}$	4.7707	h_1^e	$\frac{w}{1+w}$	0.5000
i_3^e	$\frac{\delta_{e1}u^{\mu_e}}{\delta u^e}$	0.3570	h_1^n	h_1^e	0.5000
i_3^n	$\frac{\delta_{n1}u^{\mu_n}}{\delta u^n}$	0.3512	h_2^e	$\frac{1}{1+w}$	0.5000
c_1	$\frac{1}{1+\iota}$	0.7672	h_2^n	h_2^e	0.5000
c_2	$\frac{\iota}{1+\iota}$	0.2329	u_1^e	$\frac{1}{\frac{\mu_e-1}{1+\frac{1}{\delta_{e1}u^{\mu_e}}}+\nu_e+1-\frac{\nu_e}{1+\frac{1-\theta_e}{\theta_e}\left(\frac{e^e}{k^e}\right)^{-\nu_e}}}$	0.9055
c_3	$\frac{1-\iota}{\epsilon(1+\iota)}$	0.4328	u_1^n	$\frac{1}{\frac{\mu_n-1}{1+\frac{1}{\delta_{n1}u^{\mu_n}}}+\nu_n+1-\frac{\nu_n}{1+\frac{1-\theta_n}{\theta_n}\left(\frac{e^n}{k^n}\right)^{-\nu_n}}}$	0.7913
c_4	βr	0.0400	u_2^e	$\frac{1}{1+\frac{1}{\delta_{e1}u^{\mu_e}}}$	0.0267
w_1	$\frac{\epsilon}{1-\iota}$	1.7726	u_2^n	$\frac{1}{1+\frac{1}{\delta_{n1}u^{\mu_n}}}$	0.0574
r_1	$\psi_{bf}b^f$	0.0003	u_3^e	$\frac{\frac{\nu_e}{1+\frac{1-\theta_e}{\theta_e}\left(\frac{e^e}{k^e}\right)^{-\nu_e}}-\nu_e-1}{\frac{\mu_e-1}{1+\frac{1}{\delta_{e1}u^{\mu_e}}}+\nu_e+1-\frac{\nu_e}{1+\frac{1-\theta_e}{\theta_e}\left(\frac{e^e}{k^e}\right)^{-\nu_e}}}$	−0.9783
k_1^e	$\frac{\epsilon/(1-\iota)}{\psi_e(1+\beta)}$	7173.7	u_3^n	$\frac{\frac{\nu_n}{1+\frac{1-\theta_n}{\theta_n}\left(\frac{e^n}{k^n}\right)^{-\nu_n}}-\nu_n-1}{\frac{\mu_n-1}{1+\frac{1}{\delta_{n1}u^{\mu_n}}}+\nu_n+1-\frac{\nu_n}{1+\frac{1-\theta_n}{\theta_n}\left(\frac{e^n}{k^n}\right)^{-\nu_n}}}$	−0.8310
k_1^n	$\frac{\epsilon/(1-\iota)}{\psi_n(1+\beta)}$	1363.8	u_4^e	$\frac{\frac{\nu_e}{1+\frac{\theta_e}{1-\theta_e}\left(\frac{e^e}{k^e}\right)^{\nu_e}}}{\frac{\mu_e-1}{1+\frac{1}{\delta_{e1}u^{\mu_e}}}+\nu_e+1-\frac{\nu_e}{1+\frac{1-\theta_e}{\theta_e}\left(\frac{e^e}{k^e}\right)^{-\nu_e}}}$	0.0728
k_2^e	k_1^e	7173.7	u_4^n	$\frac{\frac{\nu_n}{1+\frac{\theta_n}{1-\theta_n}\left(\frac{e^n}{k^n}\right)^{\nu_n}}}{\frac{\mu_n-1}{1+\frac{1}{\delta_{n1}u^{\mu_n}}}+\nu_n+1-\frac{\nu_n}{1+\frac{1-\theta_n}{\theta_n}\left(\frac{e^n}{k^n}\right)^{-\nu_n}}}$	0.0398
k_2^n	k_1^n	1363.8	u_5^e	$\frac{\frac{1}{1+\delta_{e1}u^{\mu_e}}}{\frac{\mu_e-1}{1+\frac{1}{\delta_{e1}u^{\mu_e}}}+\nu_e+1-\frac{\nu_e}{1+\frac{1-\theta_e}{\theta_e}\left(\frac{e^e}{k^e}\right)^{-\nu_e}}}$	0.8813
k_3^e	$\frac{1}{\psi_e(1+\beta)}$	4047.0	u_5^n	$\frac{\frac{1}{1+\delta_{n1}u^{\mu_n}}}{\frac{\mu_n-1}{1+\frac{1}{\delta_{n1}u^{\mu_n}}}+\nu_n+1-\frac{\nu_n}{1+\frac{1-\theta_n}{\theta_n}\left(\frac{e^n}{k^n}\right)^{-\nu_n}}}$	0.7459
k_3^n	$\frac{1}{\psi_n(1+\beta)}$	769.37	e_1^e	$\frac{1}{\nu_e+1-\frac{\nu_e}{1+\frac{\theta_e}{1-\theta_e}\left(\frac{e^e}{k^e}\right)^{\nu_e}}}$	0.8286
k_4^e	$\frac{\beta\delta_{e1}u^{\mu_e}(\mu_e-1)}{\psi_e(1+\beta)}$	95.898	e_1^n	$\frac{1}{\nu_n+1-\frac{\nu_n}{1+\frac{\theta_n}{1-\theta_n}\left(\frac{e^n}{k^n}\right)^{\nu_n}}}$	0.8211
k_4^n	$\frac{\beta\delta_{n1}u^{\mu_n}(\mu_n-1)}{\psi_n(1+\beta)}$	167.31	e_2^e	$\frac{\frac{\nu_e}{1+\frac{1-\theta_e}{\theta_e}\left(\frac{e^e}{k^e}\right)^{-\nu_e}}}{\nu_e+1-\frac{\nu_e}{1+\frac{\theta_e}{1-\theta_e}\left(\frac{e^e}{k^e}\right)^{\nu_e}}}$	0.1714
k_5^e	$\frac{1}{1+\beta}$	0.5102	e_2^n	$\frac{\frac{\nu_n}{1+\frac{1-\theta_n}{\theta_n}\left(\frac{e^n}{k^n}\right)^{-\nu_n}}}{\nu_n+1-\frac{\nu_n}{1+\frac{\theta_n}{1-\theta_n}\left(\frac{e^n}{k^n}\right)^{\nu_n}}}$	0.1789
k_5^n	k_5^e	0.5102	e_3^e	$\frac{\nu_e-\frac{\nu_e}{1+\frac{\theta_e}{1-\theta_e}\left(\frac{e^e}{k^e}\right)^{\nu_e}}}{\nu_e+1-\frac{\nu_e}{1+\frac{\theta_e}{1-\theta_e}\left(\frac{e^e}{k^e}\right)^{\nu_e}}}$	0.0666
y_1^e	$1-\alpha_e$	0.7503	e_3^n	$\frac{\nu_n-\frac{\nu_n}{1+\frac{\theta_n}{1-\theta_n}\left(\frac{e^n}{k^n}\right)^{\nu_n}}}{\nu_n+1-\frac{\nu_n}{1+\frac{\theta_n}{1-\theta_n}\left(\frac{e^n}{k^n}\right)^{\nu_n}}}$	0.0413
y_1^n	$1-\alpha_n$	0.6302	p_1	$\left(\frac{1}{\sigma}\frac{d^e}{d}\right)^{-\frac{1}{\varsigma}}$	0.4306
y_2^e	$\frac{\alpha_e}{1+\frac{1-\theta_e}{\theta_e}\left(\frac{e^e}{k^e}\right)^{-\nu_e}}$	0.1798	p_2	$\left(\frac{1-\sigma\mathsf{p}_1^{1-\varsigma}}{1-\sigma}\right)^{\frac{1}{1-\varsigma}}$	1.2424

Table 4.8: Variance Decomposition, 1949-2013 Shocks

Variable, symbol	Shocks										
	a_t^e	a_t^n	d_t^w	φ_t	φ_t^w	γ_t	g_t	ζ_t	o_t^e	o_t^n	$\mathsf{p}_{e,t}^{im}$
Aggregate output, y_t	8.72	8.87	11.9	8.70	8.70	8.72	8.70	0.03	0.15	0.19	8.70
Energy intensive output, y_t^e	8.23	8.04	14.1	8.03	8.02	8.38	8.02	0.07	1.63	0.07	8.02
Non-energy intensive output, y_t^n	8.42	8.93	11.7	8.41	8.41	8.70	8.40	0.02	0.09	0.76	8.41
Aggregate investment, i_t	4.02	3.94	50.1	3.92	3.91	4.25	3.91	0.29	0.88	1.01	3.91
Energy intensive investment, i_t^e	2.49	2.59	45.1	2.43	2.41	3.56	2.40	1.06	4.68	3.57	2.40
Non-energy intensive investment, i_t^n	1.24	1.24	54.6	1.06	1.06	1.51	1.07	0.39	3.22	1.28	1.05
Aggregate hours, h_t	9.06	9.06	9.29	9.06	9.06	9.06	9.06	0.02	0.01	0.02	9.06
Energy intensive hours, h_t^e	8.88	8.89	9.57	8.88	8.88	8.97	8.88	0.03	0.03	0.01	8.88
Non-energy intensive hours, h_t^n	8.97	8.99	9.07	8.97	8.97	9.03	8.97	0.01	0.00	0.06	8.97
Aggregate energy use, e_t	1.03	0.93	35.4	0.93	0.93	1.18	0.93	0.06	21.9	3.98	0.92
Energy intensive energy use, e_t^e	0.53	0.46	35.4	0.44	0.43	0.91	0.43	0.06	30.8	0.86	0.43
Non-energy intensive energy use, e_t^n	0.40	0.45	25.8	0.33	0.32	1.01	0.32	0.07	0.68	41.9	0.32
Domestic absorption, d_t	8.60	8.69	13.1	8.58	8.58	8.61	8.58	0.02	0.07	0.09	8.58
Aggregate imports, im_t	1.04	1.42	66.5	0.93	0.92	1.27	0.93	0.14	0.97	7.69	0.92
Energy intensive imports, im_t^e	0.49	0.90	69.7	1.21	0.37	0.73	0.38	0.15	1.02	8.12	0.56
Domestic aborption of energy intensive goods, d_t^e	8.46	8.35	13.3	8.35	8.35	8.53	8.35	0.03	0.67	0.18	8.35
Aggregate exports, ex_t	4.36	4.90	38.3	4.33	4.33	4.35	4.34	0.06	0.32	2.66	4.33
Energy intensive exports, ex_t^e	3.65	4.13	42.3	3.60	4.68	3.63	3.60	0.07	0.54	2.68	3.60
Wage, w_t	2.53	2.43	48.9	2.44	2.43	2.73	2.46	0.60	1.23	2.52	2.43
Interest rate, r_t	0.29	0.10	56.5	0.12	0.11	0.58	0.11	1.30	0.91	16.8	0.10
Price of energy intensive goods, p_t^e	7.88	7.51	13.6	7.51	7.51	7.55	7.51	0.08	3.99	0.33	7.51
Price of non-energy intensive goods, p_t^n	7.55	8.78	14.7	7.53	7.53	7.58	7.54	0.09	0.17	5.52	7.53
Net foreign assets, f_t	7.54	7.52	12.2	7.52	7.52	7.57	7.52	0.03	4.80	2.92	7.52
Consumption, c_t	9.00	9.60	9.67	8.85	8.85	8.90	9.03	0.00	0.00	0.01	8.85
Energy intensive capital, k_t^e	8.49	8.51	14.1	8.49	8.48	8.61	8.48	0.01	0.06	0.05	8.48
Non-energy intensive capital, k_t^n	8.61	8.65	12.5	8.61	8.61	8.87	8.60	0.01	0.23	0.10	8.60
Energy intensive capital utilisation rate, u_t^e	7.72	7.69	19.3	7.69	7.69	7.80	7.69	0.05	0.44	0.63	7.69
Non-energy intensive capital utilisation rate, u_t^n	8.54	8.53	13.6	8.53	8.53	8.53	8.53	0.01	0.01	0.01	8.53
Real exchange rate, p_t	5.97	8.03	23.4	5.87	5.87	5.94	5.87	0.21	1.22	10.3	5.87

Note: a_t^e: energy intensive sector productivity, a_t^n: non-energy intensive sector productivity, d_t^w: world demand, φ_t: preference for imported energy intensive goods, φ_t^w: preference for exported energy intensive goods, γ_t: preference for energy intensive goods, g_t: government-spending, ζ_t: labour supply, o_t^e: energy intensive sector energy efficiency, o_t^n: non-energy intensive sector energy efficiency, and $\mathsf{p}_{e,t}^{im}$: price of imported energy intensive goods.

Table 4.9: Variance Decomposition, 1949-2013 Shocks (contd.)

	Shocks										
Variable, symbol	q_t	r_t^f	τ_t	ϑ_t^e	ϑ_t^n	ϖ_t	ϖ_t^w	ξ_t^e	ξ_t^n	z_t^e	z_t^n
Aggregate output, y_t	8.86	0.08	0.00	0.00	0.00	0.05	0.01	8.76	8.80	0.14	0.00
Energy intensive output, y_t^e	8.30	0.13	0.00	0.00	0.00	0.21	0.05	9.82	8.67	0.25	0.00
Non-energy intensive output, y_t^n	8.58	0.09	0.00	0.00	0.00	0.02	0.00	9.22	9.71	0.16	0.00
Aggregate investment, i_t	5.15	1.33	0.00	0.00	0.00	0.34	0.02	5.43	4.76	2.83	0.02
Energy intensive investment, i_t^e	3.67	1.35	0.00	0.00	0.00	0.35	0.08	4.01	3.68	8.88	5.35
Non-energy intensive investment, i_t^n	2.15	1.26	0.02	0.00	0.00	0.31	0.07	2.49	1.35	1.99	22.7
Aggregate hours, h_t	9.06	0.00	0.00	0.00	0.00	0.00	0.00	9.07	9.12	0.01	0.00
Energy intensive hours, h_t^e	8.89	0.02	0.00	0.00	0.00	0.03	0.01	9.86	9.27	0.03	0.00
Non-energy intensive hours, h_t^n	8.97	0.00	0.00	0.00	0.00	0.00	0.00	9.29	9.71	0.00	0.00
Aggregate energy use, e_t	24.9	0.83	0.01	0.00	0.00	0.72	0.14	2.18	1.56	1.44	0.01
Energy intensive energy use, e_t^e	23.0	0.83	0.01	0.00	0.00	0.83	0.17	1.77	1.23	1.44	0.01
Non-energy intensive energy use, e_t^n	24.8	0.67	0.01	0.00	0.00	0.26	0.03	1.03	0.56	1.14	0.01
Domestic absorption, d_t	8.76	0.13	0.00	0.00	0.00	0.03	0.00	8.69	8.68	0.23	0.00
Aggregate imports, im_t	1.98	1.80	0.02	0.00	0.00	5.80	0.04	2.37	2.13	3.09	0.03
Energy intensive imports, im_t^e	1.48	1.90	0.02	0.00	0.00	6.13	0.04	1.90	1.64	3.27	0.03
Domestic aborption of energy intensive goods, d_t^e	8.55	0.14	0.00	0.00	0.00	0.03	0.00	9.29	8.80	0.26	0.00
Aggregate exports, ex_t	4.41	0.12	0.00	0.00	0.00	0.07	13.7	4.43	4.78	0.19	0.00
Energy intensive exports, ex_t^e	3.69	0.14	0.00	0.00	0.00	0.08	15.7	3.72	3.89	0.22	0.00
Wage, w_t	3.22	1.18	0.02	0.00	0.00	0.69	0.11	5.49	16.7	1.91	0.02
Interest rate, r_t	1.51	1.98	0.02	0.00	0.00	1.42	0.24	2.31	1.22	14.1	0.38
Price of energy intensive goods, p_t^e	7.59	0.15	0.00	0.00	0.00	0.09	0.01	11.6	9.32	0.25	0.00
Price of non-energy intensive goods, p_t^n	7.65	0.19	0.00	0.00	0.00	0.11	0.02	7.95	9.25	0.30	0.01
Net foreign assets, f_t	7.63	1.08	0.01	0.00	0.00	2.69	0.57	7.70	7.62	0.03	0.00
Consumption, c_t	9.04	0.03	0.00	0.00	0.00	0.00	0.00	9.27	8.91	0.00	0.00
Energy intensive capital, k_t^e	8.65	0.17	0.00	0.00	0.00	0.01	0.00	8.70	8.64	0.07	0.02
Non-energy intensive capital, k_t^n	8.67	0.07	0.00	0.00	0.00	0.01	0.00	8.67	8.61	0.13	0.42
Energy intensive capital utilisation rate, u_t^e	7.99	0.33	0.00	0.00	0.00	0.32	0.07	8.14	7.92	0.80	0.02
Non-energy intensive capital utilisation rate, u_t^n	8.64	0.14	0.00	0.00	0.00	0.07	0.01	8.69	8.58	0.26	0.03
Real exchange rate, p_t	6.15	0.45	0.01	0.00	0.00	0.26	0.04	6.23	7.59	0.74	0.01

Note: q_t: energy price, r_t^f: foreign interest rate, τ_t: intertemporal preference, ϑ_t^e: energy intensive sector capital cost shifter, ϑ_t^n: non-energy intensive sector capital cost shifter, ϖ_t: preference for aggregate imported goods, ϖ_t^w: preference for aggregate exported goods, ξ_t^e: energy intensive sector wage bill shifter, ξ_t^n: non-energy intensive sector wage bill shifter, z_t^e: energy intensive investment-specific technology, and z_t^n: non-energy intensive investment-specific technology.

Table 4.10: Variance Decomposition, 2006-2012 Shocks

	Shocks										
Variable, symbol	a_t^e	a_t^n	d_t^w	φ_t	φ_t^w	γ_t	g_t	ζ_t	o_t^e	o_t^n	$\mathsf{p}_{e,t}^{im}$
Aggregate output, y_t	9.06	9.13	9.33	9.05	9.06	9.02	9.05	0.00	0.02	0.02	9.06
Energy intensive output, y_t^e	9.05	9.06	9.46	9.01	9.02	8.84	9.02	0.01	0.19	0.01	9.03
Non-energy intensive output, y_t^n	9.03	9.19	9.33	9.05	9.04	9.12	9.04	0.00	0.01	0.08	9.04
Aggregate investment, i_t	8.64	8.73	12.0	8.64	8.66	8.45	8.64	0.04	0.19	0.21	8.67
Energy intensive investment, i_t^e	7.92	8.24	11.9	7.91	7.94	7.76	7.93	0.20	1.50	1.10	7.96
Non-energy intensive investment, i_t^n	5.95	5.80	14.4	5.82	5.80	6.56	5.76	0.13	1.82	0.69	5.78
Aggregate hours, h_t	9.09	9.08	9.15	9.09	9.09	9.08	9.09	0.00	0.00	0.00	9.09
Energy intensive hours, h_t^e	9.07	9.09	9.19	9.08	9.08	8.99	9.08	0.00	0.00	0.00	9.08
Non-energy intensive hours, h_t^n	9.09	9.07	9.13	9.10	9.10	9.14	9.10	0.00	0.00	0.01	9.09
Aggregate energy use, e_t	6.03	6.07	12.3	5.99	6.01	5.81	5.96	0.03	16.1	2.80	6.03
Energy intensive energy use, e_t^e	3.96	4.01	12.8	3.86	3.88	3.79	3.84	0.04	34.8	0.93	3.91
Non-energy intensive energy use, e_t^n	4.02	3.97	7.93	3.82	3.82	3.95	3.88	0.05	0.74	43.5	3.82
Domestic absorption, d_t	9.05	9.11	9.40	9.05	9.05	9.01	9.05	0.00	0.01	0.01	9.05
Aggregate imports, im_t	6.60	6.33	20.1	6.50	6.51	6.53	6.43	0.07	0.83	6.33	6.53
Energy intensive imports, im_t^e	4.35	3.97	29.0	4.44	4.08	4.48	3.99	0.14	1.66	12.6	3.99
Domestic aborption of energy intensive goods, d_t^e	9.06	9.05	9.43	9.04	9.04	8.90	9.04	0.00	0.07	0.02	9.05
Aggregate exports, ex_t	8.99	9.17	9.51	8.96	8.95	9.02	8.98	0.01	0.06	0.52	8.95
Energy intensive exports, ex_t^e	8.96	9.15	9.60	8.92	8.90	8.99	8.95	0.01	0.13	0.62	8.91
Wage, w_t	8.69	8.54	10.0	8.58	8.57	8.81	8.67	0.12	0.41	0.80	8.56
Interest rate, r_t	1.81	1.24	25.1	1.26	1.24	2.54	1.25	1.42	1.68	29.6	1.24
Price of energy intensive goods, p_t^e	8.98	9.03	9.46	9.02	9.02	8.99	9.00	0.01	0.48	0.04	9.02
Price of non-energy intensive goods, p_t^n	8.97	8.84	9.47	8.98	8.98	8.96	8.96	0.01	0.02	0.63	8.99
Net foreign assets, f_t	9.00	8.99	8.86	8.99	8.99	9.04	9.00	0.00	0.57	0.33	8.99
Consumption, c_t	9.10	9.18	9.11	9.08	9.08	9.11	9.03	0.00	0.00	0.00	9.08
Energy intensive capital, k_t^e	9.08	9.10	9.22	9.08	9.08	9.01	9.08	0.00	0.01	0.00	9.08
Non-energy intensive capital, k_t^n	9.04	9.01	9.29	9.06	9.05	9.16	9.04	0.00	0.02	0.01	9.05
Energy intensive capital utilisation rate, u_t^e	9.00	9.03	9.71	9.00	9.01	8.90	8.99	0.00	0.05	0.07	9.02
Non-energy intensive capital utilisation rate, u_t^n	9.05	9.05	9.39	9.05	9.05	9.03	9.04	0.00	0.00	0.00	9.05
Real exchange rate, p_t	8.95	9.29	8.81	8.90	8.90	9.01	8.94	0.02	0.18	1.44	8.89

Note: a_t^e: energy intensive sector productivity, a_t^n: non-energy intensive sector productivity, d_t^w: world demand, φ_t: preference for imported energy intensive goods, φ_t^w: preference for exported energy intensive goods, γ_t: preference for energy intensive goods, g_t: government-spending, ζ_t: labour supply, o_t^e: energy intensive sector energy efficiency, o_t^n: non-energy intensive sector energy efficiency, and $\mathsf{p}_{e,t}^{im}$: price of imported energy intensive goods.

Table 4.11: Variance Decomposition, 2006-2012 Shocks (contd.)

	Shocks										
Variable, symbol	q_t	r_t^f	τ_t	ϑ_t^e	ϑ_t^n	ϖ_t	ϖ_t^w	ξ_t^e	ξ_t^n	z_t^e	z_t^n
Aggregate output, y_t	9.14	0.00	0.00	0.00	0.00	0.00	0.00	9.06	8.98	0.01	0.00
Energy intensive output, y_t^e	9.15	0.01	0.00	0.00	0.00	0.01	0.00	9.00	9.10	0.02	0.00
Non-energy intensive output, y_t^n	9.13	0.01	0.00	0.00	0.00	0.00	0.00	9.08	8.84	0.01	0.00
Aggregate investment, i_t	9.27	0.20	0.00	0.00	0.00	0.04	0.00	8.78	8.39	0.44	0.01
Energy intensive investment, i_t^e	8.72	0.30	0.00	0.00	0.00	0.07	0.00	8.09	7.58	2.03	2.87
Non-energy intensive investment, i_t^n	6.79	0.50	0.01	0.00	0.00	0.10	0.00	5.97	5.84	0.80	21.4
Aggregate hours, h_t	9.10	0.00	0.00	0.00	0.00	0.00	0.00	9.09	9.04	0.00	0.00
Energy intensive hours, h_t^e	9.10	0.00	0.00	0.00	0.00	0.00	0.00	9.06	9.16	0.00	0.00
Non-energy intensive hours, h_t^n	9.10	0.00	0.00	0.00	0.00	0.00	0.00	9.11	8.97	0.00	0.00
Aggregate energy use, e_t	13.5	0.43	0.00	0.00	0.00	0.31	0.00	6.22	5.70	0.75	0.01
Energy intensive energy use, e_t^e	14.1	0.65	0.01	0.00	0.00	0.55	0.01	4.16	3.60	1.16	0.02
Non-energy intensive energy use, e_t^n	11.0	0.51	0.01	0.00	0.00	0.17	0.00	3.85	4.11	0.88	0.02
Domestic absorption, d_t	9.15	0.01	0.00	0.00	0.00	0.00	0.00	9.06	8.98	0.02	0.00
Aggregate imports, im_t	8.02	1.08	0.01	0.00	0.00	2.95	0.00	6.73	6.56	1.89	0.04
Energy intensive imports, im_t^e	6.64	2.15	0.00	0.00	0.00	5.89	0.00	4.44	4.29	3.77	0.08
Domestic aborption of energy intensive goods, d_t^e	9.15	0.00	0.00	0.00	0.00	0.00	0.00	9.03	9.09	0.02	0.00
Aggregate exports, ex_t	8.93	0.02	0.00	0.00	0.00	0.01	0.09	8.94	8.88	0.03	0.00
Energy intensive exports, ex_t^e	8.89	0.02	0.00	0.00	0.00	0.01	0.12	8.90	8.87	0.04	0.00
Wage, w_t	8.53	0.27	0.00	0.00	0.00	0.14	0.00	8.59	10.3	0.45	0.01
Interest rate, r_t	4.21	2.54	0.03	0.00	0.00	1.55	0.01	1.80	1.87	18.5	1.16
Price of energy intensive goods, p_t^e	9.05	0.01	0.00	0.00	0.00	0.01	0.00	9.10	8.78	0.02	0.00
Price of non-energy intensive goods, p_t^n	9.02	0.02	0.00	0.00	0.00	0.01	0.00	8.98	9.14	0.03	0.00
Net foreign assets, f_t	8.95	0.09	0.00	0.00	0.00	0.19	0.00	8.98	9.03	0.00	0.00
Consumption, c_t	9.11	0.00	0.00	0.00	0.00	0.00	0.00	9.07	9.05	0.00	0.00
Energy intensive capital, k_t^e	9.12	0.01	0.00	0.00	0.00	0.00	0.00	9.09	9.03	0.01	0.00
Non-energy intensive capital, k_t^n	9.10	0.00	0.00	0.00	0.00	0.00	0.00	9.06	9.04	0.01	0.07
Energy intensive capital utilisation rate, u_t^e	9.16	0.03	0.00	0.00	0.00	0.02	0.00	9.05	8.90	0.07	0.00
Non-energy intensive capital utilisation rate, u_t^n	9.12	0.01	0.00	0.00	0.00	0.00	0.00	9.07	9.01	0.02	0.05
Real exchange rate, p_t	8.87	0.05	0.00	0.00	0.00	0.02	0.00	8.88	8.78	0.08	0.00

Note: q_t: energy price, r_t^f: foreign interest rate, τ_t: intertemporal preference, ϑ_t^e: energy intensive sector capital cost shifter, ϑ_t^n: non-energy intensive sector capital cost shifter, ϖ_t: preference for aggregate imported goods, ϖ_t^w: preference for aggregate exported goods, ξ_t^e: energy intensive sector wage bill shifter, ξ_t^n: non-energy intensive sector wage bill shifter, z_t^e: energy intensive investment-specific technology, and z_t^n: non-energy intensive investment-specific technology.

Table 4.12: Oil Price Increases and Causes, 1947-2008

Oil Price Episode	Price Changes (%)	Principal Factors
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
2007-2008	145	Strong demand vs supply constraints

Source: Hamilton (1985, 2011).

Table 4.13: Model Predictions of Abnormal Growth and Recession

	Sample		
	1950 – 2013	1950 – 1981	1982 – 2013
Growth Episodes:			
Frequency of no abnormal growth and no oil price decreases	1.80	1.78	1.82
Frequency of abnormal growth and no oil price decreases	4.82	5.00	4.72
Frequency of no abnormal growth but oil price decreases	5.62	5.50	5.70
Frequency of abnormal growth and oil price decreases	17.09	18.14	16.15
Recession Episodes:			
Frequency of no recessions and no oil price increases	1.79	1.77	1.81
Frequency of recessions and no oil price increases	4.89	5.07	4.76
Frequency of no recessions but oil price increases	5.72	5.60	5.77
Frequency of recessions and oil price increases	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, I take as one episode every successive occurrence. For each sample period, I simulate the model 1000 times; the statistics reported is, therefore, to be viewed as having hypothetical sample $n \times 1000$ years of observations.

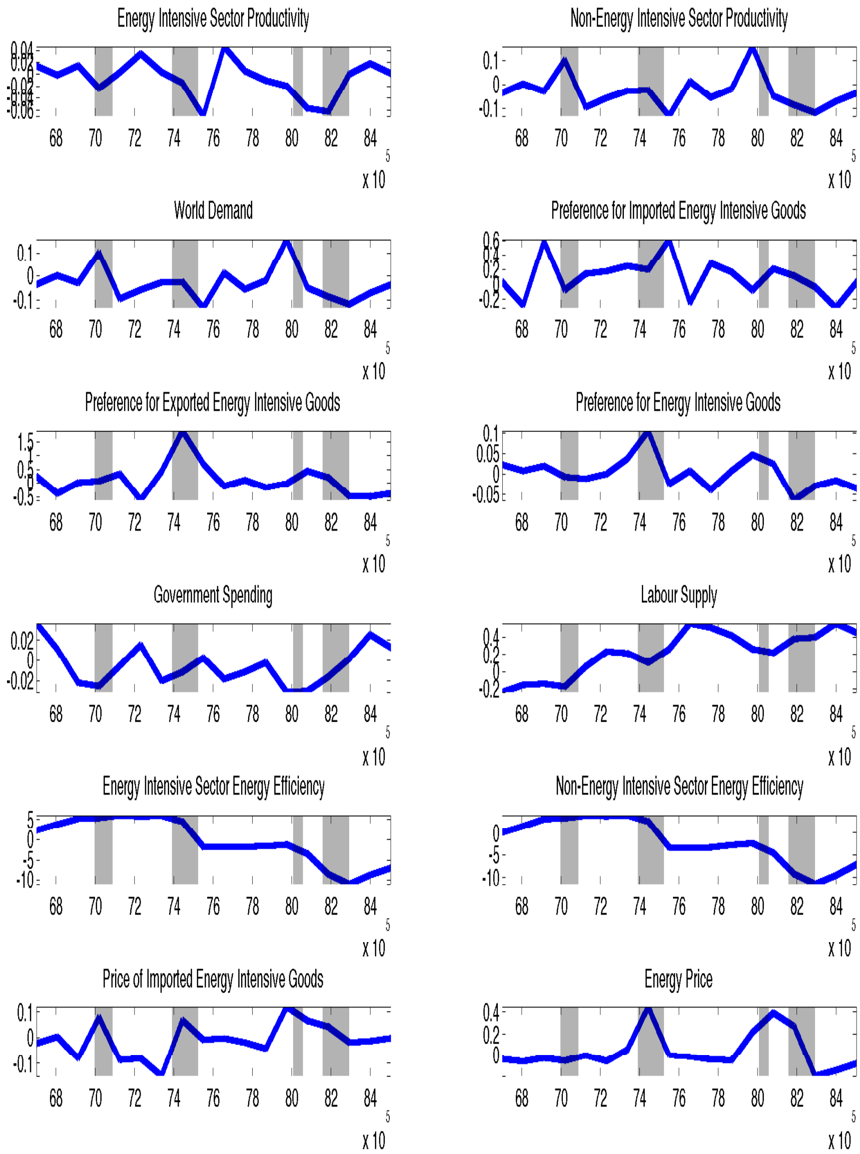


Figure 4.17: Accumulated shocks, 1967-1984.

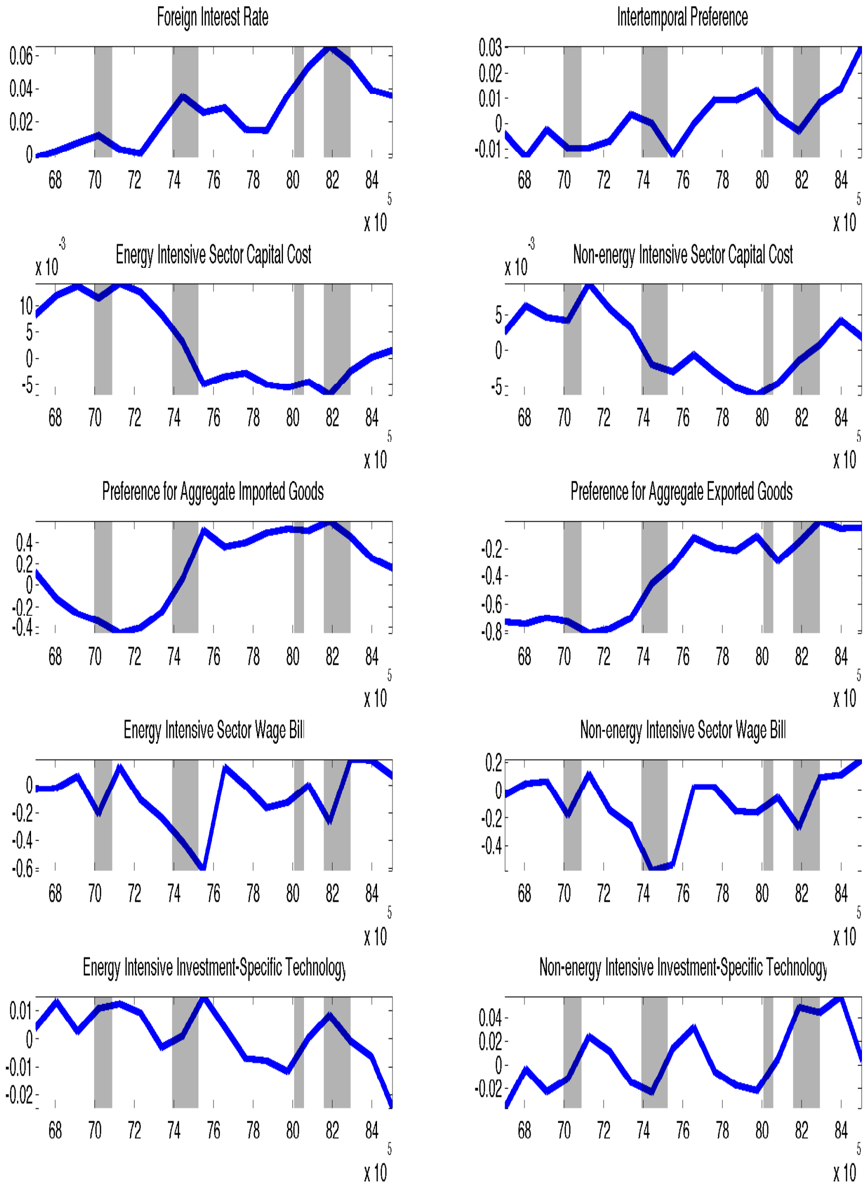


Figure 4.18: Accumulated shocks, 1967-1984 (contd.).

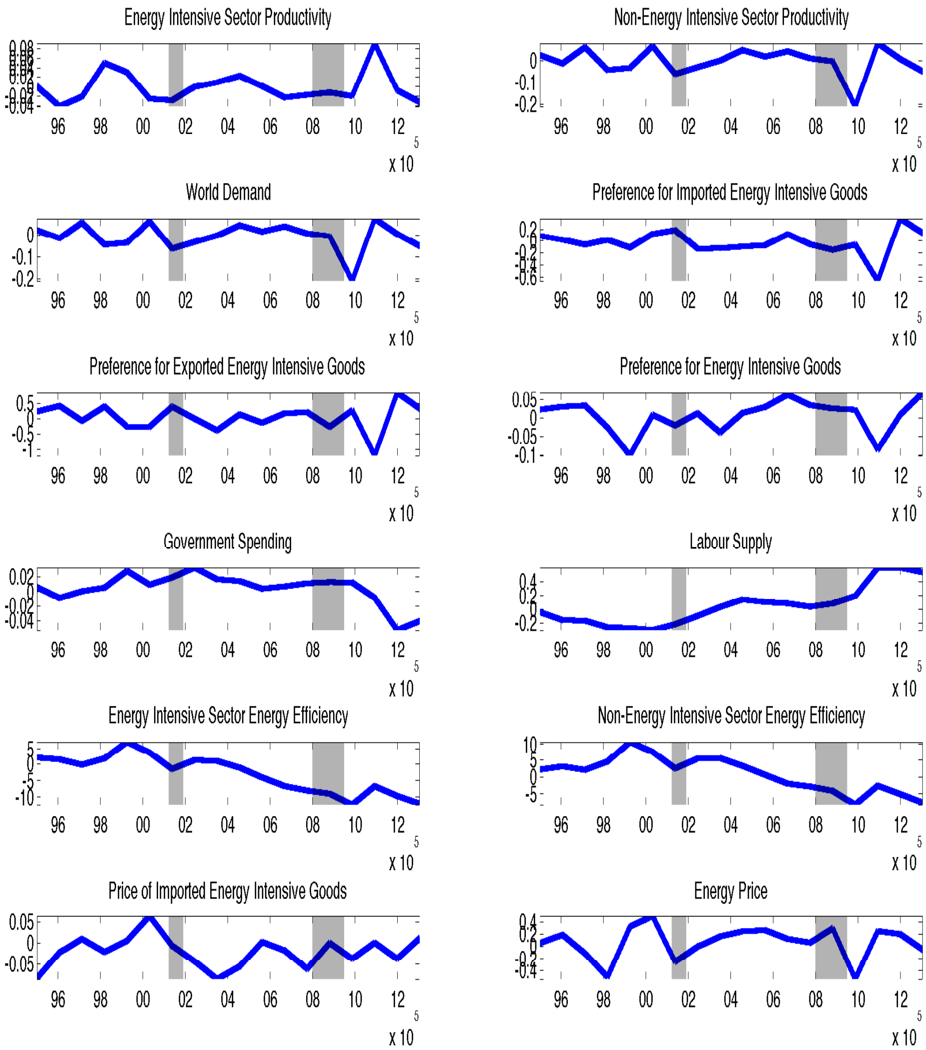


Figure 4.19: Accumulated shocks, 1995-2012.

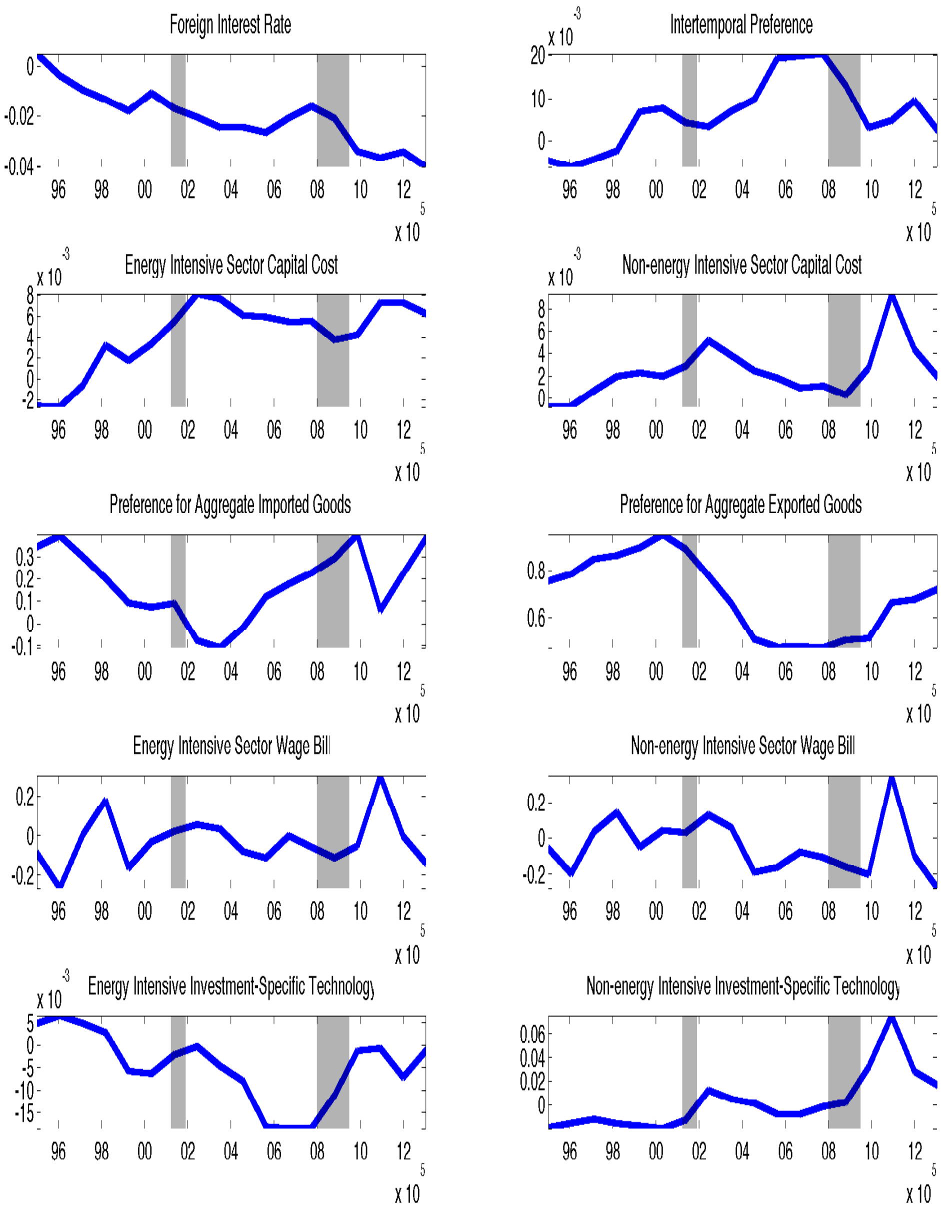


Figure 4.20: Accumulated shocks, 1995-2012 (contd.).

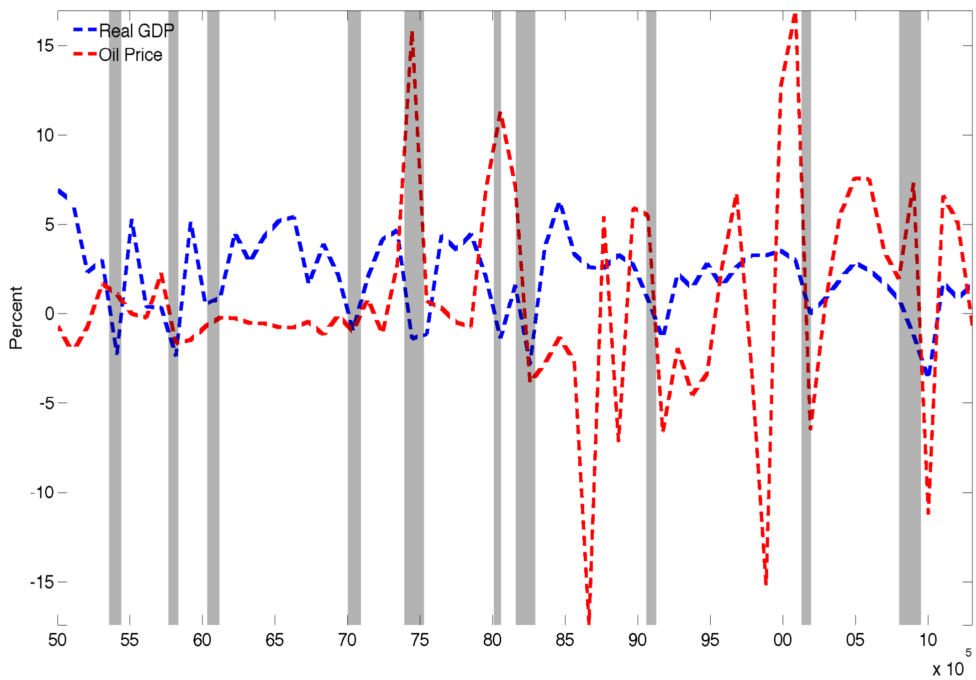


Figure 4.21: Year-on-Year Change in RGDP per capita and Crude Oil Price.

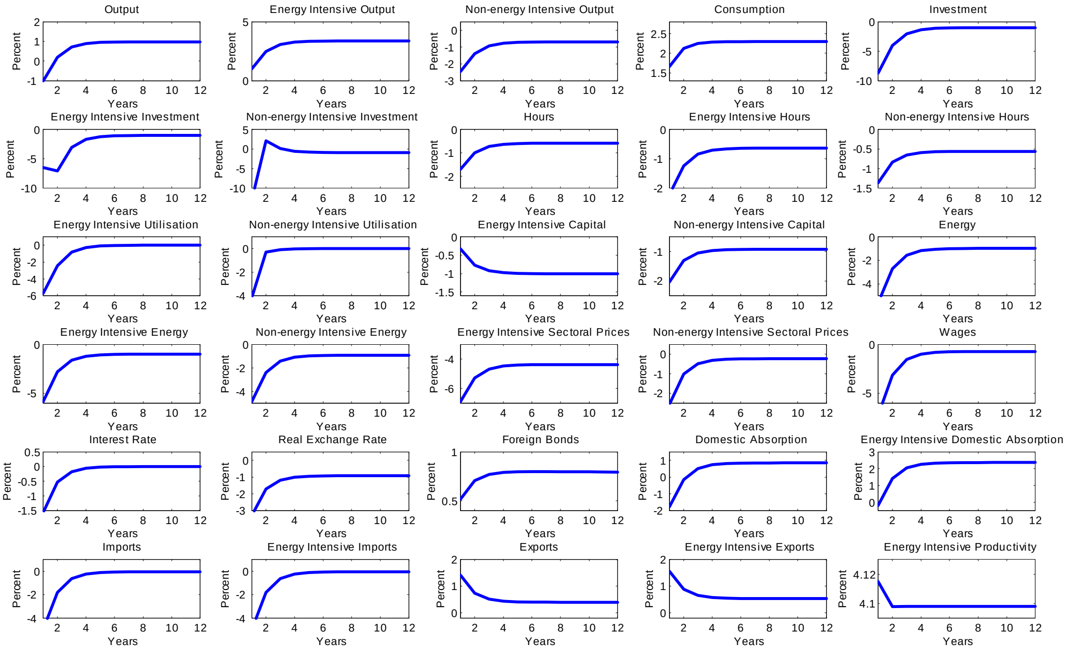


Figure 4.22: IRFs to a_t^e.

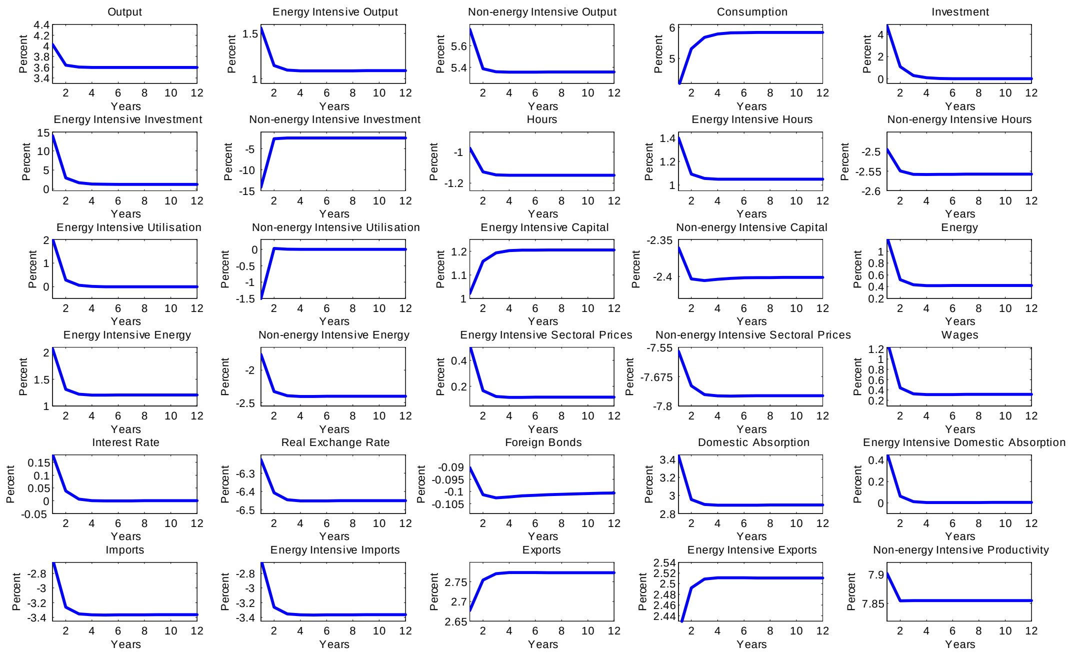


Figure 4.23: IRFs to a_t^n.

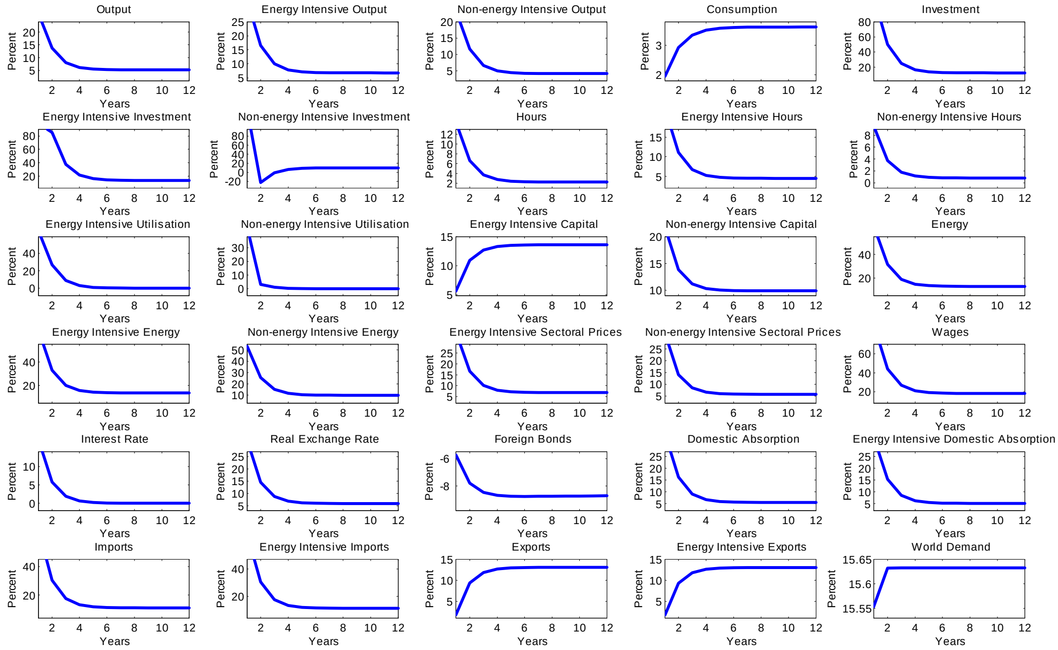


Figure 4.24: IRFs to d_t^w.

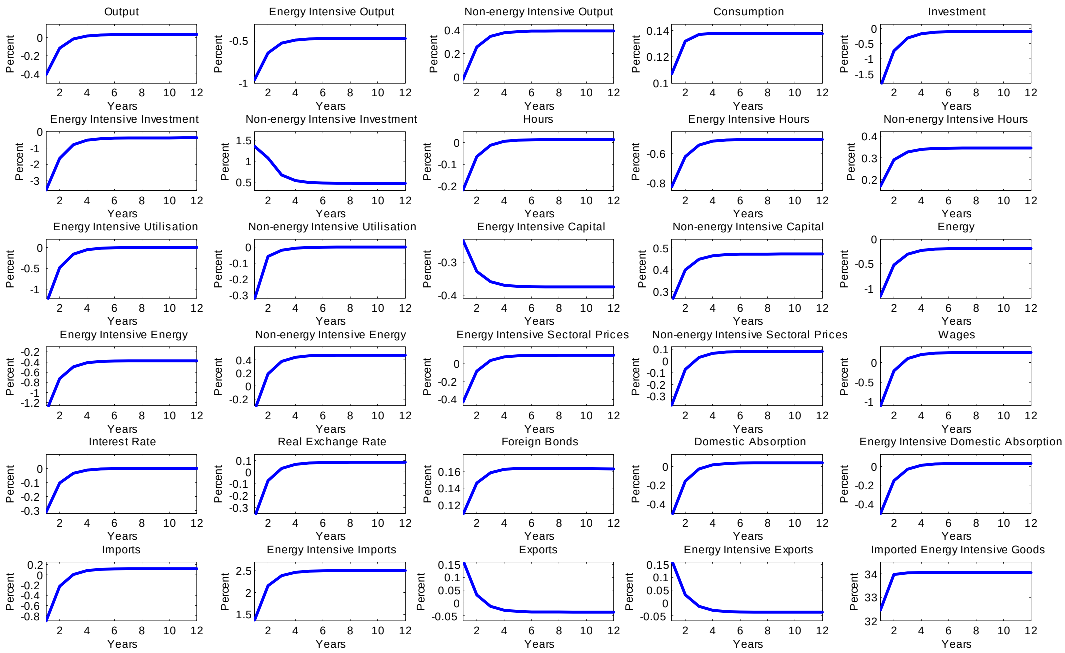


Figure 4.25: IRFs to φ_t.

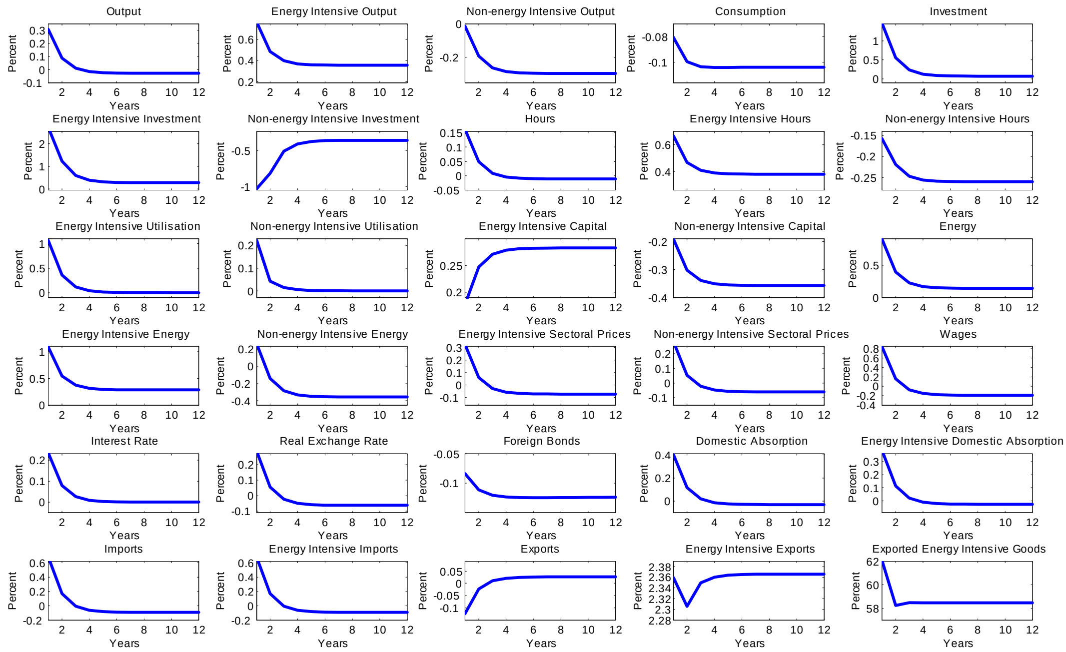


Figure 4.26: IRFs to φ_t^w.

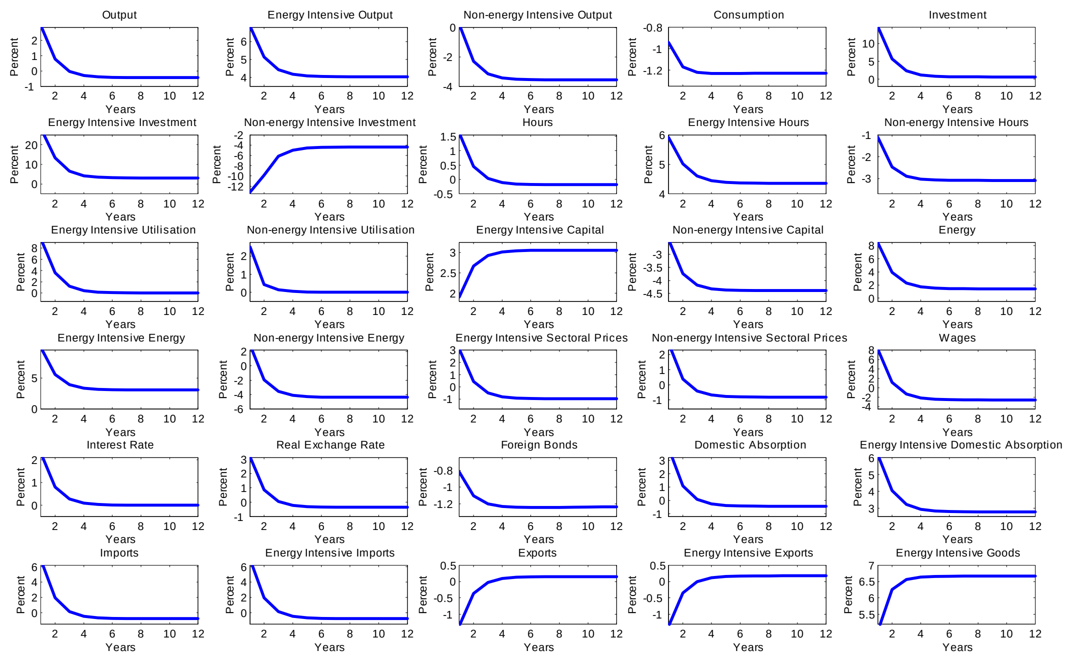


Figure 4.27: IRFs to γ_t.

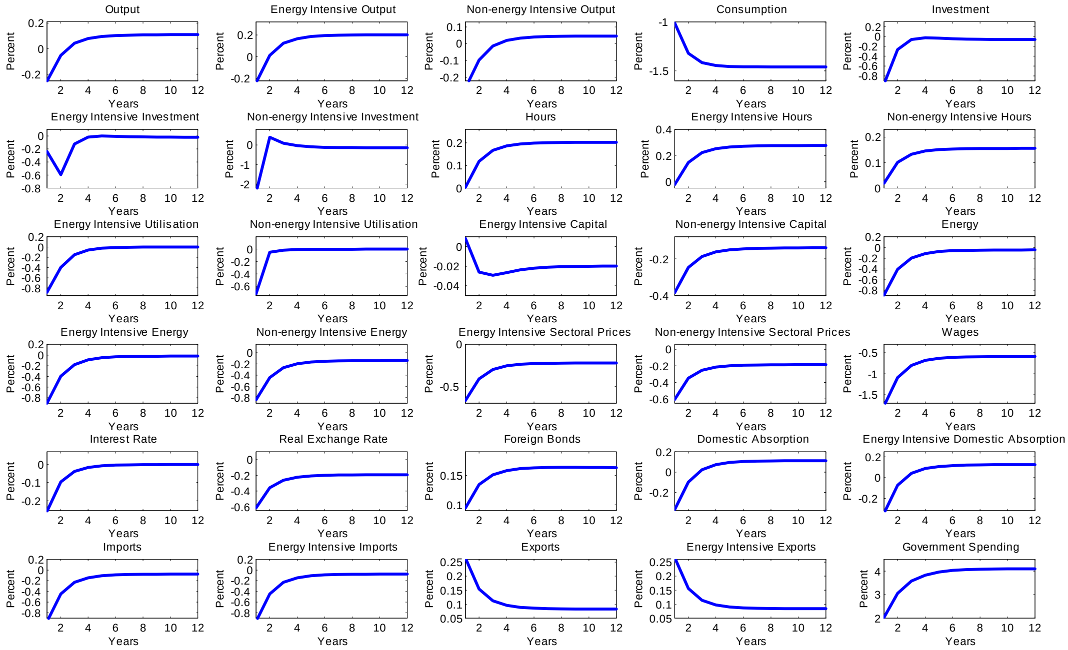


Figure 4.28: IRFs to g_t.

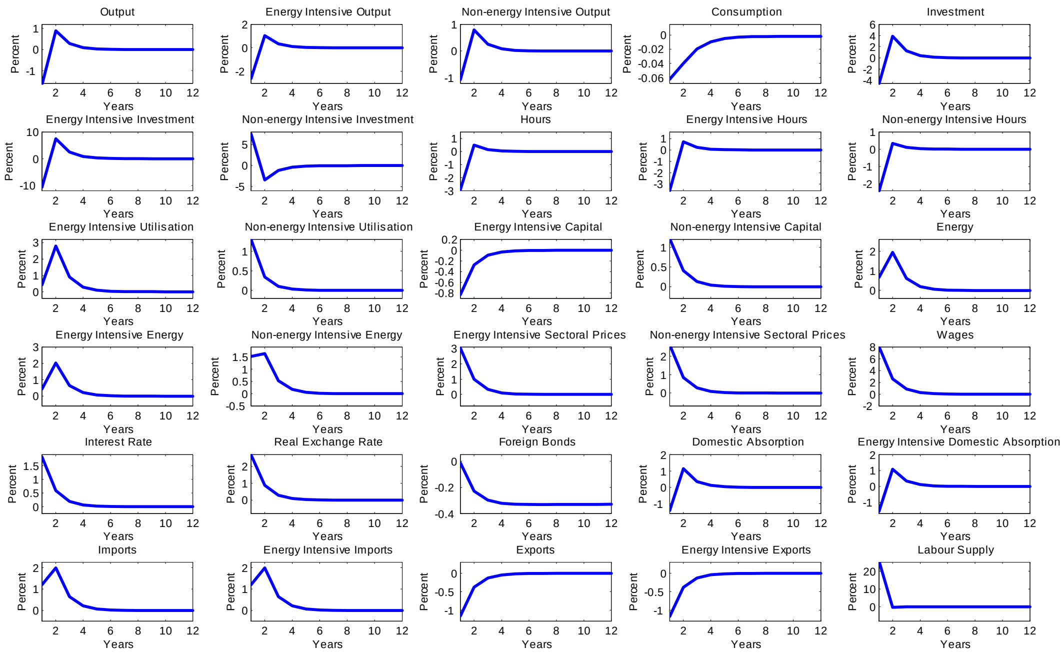


Figure 4.29: IRFs to ζ_t.

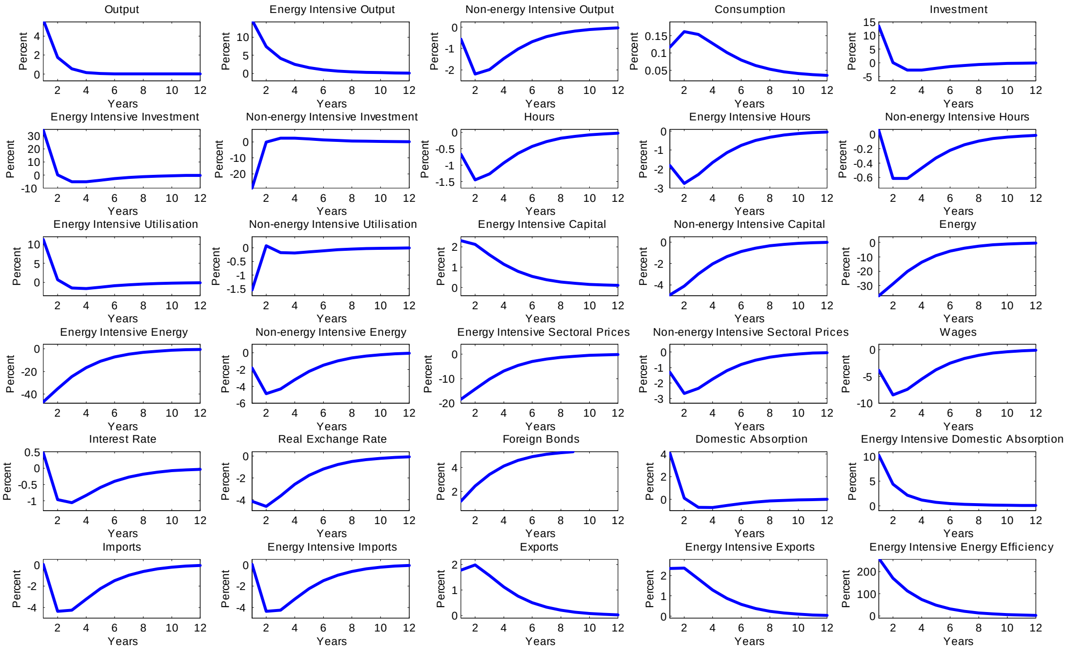


Figure 4.30: IRFs to o_t^e.

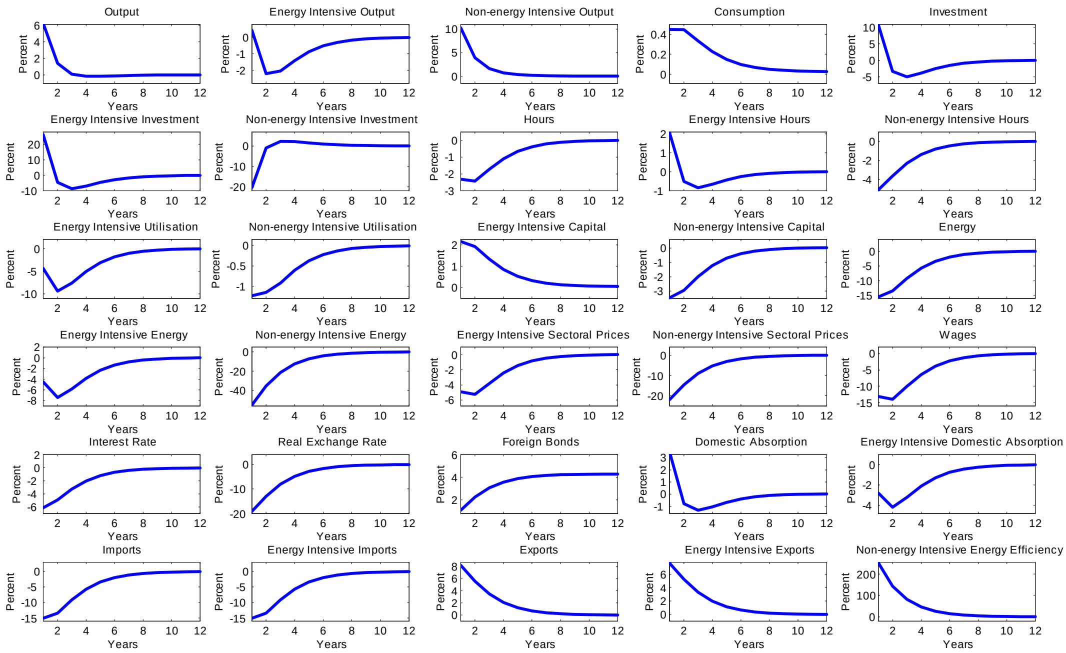


Figure 4.31: IRFs to o_t^n.

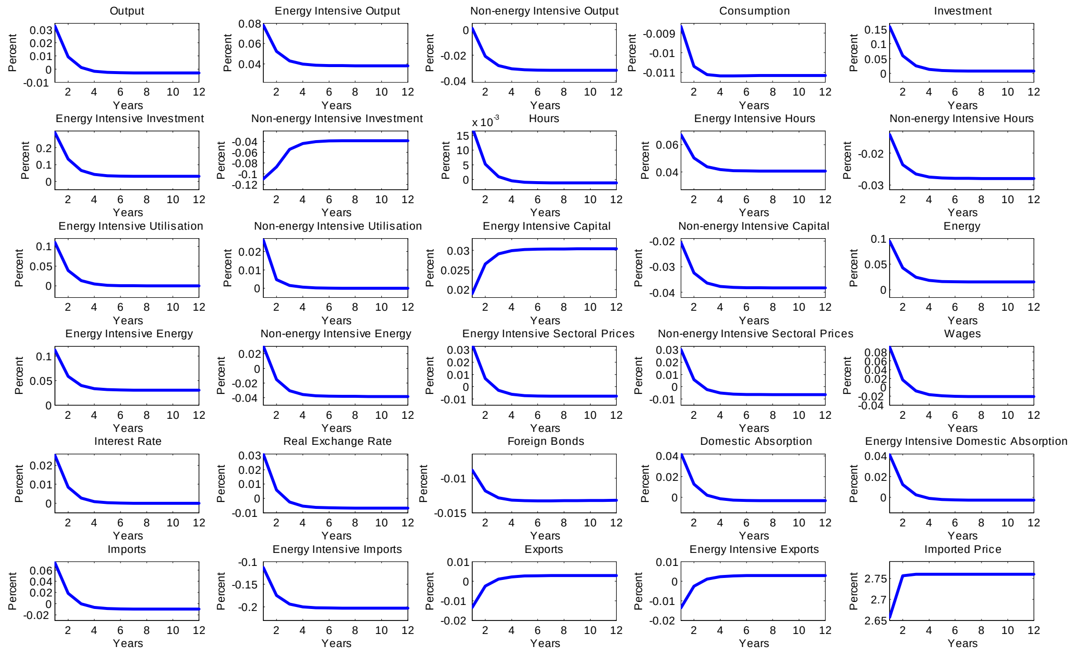


Figure 4.32: IRFs to $\mathsf{p}_{e,t}^{im}$.

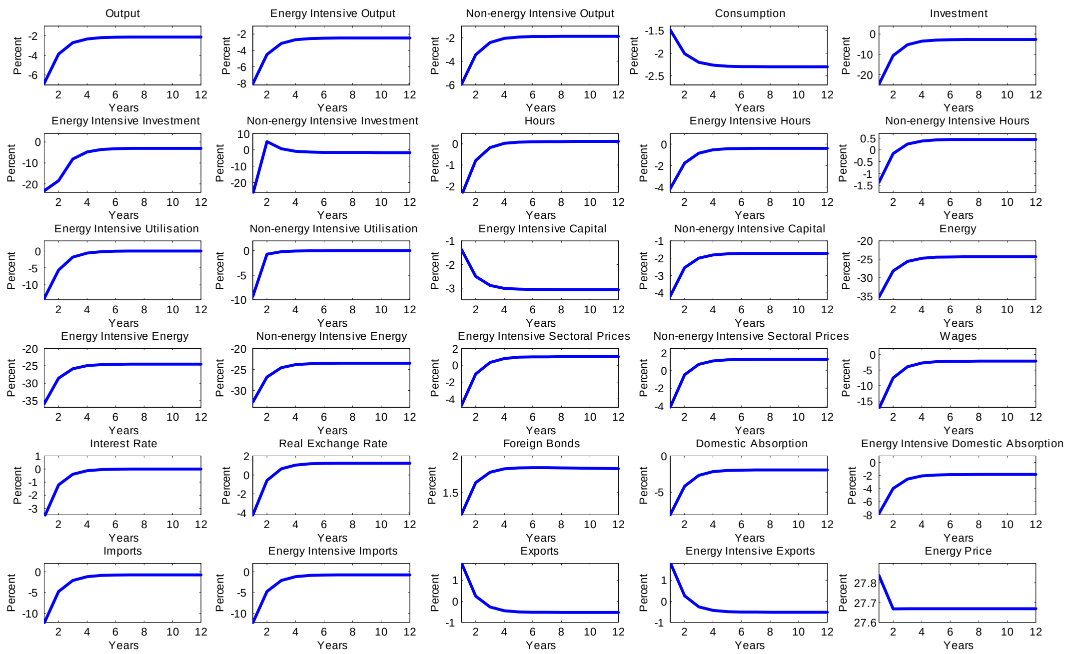


Figure 4.33: IRFs to q_t.

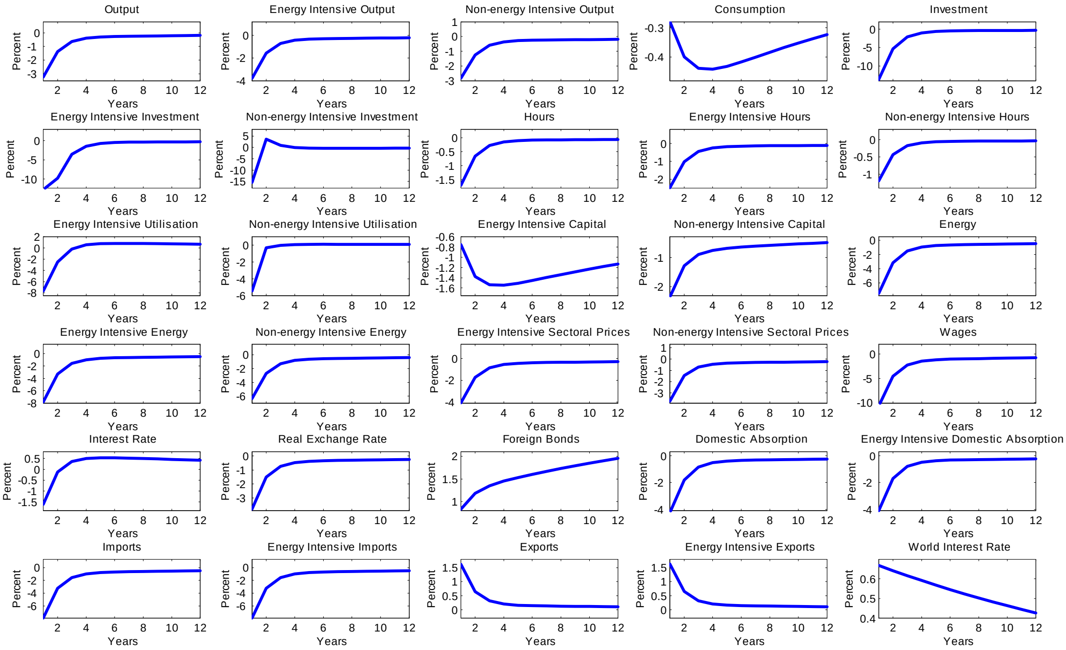


Figure 4.34: IRFs to r_t^f.

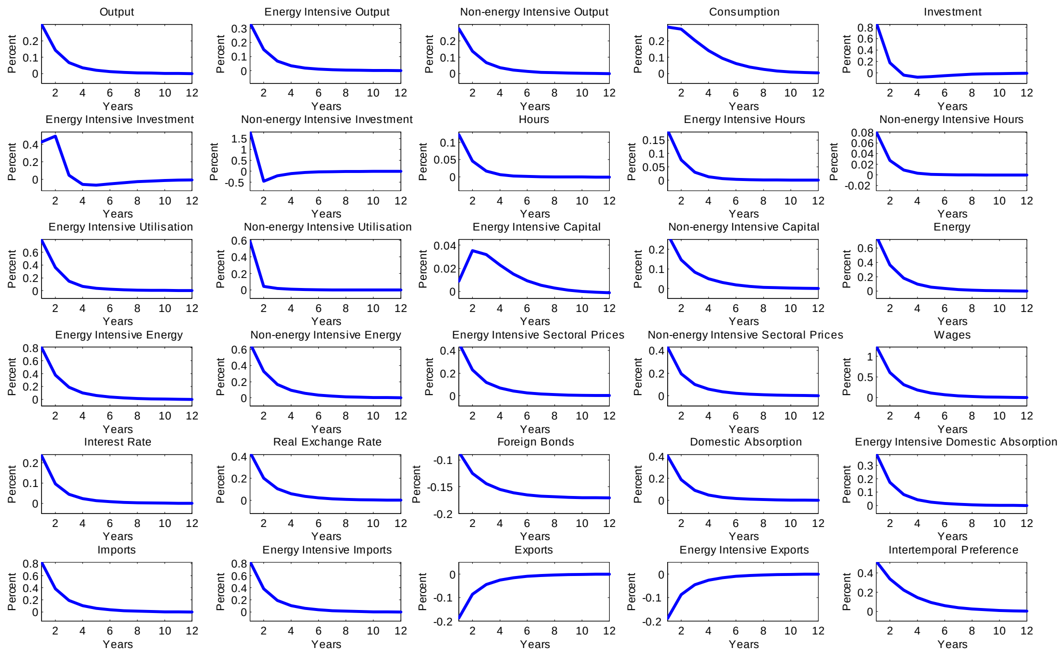


Figure 4.35: IRFs to τ_t.

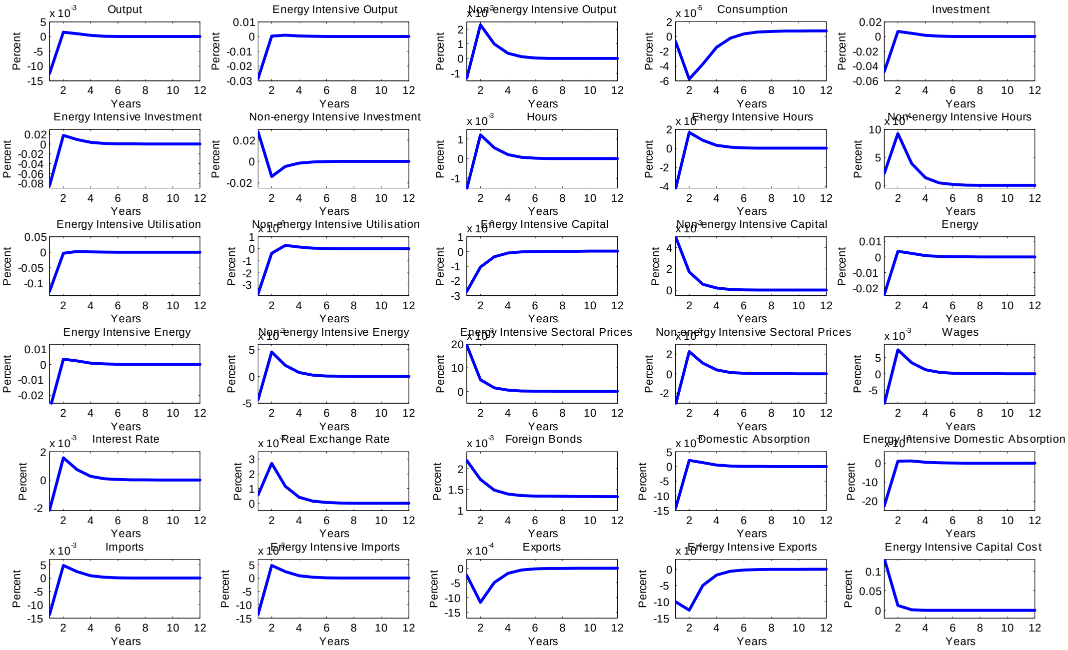


Figure 4.36: IRFs to ϑ_t^e.

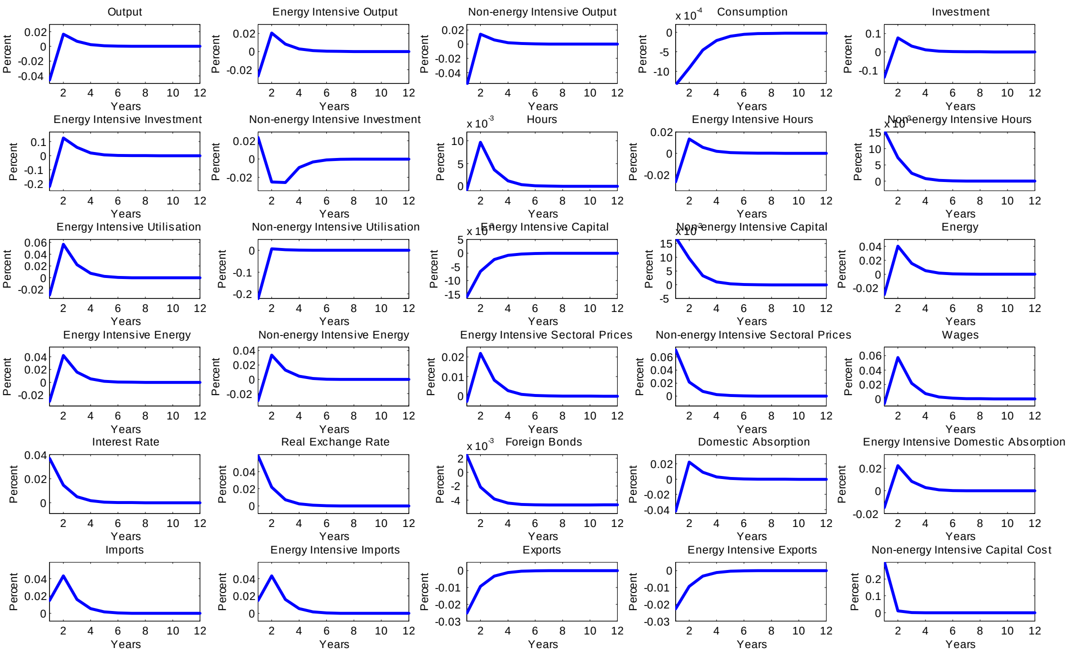


Figure 4.37: IRFs to ϑ_t^n.

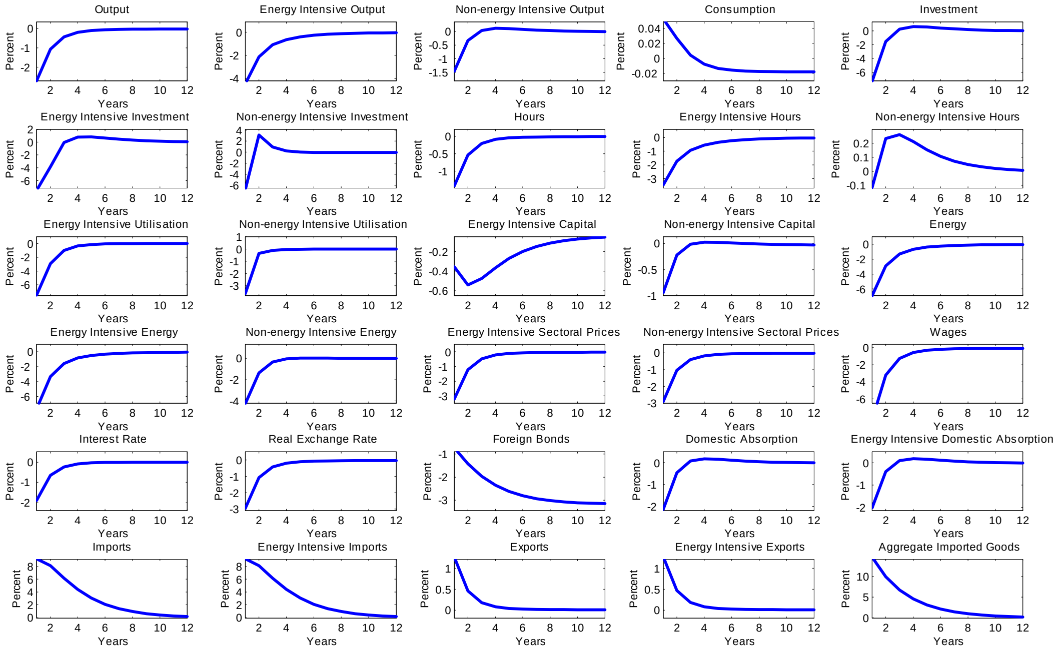


Figure 4.38: IRFs to ϖ_t.

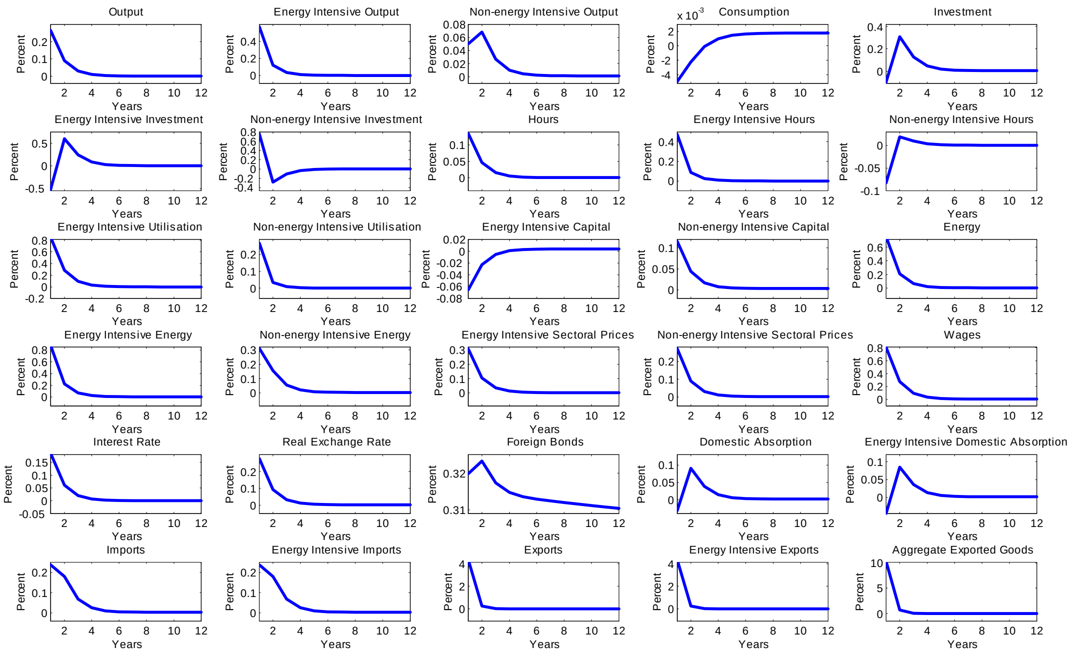


Figure 4.39: IRFs to ϖ_t^w.

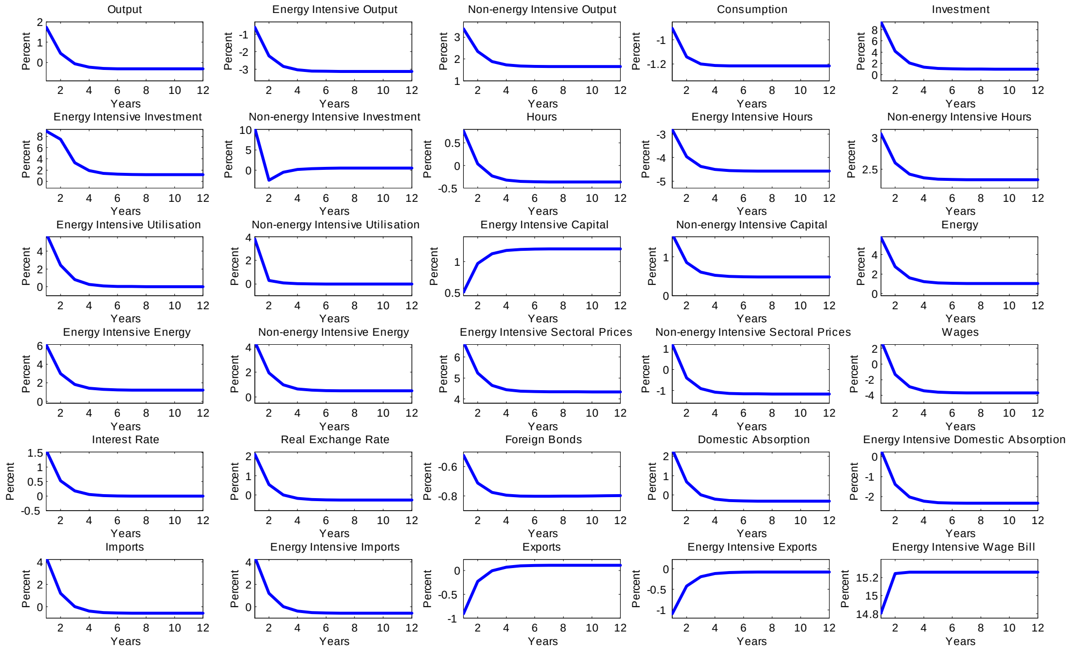


Figure 4.40: IRFs to ξ_t^e.

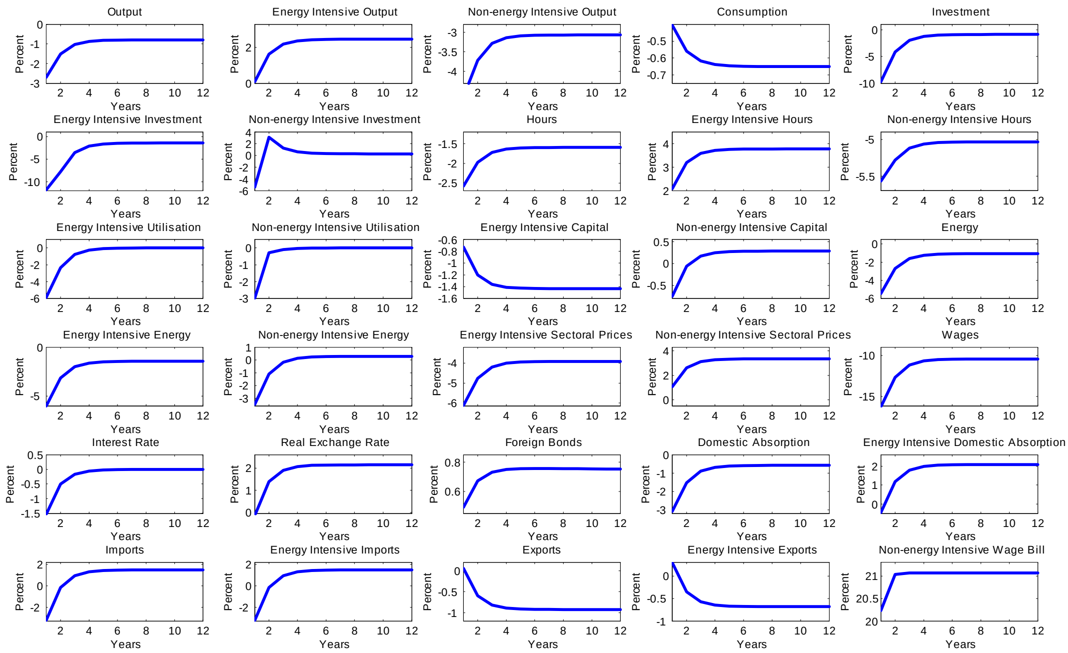


Figure 4.41: IRFs to ξ_t^n.

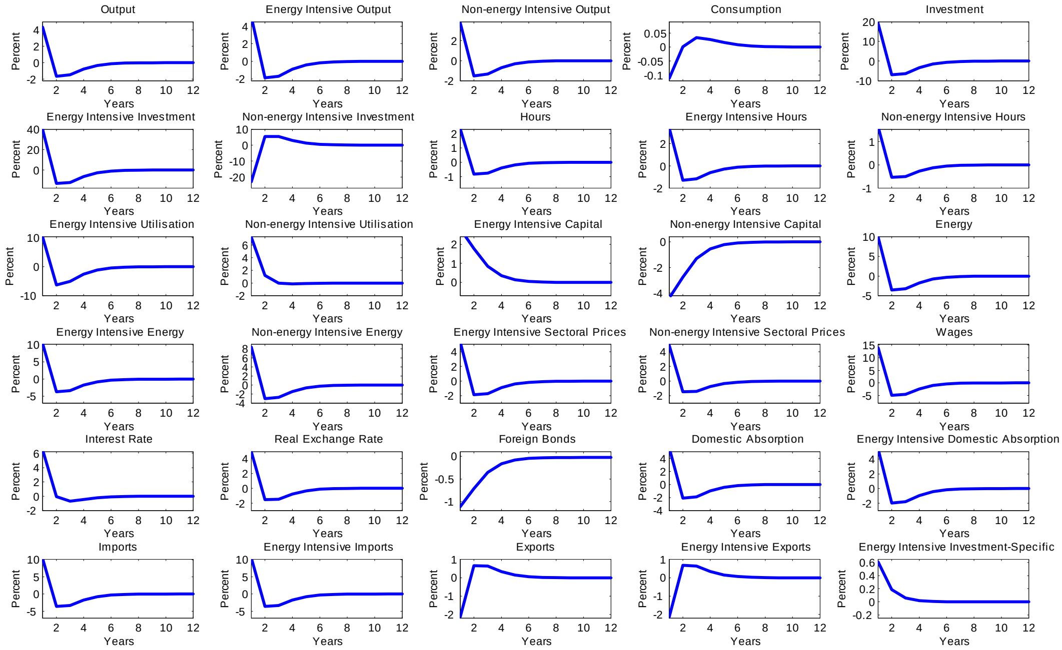


Figure 4.42: IRFs to z_t^e.

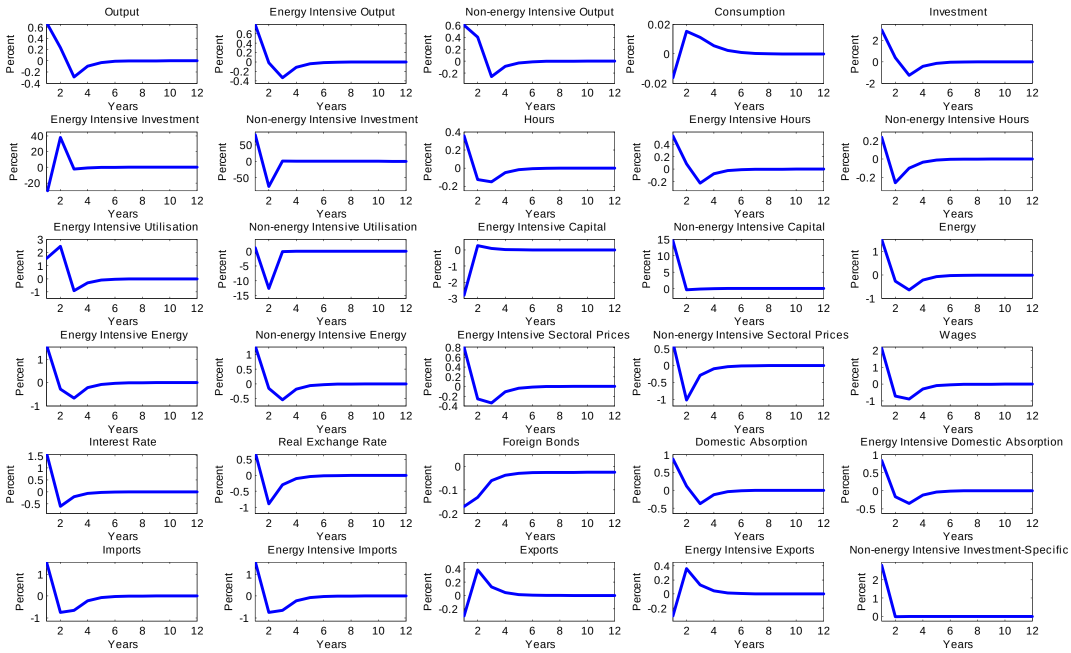


Figure 4.43: IRFs to z_t^n.

Chapter 5

Summary and Concluding Remarks

> Problems of exhaustible assets are peculiarly liable to become entangled with the infinite. Not only is there infinite time to consider, but also the possibility that for a necessity the price might increase without limit as the supply vanishes. If we are not to have property of infinite value, we must, in choosing empirical forms for cost and demand curves, take precautions to avoid assumptions, perfectly natural in static problems, which lead to such conditions.
> Harold Hotelling (1931, p. 139).

I provide a summary of the exercises carried out in this thesis and make some concluding comments on possible ways to extend the work in the future. Generally, I have reviewed some of the earlier contributions to the literature in the field of energy macroeconomics and extended the standard closed economy representative agent model of Kydland and Prescott (1982), Long and Plosser (1983) and Kim and Loungani (1992) to a novel open economy model in which trade is carried out in four goods and one commodity, namely: (1) domestic energy intensive goods; (2) domestic non-energy intensive goods; (3) foreign energy intensive goods; (4) foreign non-energy intensive goods; and (5) crude oil. Overall, I find that energy price shocks still matter both for aggregate and sectoral economic fluctuations. I argue that the focus should be more on the cross-effects of energy price movements on the changes in other factors of production such as labour and capital, and less on the balance of payments' effects once this shock hits the system.

Particularly, in Chapter 2, I comprehensively reviewed the extant literature on energy (price) and aggregate economic fluctuations, citing a number of important contributions and debates by many esteemed economists to this strand of economic research. In doing this, a few econometric and theoretical models were discussed. Building on the literature, I studied an open economy of the United States that is subjected to vagaries of decisions by its trading partners especially the oil bloc. The questions in mind were, "Can a model be organised to explain the behaviour of a multi-sector economy such as the U.S. given a supply-side shock such as an energy (price) shock? Further, given an array of supply- and demand-side shocks perturbing the economy per period, how important is the effect of energy (price) shock? How are these shocks transmitted through the economy? Which is more disturbing between the impact and the transition effects of an energy (price) shock?"

Thus beginning with Chapter 3, I turned my attention to designing a two-sector computable dynamic stochastic general equilibrium (CDSGE) open economy model of the U.S. that formally admit energy into the production process in a way that can generate plausible parameter values with which an applied study can deal with a broad range of economic issues. The model in this chapter falls in the lineage of Kydland and Prescott (1982), Long and Plosser (1983), and Kim and Loungani (1992) models in which I assume that (1) representative agents reside in a perfectly competitive economy making decisions regarding consumption, labour, investment, and output; (2) representative agents in the domestic country trade with their foreign counterparts; (3) imported crude oil is essential for production; and also (4) production takes place in two sectors and four types of goods are available for consumption and investment purposes. Twelve shocks, domestic and imported, were added to the model and I required as a benchmark that the model fits the data for output, real exchange rate, energy use, and consumption: output because it serves as a measure of a country's total income; real exchange rate because it serves as a determinant of a country's relative competitiveness; energy use because it serves as an indicator of special inputs into a country's production process; and consumption because it serves as a yardstick for evaluating a country's welfare.

Furthermore, in Chapter 4, I examine the role of energy price shocks in effecting changes both at the aggregate and sectorial levels further by extending the model of Chapter 3 to include capital account, added more domestic and imported shocks and frictions before re-estimating the model on non-stationary data sets using the method of indirect inference. The focus of the explanation in this chapter was output and the real exchange rate. I showed that the main channels through which imported oil 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. I have shown qualitatively that output is affected both intratemporally through what I termed the *impact effect* and intertemporally through what I labelled the *transition effect*. In addition, a quantitative assessment of the results in the estimated model model was presented. A main contribution is that I was able to use a micro-founded multi-sector DSGE model to find results that support some already established facts in relation to the size of the effects of oil price shock on macroeconomic variables like output and the real exchange rate.

Next, I speculate on a few possible extensions to the model that could yet prove fruitful in a future research endeavour. First, a useful extension for model implications regarding energy policies and welfare evaluation would be to consider an economy with money (M/P) and energy use (E^h) by household,[1] which can be achieved by increasing the arguments in the utility function 4.1

$$\mathbb{E}\sum\nolimits_0^\infty \beta\tau U\left(C-\iota C_{-1},\zeta H,\mathsf{j}E^h,\mathsf{v}\frac{M}{P}\right) \tag{5.1}$$

where j and v are optional exogenous disturbances to energy use and real money balances, respectively. Then, depending on if we are interested in considering the extent of price flexibility in the economy, quadratic adjustment costs for nominal wage and price rigidities can be specified [see, for example, Hairault and Portier (1993) and Kim (2000)]. Moreover, explicit modelling of the four goods may be important. I do think that the most rele-

[1] As an example, see Dhawan and Jeske (2008) and Blanchard and Gali (2010) who modelled energy use by household providing stylised facts on the share of household energy use in total GDP in the vicinity of that reported for the firms.

vant contribution for this approach may be pursued by allowing traded goods to not only be used for consumption/ investment purposes, but to be translated into the production process as not all exchanged goods are completely finished goods [see, for example, Goldberg and Campa (2010), Bergholt and Sveen (2014), and Eyquem and Kamber (2014)].[2] This particular extension may have the following added advantages: (1) Beyond incorporating the level of energy intensity, this should help to admit the different levels of trade intensities of the two sectors; and (2) We may also be able to examine the terms of trade for goods of both sectors with the addition of extra cost channels via trade in intermediate goods - this would be an extension to many open economy models that only analyse aggregate terms of trade [see for example Backus et al. (1995), Mendoza (1995), and Backus and Crucini (2000)]. Meanwhile, an extra dimension can be introduced if we are content to assume that government spending is productive as in Finn (1998). Lastly, there are two features of the model that have also been shut down to make the experiment less complicated. The first is the non-inclusion of the non-traded sector, which Bruno (1976) refers to as an "unimportant appendage" perhaps included for completeness. It has however been studied as an important sector of the economy since [see, for example, Tesar (1989), Stockman (1990), Stockman and Tesar (1995)]. In fact, Stockman (1990) wrote that "Both theory and evidence on open economies suggest the inclusion of non-traded goods and multiple traded goods", which in that sense could further improve the model presented in this thesis.

Finally, the story of this thesis is that we cannot continue to relegate interests in the study of commodities in particular those that enter into the production process at one stage or form to only when a shock occurs. There should indeed be a concerted and maintained curiosity in the research of energy resources and this is not just in economics, but a call to all disciplines that have been brought together by this *matter*. I belief that this is the only way by which we will solve the *energy question*.

[2] A simplifying assumption in the model presented in Chapters 3 and 4 is that imported/ exported goods can directly be consumed or invested on arrival without any need for added value. This is rarely the case.

Appendix A

Data Sources

Below is a detailed list and sources of the raw/ borrowed data that are made use of in constructing the data series serving as the empirical counterparts to the model macroeconomic variables in the main text.

A.1 Chapter 2

Bureau of Economic Analysis (www.bea.gov), 1949-2013

National Data, GDP and Personal Income

1. Table 1.1.5: Gross Domestic Product, billions of dollars, seasonally adjusted at annual rate, extracted: 27 January, 2015.
2. Table 1.1.9: Implicit Price Deflators for Gross Domestic Product, 2009=100, seasonally adjusted at annual rate, extracted: 27 January, 2015.
3. Table 2.4.5: Personal Consumption Expenditures by Type of Product, billions of dollars, seasonally adjusted at annual rate, extracted: 30 January, 2015.
4. Table 3.9.5: Government Consumption Expenditures and Gross Investment, billions of dollars, seasonally adjusted at annual rate, extracted: 30 January, 2015.
5. Tables 6.4B-6.4D: Full-Time and Part-Time Employees, extracted: 31 January, 2015.

6. Tables 6.5B-6.5D: Full-Time Equivalent Employees by Industry, extracted: 31 January, 2015.
7. Tables 6.7B-6.7D: Self-Employed Persons by Industry, extracted: 31 January, 2015.
8. Tables 6.8B-6.8D: Persons Engaged in Production by Industry, extracted: 31 January, 2015.
9. Tables 6.9B-6.9D: Hours Worked by Full-Time and Part-Time Employees by Industry, extracted: 31 January, 2015.

National Data, Fixed Assets

1. Table 1.1: Current-Cost Net Stock of Fixed Assets and Consumer Durable Goods, billions of dollars, seasonally adjusted at annual rate, extracted: 25 February, 2015.
2. Table 2.1: Current-Cost Net Stock of Private Fixed Assets, Equipment, Structures, and Intellectual Property Products by Type, billions of dollars, seasonally adjusted at annual rate, extracted: 30 January, 2015.
3. Table 2.7: Investment in Private Fixed Assets, Equipment, Structures, and Intellectual Property Products by Type, billions of dollars, seasonally adjusted at annual rate, extracted: 30 January, 2015.
4. Tables 7.1A-7.1B: Current-Cost Net Stock of Government Fixed Assets, billions of dollars, seasonally adjusted at annual rate, extracted: 30 January, 2015.
5. Tables 7.5A-7.5B: Investment in Government Fixed Assets, billions of dollars, seasonally adjusted at annual rate, extracted: 30 January, 2015.
6. Table 8.1: Current-Cost Net Stock of Consumer Durable Goods, billions of dollars, seasonally adjusted at annual rate, extracted: 30 January, 2015.

Industry Data, GDP-by-Industry and Output-Input

1. Full-Time and Part-Time Employees by Industry.[1]

[1] The values for 1949 -1997 were downloaded from www.bea.gov/industry/gdpbyind_data.htm while the rest of the series (1998 - 2011) were obtained from the usual interactive section of the BEA's GDP-by-Industry. To construct the values for 2012-2013, we calculate the growth rate of the series between 1998 and 2011 using the expression $g = \exp[\frac{1}{14} \times \ln(\frac{obs_{1998}}{obs_{2011}})] - 1$ and this is then used to project the values for 2012 and 2013. All tables are extracted on 31 January, 2015 except the BEA's GDP-by-Industry series, which was downloaded in January, 2013. Currently, employment data are no longer available at the BEA's GDP-by-Industry section.

2. GDP by Industry, Value Added, millions of current dollars, extracted: 13 May, 2015.

Bureau of Labour Statistics (www.bls.gov), 1949-2013

1. Series ID: LNU00000000, Civilian Non-institutional Population between 16 and 64 Years Old, extracted: 27 January, 2015.[2]
2. Series ID: CUUR0000SA0, Consumer Price Index for All Urban Consumers: All Items, Index 1982-84=100, seasonally adjusted, extracted: 29 January, 2015.[3]

Federal Reserve Bank of St. Louis (www.stlouisfed.org), 1949-2013

1. Series ID: PRS85006063, Nonfarm Business Sector: Compensation, Index 2009=100, seasonally adjusted, extracted: 30 January, 2015.
2. Series ID: TFAABSHNO, Households and Non-profit Organizations; Total Financial Assets, Level, Billions of Dollars, extracted: 13 May, 2015.
3. Series ID: TLBSHNO, Households and Non-profit Organizations; Total Liabilities, Level, Billions of Dollars, extracted: 13 May, 2015.

Board of Governors of the Federal Reserve System (www.federalreserve.gov), 1949-2013

1. Series ID: G17/CAPUTL/CAPUTL.B00004.A, Manufacturing (SIC), n.s.a, per cent of capacity in G17: Industrial Production and Capacity Utilization, G.17 Release, extracted: 30 January, 2015.
2. Series ID: G17/CAPUTL/CAPUTL.G3361T3.A, Motor Vehicles and Parts (NAICS), n.s.a, per cent of capacity in G17: Industrial Production and Capacity Utilization, G.17 Release, extracted: 30 January, 2015.
3. Series ID: H15/H15/RIFSPFF_N.A, Federal Funds Effective Rate, 1955-2013, H15 Release, extracted: 30 January, 2015.

[2] We transformed the population data above into an index with 2009 value set to 100 following the approach of Smets and Wouters (2007).

[3] Before use, the base year for the CPI index is transformed to 2009=100 from 1982-84=100.

Energy Information Administration (www.eia.gov), 1949-2013

1. Table 2.1: Energy Consumption by Sector, January, 2015 Monthly Energy Review, extracted: 30 January, 2015.
2. Table 9.1: Crude Oil Price Summary, December 2014 Monthly Energy Review, extracted: 30 January, 2015.

Smets and Wouters (2007)

1. 3-month treasury bill rates, 1949-1954.[4]

A.2 Chapter 3

As in Chapter 2 plus the following additional sources

United Nations

1. Total (world) population, both sexes combined, as of 1 July (thousands), 1950-2010.

World Bank

1. World population, World Development Indicators, World Bank Data, 1960-2013.[5]

International Monetary Fund

1. World Trade, Value in Millions of U.S. Dollars, International Financial Statistics, 1949-2013.
2. Prices of Major World Trade Commodities in U.S. Dollars, International Financial Statistics, 1949-2013.

[4] I convert their quarterly data into annual data by averaging.

[5] The population data for 1950-1959 are taken from the United Nations; we calculated the growth rate for these 10 years and use it to obtain the data for 1949, while we use the population data from World Development Indicators for 1960-2013. The series used to normalise the RoW variables is the above less the U.S. population.

3. Interest rates for Canada, France, Germany, Italy, Japan, and the U.K., International Financial Statistics, 1949-2013.

Appendix B

Supplementary Notes: Chapter 3

B.1 Data Construction

Output

Model variables: Y, Y_e, Y_n.

Data: Aggregate output, Y, is measured as the sum of the two sectoral outputs, Y_e+Y_n. That is, the sum of gross outputs of the energy and non-energy intensive sectors. However, due to a lack of data on gross output by industry dating back to 1949, which is the general starting year of the variables, I instead construct the two sectoral gross domestic products from the value added by industry data (Taken from GDP by Industry). More specifically, aggregate output is defined as the total value added of all industries. Consequently, energy intensive sector output, Y_n, is defined as the sum of value added from agriculture (including forestry, fishing, and hunting), mining, utilities, construction, manufacturing, and transportation (and warehousing due to lack of further disaggregation) - sum of excel worksheet lines 5, 8, 12, 13, 14, and 38; the non-energy intensive sector output, Y_n, is defined as the sum of value added from wholesale and retail trade, information, finance (including insurance, real estate, rental, and leasing), professional and business services, educational services (including health care, and social assistance), arts (including entertainment accommodation, and food services), and other services except government - sum of excel worksheet lines 36, 37, 47, 52, 61, 70, 76, and 83. Lastly, due to lack of sufficient disaggregation of government output, I split the output of the public sector into two and added half each to Y_e and Y_n.

Consumption

Model variable: C.

Data: This is defined as personal consumption expenditures less durable goods (Taken from Table 1.1.5. Gross Domestic Product).

Investment

Model variables: I_t, I_e, I_n.

Data: The measure of gross investment is taken to be the sum of personal consumption expenditure on durable goods, and private nonresidential (structures and equipment) and residential fixed investments. This was applied to the definition the two types of investment variables noting that aggregate investment is given as $I = I_e + I_n$. For investment series, I combine Table 2.7: Investment in Private Fixed Assets, Equipment, Structures, and Intellectual Property Products by Type and the series for consumer durables from Table 2.4.5: Personal Consumption Expenditures by Type of Product, lines 3-24. Beginning with the consumption of durable goods in Table 2.4.5, the following are assigned investments that are non-energy intensive denoted by I_n^{dg}: furnishings and durable household equipment, recreational goods and vehicles, and other durable goods (sum of lines 8, 13, and 19) such that investment in the energy intensive type consumption durable goods is given by I_e^{dg} =Durable goods$-I_n^{dg}$ (that is, line 3 minus the sum of lines 8, 13, and 19). Further, assignment of Table 2.7 into investment by type is as follows. Investment in the energy intensive goods are deemed to be given by the sum of equipment and structures less residential equipment and improvements (sum of lines 2 and 35 minus the sum of lines 34 and 74). Thus, investment in the non-energy intensive type goods is the sum of residential equipment, improvements, and intellectual property products (sum of lines 34, 74, and 76).

Capital

Model variables: K_e, K_n.

Data: Following the constructions of energy and non-energy intensive investments above, I build the series for capital using Table 8.1. Current-Cost Net Stock of Consumer Durable Goods and Table 2.1. Current-Cost Net Stock of Private Fixed Assets, Equipment, Structures, and Intellectual Property Products by Type. I have not modelled aggregate capital in Chapter 3, and therefore have no need to construct an empirical counterpart for it. I construct capital stock of the energy intensive goods as the sum of nonresidential equipment and structures (that is, sum of lines 2 and 35 minus 34) and capital stock of the non-energy intensive goods is calculated as the sum of residential equipment and structures, and intellectual property products (that is, line 34). As in the investment series above, non-energy intensive type capital stocks is taken as the sum of furnishings and durable household equipment, recreational goods and vehicles, and other durable goods (sum of lines 6, 11, and 17) such that capital stock in the energy intensive type consumption durable goods is given by motor vehicles and parts (that is, line 2).

Labour hours

Model variables: H, H_e, H_n.

Data: Aggregate labour hours, H, is defined as hours of all persons engaged in production and hours worked per sector, H_e and H_n, are calculated by following the procedure of Herrendorf et al. (2013). Their procedure involves combining BEA's GDP-by-Industry data reported using NAICS classification with BEA's Income-and-Employment-by-Industry data reported with three different classifications over the sample period (SIC72 for pre-1987, SIC87 between 1987-2000, and NAICS since 2001). This is necessary because while the former data source follows the classification I would prefer, they indicate that the latter provides us with the kind of detailed industry level information I require for assignment into the two sectors. Hence, for assignment into the two sectors, I follow in similar veins as closely as feasibly permitted by the level of data disaggregation the definitions of other sectoral variables as shown already above. Specifically, for each of the series, employment and hours in agriculture, mining, utilities, construction, manufacturing and transportation are classed as related to the energy intensive sector, while employment and hours in wholesale, retail trade, information, finance, professional services, education, arts, and other services are non-energy intensive. Formally, the sectoral labour hours are obtained using $h^j = NAICS$ hours of full-time equivalent employees + $NAICS$ hours of full-time equivalent employees $\div$ $NAICS$ full-time employees $\times$ $NAICS$ self-employed, where $NAICS$ self-employed $= SIC$ self-employed $\times$ $NAICS$ full-time and part-time employees $\div$ SIC full- and part-time employees, $NAICS$ full-time equivalent employees $=$ SIC full-time equivalent employees $\times$ $NAICS$ full-time and part-time employees $\div$ SIC full-time and part-time employees, and $NAICS$ hours of full-time equivalent employees $= SIC$ hours of full-time equivalent employees $\times$ $NAICS$ full-time equivalent employees $\div$ SIC full-time equivalent employees.

Capital utilisation rate

Model variables: U_e, U_n.

Data: Following the assignment of industries into the two sectors, I deem it fit to have two definitions of capital utilisation rate. Thus, capacity utilisation rate for total manufacturing industry and capacity utilisation rate for motor vehicles and parts are used as proxies for the measures of capital utilisation rates in the energy and non-energy intensive sectors, respectively.

Energy use

Model variables: E, E_e, E_n.

Data: For total energy consumption in the economy, E, I take this to be the aggregate consumption of primary energy or the consumption of fossil fuels comprising of petroleum, coal, and natural gas measured in trillion British thermal units (BTUs) of the private sector excluding the electric power sector.[1] Energy consumption are provided for

[1] I do not 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, I excluded the electric power generating sector, which would have been classed as 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. I have however not included it for one I have not modelled an energy producing sector, which would be the

four end-use sectors namely industrial, transportation, residential and commercial sectors. Given a lack of further disaggregation, I use the primary energy consumption in both the industrial and transportation sectors to proxy energy use in the energy intensive sector, and primary energy consumption in both the residential and commercial sectors to proxy energy use in the non-energy intensive sector. Hence, aggregate energy consumption in this economy is formally given by $E = E_e + E_n$ = dollar value of total primary energy use $= q_t \frac{(E_t \times 1 \ trillion/\varkappa \times 1 \ million)}{1 \ billion}$, where $\varkappa = 5.78$ is the conversion factor assumed for relating BTUs to barrels of oil, which is similar to the figure employed by the industry.

Domestic absorption

Model variable: D.

Data: By theoretical construction, $D = Y$, so that I use the same data for aggregate output for domestic absorption.

Domestic demand of energy intensive goods

Model variable: D_e.

Data: This is constructed as D_e = private consumption of energy intensive goods (Taken from Table 2.4.5: Personal Consumption Expenditures by Type of Product) + private investment in energy intensive goods (Taken from Table 2.4.5: Personal Consumption Expenditures by Type of Product and Table 2.7: Investment in Private Fixed Assets, Equipment, Structures, and Intellectual Property Products by Type) + government consumption of energy intensive goods (Taken from Table 3.9.5: Government Consumption Expenditures and Gross Investment) + government investment in energy intensive goods (Taken from Tables 7.5A-7.5B: Investment in Government Fixed Assets). Note that given a lack of disaggregated data on government consumption expenditure, I therefore assume that the share of government consumption in energy intensive goods is the same as for government investment in energy intensive goods, and apply this share to the consumption data.

case if I incorporate electricity into our total for energy consumption.

Aggregate import

Model variable: IM.

Data: This is taken to be the aggregate import (Taken from Table 1.1.5. Gross Domestic Product).

Import of energy intensive goods

Model variable: IM_e.

Data: This is taken to be the import of goods (Taken from Table 1.1.5. Gross Domestic Product).

Aggregate export

Model variable: EX.

Data: This is taken to be the aggregate export (Taken from Table 1.1.5. Gross Domestic Product).

Export of energy intensive goods

Model variable: EX_e.

Data: This is taken to be the export of goods (Taken from Table 1.1.5. Gross Domestic Product).

Wage rate

Model variable: W.

Data: This is a real index of hourly compensation (Series ID: PRS85006063, Nonfarm Business Sector: Compensation).

Interest rate

Model variable: R.

Data: This is the three-month Treasury bill rate for 1949-1954 (Taken from Smets and Wouters, 2007) where I have converted their quarterly data into annual data by averaging; I use the federal funds rate for 1955-2013.

Real exchange rate

Model variable: P.

Data: General price level in the domestic country, which is taken to be the consumer price index (CPI) for all urban consumers, relative to world CPI.

Price of energy intensive goods

Model variable: P_e.

Data: Calculated as the weighted average of the chain-type price indexes for value added from agriculture, mining, utilities, construction, manufacturing, and transportation (Taken from GDP by Industry).

Price of non-energy intensive goods

Model variable: P_n.

Data: Calculated as the weighted average of the chain-type price indexes for value added from wholesale and retail trade, information, finance, professional and business services, educational services, arts, and other services (Taken from GDP by Industry).

In summary, the final transformed observable variables are put in a vector as

$$
\begin{bmatrix}
\widehat{Y} \\ \widehat{Y}_e \\ \widehat{Y}_n \\ \widehat{C} \\ \widehat{I} \\ \widehat{I}_e \\ \widehat{I}_n \\ \widehat{K}_e \\ \widehat{K}_n \\ \widehat{H} \\ \widehat{H}_e \\ \widehat{H}_n \\ \widehat{U}_e \\ \widehat{U}_n \\ \widehat{E} \\ \widehat{E}_e \\ \widehat{E}_n \\ \widehat{D} \\ \widehat{D}_e \\ \widehat{IM} \\ \widehat{IM}_e \\ \widehat{EX} \\ \widehat{EX}_e \\ \widehat{W} \\ \widehat{R} \\ \widehat{P} \\ \widehat{P}_e \\ \widehat{P}_n
\end{bmatrix}
=
\begin{bmatrix}
\text{HP-FILTER}[\ln\left(\left(\left(Y_e+Y_n\right)/CPI\right)/POP\right)] \\
\text{HP-FILTER}[\ln\left(\left(Y_e/CPI\right)/POP\right)] \\
\text{HP-FILTER}[\ln\left(\left(Y_n/CPI\right)/POP\right)] \\
\text{HP-FILTER}[\ln\left(\left(C/CPI\right)/POP\right)] \\
\text{HP-FILTER}[\ln\left(\left(\left(I_e+I_n\right)/CPI\right)/POP\right)] \\
\text{HP-FILTER}[\ln\left(\left(I_e/CPI\right)/POP\right)] \\
\text{HP-FILTER}[\ln\left(\left(I_n/CPI\right)/POP\right)] \\
\text{HP-FILTER}[\ln\left(\left(K_e/CPI\right)/POP\right)] \\
\text{HP-FILTER}[\ln\left(\left(K_n/CPI\right)/POP\right)] \\
\text{HP-FILTER}[\ln\left(H_e+H_n/POP\right)] \\
\text{HP-FILTER}[\ln\left(H_e/POP\right)] \\
\text{HP-FILTER}[\ln\left(H_n/POP\right)] \\
\text{HP-FILTER}[\ln U_e] \\
\text{HP-FILTER}[\ln U_n] \\
\text{HP-FILTER}[\ln\left(\left(\left(E_e+E_n\right)/CPI\right)/POP\right)] \\
\text{HP-FILTER}[\ln\left(\left(E_e/CPI\right)/POP\right)] \\
\text{HP-FILTER}[\ln\left(\left(E_n/CPI\right)/POP\right)] \\
\widehat{Y} \\
\text{HP-FILTER}[\ln\left(\left(D_e/CPI\right)/POP\right)] \\
\text{HP-FILTER}[\ln\left(\left(IM/CPI\right)/POP\right)] \\
\text{HP-FILTER}[\ln\left(\left(IM_e/CPI\right)/POP\right)] \\
\text{HP-FILTER}[\ln\left(\left(EX/CPI\right)/POP\right)] \\
\text{HP-FILTER}[\ln\left(\left(EX_e/CPI\right)/POP\right)] \\
\text{HP-FILTER}[\ln\left(W\right)] \\
\text{HP-FILTER}[R] \\
\text{HP-FILTER}[\ln\left(P\right)] \\
\text{HP-FILTER}[\ln\left(P_e\right)] \\
\text{HP-FILTER}[\ln\left(P_n\right)]
\end{bmatrix}
\tag{B.1}
$$

where the Hodrick-Prescott smoothing parameter has been set to 400, CPI is consumer price index, and POP is population index.

B.2 Technical Appendix

This section of the note provides details of the model set up and derivations of the equilibrium conditions that appear in the main text. This is a two-sector two-region open economy real business cycle (RBC) model where the sectors are the energy and non-energy intensive sectors, and the regions are the domestic country and the rest of the world (RoW). An essential feature of the model is that I recognise that all aspects of the economy must be 'powered'. I, however, only included energy in the production sides. I assume that the consumer price index (CPI) in the RoW, P^{im}, is the numeraire and I defined all domestic prices relative to this. Hence, domestic country's CPI, P, is a measure of the real exchange rate. Other important prices are the consumer real wage, W, producer real wage in the energy intensive sector, W/P_e, and producer real wage in the non-energy intensive sector, W/P_n, where P_e and P_n correspond, respectively, to the relative prices of energy and non-energy intensive goods.

I use the following notations for convenience: UPPER-CASE letters $X' \equiv X_{t+1}$, $X \equiv X_t$, and $X_{-1} \equiv X_{t-1}$ for dynamic variables for next, current, and lagged periods, respectively; lower-case letters, say x, to denote non-stochastic steady state variables; hatted letters, "$\hat{}$", to denote variables in their log-linear form; and ζ, τ_t, and $\mathsf{sans\ serif}$ letters denote the exogenous state variables. I characterise the model in terms of the domestic country.

Households Their dynamic problem can be formalised as that of

$$\max_{\{C,H,I,I_e,I_n,B',U_e,U_n,K_e,K_n\}_{t=0}^{\infty}} \underbrace{\left[\sum_{0}^{\infty} \beta\tau \left(\frac{(C-\iota C_{-1})^{1-\epsilon}}{1-\epsilon} - \zeta\frac{H^{1+\omega}}{1+\omega}\right)\right]}_{\mathfrak{U}} \tag{B.2}$$

where the period utility, $\mathfrak{U}$, is assumed to obey the following standard regularity conditions:

$\mathfrak{U}' > 0$, $\mathfrak{U}'' < 0$, $\mathfrak{U}_1 > 0$, $\mathfrak{U}_2 < 0$, $\mathfrak{U}_{11}$, $\mathfrak{U}_{22} < 0$, and $\mathfrak{U}_{11}\mathfrak{U}_{22} - \mathfrak{U}_{12}^2 > 0$ (see Greenwood et al., 1988); τ and ζ are the exogenous stochastic intertemporal preference and labour supply shocks, respectively, and are both assumed to be following AR(1) processes in logarithm, which I write as

$$\ln \tau = \rho_\tau \ln \tau_{-1} + \varepsilon^\tau \tag{S29}$$

$$\ln \zeta = \rho_\zeta \ln \zeta_{-1} + \varepsilon^\zeta \tag{S30}$$

where for $\mathfrak{s}_1 = (\tau_t, \zeta_t)$, the autoregressive parameters are conditioned by $\rho_{\mathfrak{s}_1} \in [0, 1)$ and $\varepsilon^{\mathfrak{s}_1}$ are i.i.d. normal distributions with zero means and innovation standard deviations, $\sigma_{\mathfrak{s}_1}$. I have included habit formation, ι, to aid the model in replicating the data properties, especially that of autocorrelation of consumption.

Denoting by λ^C the marginal utility of consumption and by λ^H the marginal disutility of labour hours, I have that

$$\lambda^C = \tau \left(C - \iota C_{-1}\right)^{-\epsilon} \tag{B.3}$$

$$\lambda^H = \tau \zeta H^\omega \tag{B.4}$$

Further, households can accumulate two types of physical capital goods, which are assumed to follow the laws of motion

$$K_e = \left(1 - \delta_{e0} - \frac{\delta_{e1} \left(U_e\right)^{\mu_e}}{\mu_e}\right) K_{e,-1} + \mathsf{Z}_e I_e - 0.5\psi_e \left(\frac{K_e}{K_{e,-1}} - 1\right)^2 K_{e,-1} \tag{B.5}$$

$$K_n = \left(1 - \delta_{n0} - \frac{\delta_{n1} \left(U_n\right)^{\mu_n}}{\mu_n}\right) K_{n,-1} + \mathsf{Z}_n I_n - 0.5\psi_n \left(\frac{K_n}{K_{n,-1}} - 1\right)^2 K_{n,-1} \tag{B.6}$$

where for type $\mathfrak{t} = e, n$, I have allowed for both capital utilisation rates and adjustment costs. In particular, capital utilisation rates are assumed to satisfy some standard regularity conditions: $0 \leq \delta U_\mathfrak{t} \leq 1$ and $\Delta U_\mathfrak{t}$, $\Delta\Delta U_\mathfrak{t} > 0$ [see Greenwood et al. (1988), Baxter and Farr (2002)]. Also, capital adjustment costs are assumed to satisfy some standard regularity conditions: $\psi_{\mathfrak{t}}(\cdot) = \Delta\psi_{\mathfrak{t}}(\cdot) = 0$ and $\Delta\Delta\psi_{\mathfrak{t}}(\cdot) > 0$ [see Baxter and Crucini (1995)]. The inclusion of capital utilisation rates and adjustment costs aid the model to create some real rigidities. Variables Z_e and Z_n are the exogenous stochastic investment-specific technology shocks for the two types of physical capital, and are both assumed to be following AR(1) processes in logarithm, which I write as

$$\ln \mathsf{Z}_e = \rho_{\mathsf{z}_e} \ln \mathsf{Z}_{e,-1} + \varepsilon^{\mathsf{z}_e} \tag{S31}$$

$$\ln \mathsf{Z}_n = \rho_{\mathsf{z}_n} \ln \mathsf{Z}_{n,-1} + \varepsilon^{\mathsf{z}_n} \tag{S32}$$

where for $\mathfrak{s}_2 = (\mathsf{Z}_e, \mathsf{Z}_n)$, the autoregressive parameters are conditioned by $\rho_{\mathfrak{s}_2} \in [0, 1)$ and $\varepsilon^{\mathfrak{s}_2}$ are i.i.d. normal distributions with zero means and innovation standard deviations, $\sigma_{\mathfrak{s}_2}$.

Equipped with the knowledge that households consume and invest, are assumed to get income from renting their labour hours and capital services to the firms at the market rates W, R_e, and R_n, make profits, Π, from ownership of the firms, and noting that they pay (receive) taxes (transfers), T, to (from) the government, I write the sequential budget constraint being faced by a representative agent as

$$\begin{aligned}
&\mathbb{E}R'B' + C + T + \frac{K_e}{\mathsf{Z}_e} + \frac{K_n}{\mathsf{Z}_n} + 0.5\psi_e \left(\frac{K_e}{K_{e,-1}} - 1\right)^2 \frac{K_{e,-1}}{\mathsf{Z}_e} \\
&+0.5\psi_n \left(\frac{K_n}{K_{n,-1}} - 1\right)^2 \frac{K_{n,-1}}{\mathsf{Z}_n} = B + \left(R_e U_e + \frac{1 - \delta_{e0} - \frac{\delta_{e1}(U_e)^{\mu_e}}{\mu_e}}{\mathsf{Z}_e}\right) K_{e,-1} \\
&+WH + \left(R_n U_n + \frac{1 - \delta_{n0} - \frac{\delta_{n1}(U_n)^{\mu_n}}{\mu_n}}{\mathsf{Z}_n}\right) K_{n,-1} + \Pi
\end{aligned} \tag{B.7}$$

where $\mathbb{E}$ is the expectations operator, $\mathbb{E}R' = \frac{1}{R}$ is the stochastic discount factor, in which case $\mathbb{E}R'B'$ represents the current period's price of a future period's random payment of B'.

In addition, I impose a borrowing constraint on the household to preclude them from engaging in Ponzi-type schemes

$$\lim_{\to\infty} \mathbb{E}R'B' \geq 0 \tag{B.8}$$

Households decision variables must satisfy (B.5), (B.6), aggregate investment

$$I = I_e + I_n \tag{B.9}$$

and the following first-order necessary conditions

$$\lambda^H = \lambda^C W \tag{B.10}$$

$$\lambda^C = \beta\left(1+r\right)\mathbb{E}\lambda^{C\prime} \tag{B.11}$$

$$R_e U_e \mathsf{Z}_e = \delta_{e1} U_e^{\mu_e} \tag{B.12}$$

$$R_n U_n \mathsf{Z}_n = \delta_{n1} U_n^{\mu_n} \tag{B.13}$$

$$\left(1+\psi_e\left(\frac{K_e}{K_{e,-1}}-1\right)\right) = \beta\mathbb{E}\frac{\mathsf{Z}_e}{\mathsf{Z}_e'}\frac{\lambda^{C\prime}}{\lambda^C}\left\{R_e'U_e'\mathsf{Z}_e' - 0.5\psi_e\left(\frac{K_e'}{K_e}-1\right)^2 \right. \\ \left. +1-\delta_{e0}-\frac{\delta_{e1}U_e'^{\mu_e}}{\mu_e}+\psi_e\left(\frac{K_e'}{K_e}-1\right)\frac{K_e'}{K_e}\right\} \tag{B.14}$$

$$\left(1+\psi_n\left(\frac{K_n}{K_{n,-1}}-1\right)\right) = \beta\mathbb{E}\frac{\mathsf{Z}_n}{\mathsf{Z}_n'}\frac{\lambda^{C\prime}}{\lambda^C}\left\{R_n'U_n'\mathsf{Z}_n' - 0.5\psi_n\left(\frac{K_n'}{K_n}-1\right)^2 \right. \\ \left. +1-\delta_{n0}-\frac{\delta_{n1}U_n'^{\mu_n}}{\mu_n}+\psi_n\left(\frac{K_n'}{K_n}-1\right)\frac{K_n'}{K_n}\right\} \tag{B.15}$$

where these conditions have their usual interpretations as already discussed in the main text.

Firms Production is assumed to require three factors of production, viz: labour hours, capital services, and primary energy. I assume that primary energy is an imported input into the production process. Also, producers are assumed to be price-takers both in the input and output markets. Hence, the joint static maximisation problem of representative firms from the two sectors can be written down as

$$\max_{\{H_e,H_n,U_eK_{e,-1},U_nK_{n,-1},E_e,E_n\}} \Pi = \underbrace{P_eY_e + P_nY_n}_{\text{Value of output}} \tag{B.16}$$
$$-\underbrace{[WH_e + WH_n + R_eU_eK_{e,-1} + R_nU_nK_{n,-1} + \mathsf{Q}E_e + \mathsf{Q}E_n]}_{\text{Cost of production}}$$

subject to the sectoral production functions

$$Y_e = \mathsf{A}_e\,(H_e)^{1-\alpha_e}\left(\theta_e\,(U_eK_{e,-1})^{-\nu_e} + (1-\theta_e)\,(\mathsf{O}_eE_e)^{-\nu_e}\right)^{-\frac{\alpha_e}{\nu_e}} \tag{B.17}$$

$$Y_n = \mathsf{A}_n\,(H_n)^{1-\alpha_n}\left(\theta_n\,(U_nK_{n,-1})^{-\nu_n} + (1-\theta_n)\,(\mathsf{O}_nE_n)^{-\nu_n}\right)^{-\frac{\alpha_n}{\nu_n}} \tag{B.18}$$

where variables A_e, A_n, O_e, O_n, and Q are, respectively, the exogenous stochastic energy intensive sector neutral technology, non-energy intensive sector neutral technology, energy intensive sector energy efficiency, non-energy intensive sector energy efficiency, and the energy price shocks. I assume that they all follow AR(1) processes in logarithm, which I write as

$$\ln \mathsf{A}_e = \rho_{\mathsf{a}_e} \ln \mathsf{A}_{e,-1} + \varepsilon^{\mathsf{a}_e} \tag{S33}$$

$$\ln \mathsf{A}_n = \rho_{\mathsf{a}_n} \ln \mathsf{A}_{n,-1} + \varepsilon^{\mathsf{a}_n} \tag{S34}$$

$$\ln \mathsf{O}_e = \rho_{\mathsf{o}_e} \ln \mathsf{O}_{e,-1} + \varepsilon^{\mathsf{o}_e} \tag{S35}$$

$$\ln \mathsf{O}_n = \rho_{\mathsf{o}_n} \ln \mathsf{O}_{n,-1} + \varepsilon^{\mathsf{o}_n} \tag{S36}$$

$$\ln \mathsf{Q} = \rho_{\mathsf{q}} \ln \mathsf{Q}_{-1} + \varepsilon^{\mathsf{q}} \tag{S37}$$

where for $\mathfrak{s}_3 = (\mathsf{A}_e, \mathsf{A}_n, \mathsf{O}_e, \mathsf{O}_n, \mathsf{Q})$, the autoregressive parameters are conditioned by $\rho_{\mathfrak{s}_3} \in [0,1)$ and $\varepsilon^{\mathfrak{s}_3}$ are i.i.d. normal distributions with zero means and innovation standard deviations, $\sigma_{\mathfrak{s}_3}$.

The first-order necessary conditions are

$$\frac{(1-\alpha_e)\,Y_e}{H_e} = \frac{W}{P_e} \tag{B.19}$$

$$\frac{(1-\alpha_n)\,Y_n}{H_n} = \frac{W}{P_n} \tag{B.20}$$

$$\frac{\alpha_e\theta_e Y_e\,(U_e K_{e,-1})^{-\nu_e-1}}{\left(\theta_e\,(U_e K_{e,-1})^{-\nu_e} + (1-\theta_e)\,(\mathsf{O}_e E_e)^{-\nu_e}\right)} = \frac{R_e}{P_e} \tag{B.21}$$

$$\frac{\alpha_n\theta_n Y_n\,(U_n K_{n,-1})^{-\nu_n-1}}{\left(\theta_n\,(U_n K_{n,-1})^{-\nu_n} + (1-\theta_n)\,(\mathsf{O}_n E_n)^{-\nu_n}\right)} = \frac{R_n}{P_n} \tag{B.22}$$

$$\frac{\alpha_e\,(1-\theta_e)\,Y_e\,(\mathsf{O}_e E_e)^{-\nu_e-1}\,\mathsf{O}_e}{\left(\theta_e\,(U_e K_{e,-1})^{-\nu_e} + (1-\theta_e)\,(\mathsf{O}_e E_e)^{-\nu_e}\right)} = \frac{\mathsf{Q}}{P_e} \tag{B.23}$$

$$\frac{\alpha_n\,(1-\theta_n)\,Y_n\,(\mathsf{O}_n E_n)^{-\nu_n-1}\,\mathsf{O}_n}{\left(\theta_n\,(U_n K_{n,-1})^{-\nu_n} + (1-\theta_n)\,(\mathsf{O}_n E_n)^{-\nu_n}\right)} = \frac{\mathsf{Q}}{P_n} \tag{B.24}$$

where the equations define the respective sector's demand for labour hours, capital services, and primary energy.

Government Spending I assume that the government is fully Ricardian and faces the following budget constraint

$$\mathsf{G} + B = T + \mathbb{E}R'B' \tag{B.25}$$

where G is treated as an exogenous stochastic process assumed to follow an AR(1) process in logarithm that takes the form

$$\ln\mathsf{G} = \rho_{\mathsf{g}}\ln\mathsf{G}_{-1} + \varepsilon^{\mathsf{g}} \tag{S38}$$

where the autoregressive parameter is conditioned by $\rho_{\mathsf{g}} \in [0,1)$ and ε^{g} is i.i.d. normal distribution with zero mean and innovation standard deviation, σ_{g}.

Trade in Goods with the RoW In the present model economy, I am assuming that agents in the domestic country trade both types of produced goods with the RoW. I now focus on the transactions that determine the current account position of the domestic country. An implication of international trade in goods is that I end up with a four-goods world: domestically produced energy and non-energy intensive goods, and foreign-produced energy and non-energy intensive goods.[2] Again, and without loss of generality, the discussion follows from the perspective of domestic agents. I later, however, make use of some RoW agents' decisions to infer some decisions for the domestic residents. Specifically, I use the RoW's supposed import functions to infer the export functions of the domestic country.

Aggregate domestic demand or absorption, D, is defined by

$$D = C + I + \mathsf{G} \tag{B.26}$$

where D is a composite of all the four types of goods, which domestic agents use for three purposes: consumption, investment, and to pay government bills. In addition, I assume that domestic agents in both the domestic country and in the RoW only begin to trade once they realize the aggregate output, Y. This indeed forms a constraint on them as they need to choose the share of expenditure to allocate to domestically produced goods vis-a-vis their expenditure on the goods produced in the RoW, and vice versa. To appropriately weigh these choices between types (energy and non-energy intensive goods) and production locations (domestic and foreign goods) of output, I follow a two-cascade Armington (1969) type aggregator function.[3]

More formally, the problem of the domestic agents consists of choosing $\{D_e$, IM,

[2] Remember that I am assuming that all four types of goods are being demanded per period both in the domestic country and in the RoW.

[3] Note that my application here of the Armington aggregator function is an extension of the way Backus et al. (1995) employed it. Their model contains one home-produced and one foreign-produced goods in a two-good, two-country environment whereas I have four goods being traded between the two regions in this model.

$IM_e\}$. Their unconstrained maximisation problem can be written as

$$\max\left\{ P\underbrace{\left(\sigma^{\frac{1}{\varsigma}}\left(D_e\right)^{\frac{\varsigma-1}{\varsigma}}+(1-\sigma)^{\frac{1}{\varsigma}}\left(D_n\right)^{\frac{\varsigma-1}{\varsigma}}\right)^{\frac{\varsigma}{\varsigma-1}}}_{D \text{ aggregate by type of goods}} - P_e D_e - P_n D_n \right. \tag{B.27}$$

$$+P\underbrace{\left(\kappa^{\frac{1}{\phi}}\left(D^d\right)^{\frac{\phi-1}{\phi}}+(1-\kappa)^{\frac{1}{\phi}}\left(IM\right)^{\frac{\phi-1}{\phi}}\right)^{\frac{\phi}{\phi-1}}}_{D \text{ aggregate by location of production}} - P^d D^d - IM$$

$$\left. +\underbrace{\left(\chi^{\frac{1}{\eta}}\left(IM_e\right)^{\frac{\eta-1}{\eta}}+(1-\chi)^{\frac{1}{\eta}}\left(IM_n\right)^{\frac{\eta-1}{\eta}}\right)^{\frac{\eta}{\eta-1}}}_{\text{Split of import bundle, } IM\text{, by type of goods}} - \mathsf{P}_e^{im} IM_e - \mathsf{P}_n^{im} IM_n \right\}$$

The first-order necessary conditions are

$$D_e = \sigma\left(\frac{P_e}{P}\right)^{-\varsigma} D \tag{B.28}$$

$$IM = (1-\kappa)\left(\frac{1}{P}\right)^{-\phi} D \tag{B.29}$$

$$IM_e = \chi\left(\mathsf{P}_e^{im}\right)^{-\eta} IM \tag{B.30}$$

where (B.28)-(B.30) correspond to domestic absorption of energy intensive goods, the demand for composite imported goods, and the demand for imported energy intensive goods by domestic residents. Also, the real exchange rate is defined as a function of the two sectoral relative prices as[4]

$$P = \left(\sigma\left(P_e\right)^{1-\varsigma}+(1-\sigma)\left(P_n\right)^{1-\varsigma}\right)^{\frac{1}{1-\varsigma}} \tag{B.31}$$

and P_e^{im} is the price of imported energy intensive goods being treated as an exogenous stochastic process assumed to follow AR(1) process in logarithm:

$$\ln \mathsf{P}_e^{im} = \rho_{\mathsf{P}_e^{im}} \ln \mathsf{P}_{e,-1}^{im} + \varepsilon^{\mathsf{P}_e^{im}} \tag{S39}$$

[4]See Obstfeld and Rogoff (1996, p. 227) for details.

where for $\mathfrak{s}_4 = (\mathsf{P}_e^{im})$, the autoregressive parameter is conditioned by $\rho_{\mathfrak{s}_4} \in [0,1)$ and $\varepsilon^{\mathfrak{s}_4}$ is i.i.d. normal distribution with zero mean and innovation standard deviation, $\sigma_{\mathfrak{s}_4}$.

I obtain the export functions for the domestic country as a deduction from the import function of the RoW. Focusing on this, one can conjecture the following problem for the agents residing in the RoW

$$\max \left\{ \underbrace{\left(\kappa_w^{\frac{1}{\phi_w}} \left(D^f\right)^{\frac{\phi_w - 1}{\phi_w}} + (1-\kappa_w)^{\frac{1}{\phi_w}} (EX)^{\frac{\phi_w - 1}{\phi_w}} \right)^{\frac{\phi_w}{\phi_w - 1}}}_{\mathsf{D}^w \text{ aggregate by location of production}} - P^f D^f - PEX \right. \tag{B.32}$$

$$\left. + P \underbrace{\left(\chi_w^{\frac{1}{\eta_w}} (EX_e)^{\frac{\eta_w - 1}{\eta_w}} + (1-\chi_w)^{\frac{1}{\eta_w}} (EX_n)^{\frac{\eta_w - 1}{\eta_w}} \right)^{\frac{\eta_w}{\eta_w - 1}}}_{\text{Split of export bundle, } EX \text{, by type of goods}} - P_e EX_e - P_n EX_n \right\}$$

The first-order necessary conditions are

$$EX = (1-\kappa_w)(P)^{-\phi_w} \mathsf{D}^w \tag{B.33}$$

$$EX_e = \chi_w \left(\frac{P_e}{P}\right)^{-\eta_w} EX \tag{B.34}$$

where (B.33) and (B.34) correspond to the composite export and export of energy intensive goods by the domestic country to the RoW. Finally, I assume that world demand, D^w, is an exogenous stochastic process assumed to follow an AR(1) process in logarithm

$$\ln \mathsf{D}^w = \rho_{\mathsf{d}^w} \ln \mathsf{D}^w_{-1} + \varepsilon^{\mathsf{d}^w} \tag{S40}$$

and for $\mathfrak{s}_5 = (\mathsf{D}^w)$, the autoregressive parameter is conditioned by $\rho_{\mathfrak{s}_5} \in [0,1)$ and $\varepsilon^{\mathfrak{s}_5}$ is i.i.d. normal distributions with zero mean and innovation standard deviation, $\sigma_{\mathfrak{s}_5}$.

Markets and Equilibrium Together with (B.9), the other aggregate variables and market clearing conditions are

$$Y = Y_e + Y_n \tag{B.35}$$

$$H = H_e + H_n \tag{B.36}$$

$$E = E_e + E_n \tag{B.37}$$

$$Y_e = D_e + EX_e - IM_n \tag{B.38}$$

$$PEX = \mathsf{Q}E + IM \tag{B.39}$$

$$Y = D \tag{B.40}$$

where (B.35)-(B.40) correspond to aggregate output, aggregate labour hours, aggregate primary energy, clearing of sectoral goods market, the current account and the economy-wide resource constraint.

So, given the initial conditions $\{C_{-1}, K^e_{-1}, K^n_{-1}, B_0\}$ and the exogenous stochastic processes $\{\mathsf{A}_e,\ \mathsf{A}_n,\ \mathsf{D}^w,\ \mathsf{G},\ \zeta,\ \mathsf{O}_e,\ \mathsf{O}_n,\ \mathsf{P}^{im}_e,\ \mathsf{Q},\ \tau,\ \mathsf{Z}_e,\ \mathsf{Z}_n\}$, a competitive equilibrium[5] is a sequence of

1. sectoral goods prices $\{P_e, P_n\}$;
2. wage rate $\{W\}$;
3. interest rates $\{R, R_e, R_n\}$;
4. real exchange rate $\{P\}$;
5. consumption $\{C\}$;
6. investments $\{I, I_e, I_n\}$;
7. labour hours $\{H, H_e, H_n\}$;
8. capital $\{K_e, K_n\}$;
9. capital utilisation rates $\{U_e, U_n\}$;
10. primary energy use $\{E, E_e, E_n\}$;
11. output $\{Y, Y_e, Y_n\}$;
12. domestic absorption $\{D, D_e\}$;
13. imports $\{IM, IM_e\}$;
14. exports $\{EX, EX_e\}$;

[5]I have included four more variables here than I did in the main text in the definition of a competitive equilibrium just for convenience. In the next sub-section, these equations get subbed out and I end up with 28 equations in 28 unknown endogenous variables and 12 undetermined exogenous variables for which I have assumed AR(1) processes just as in the text.

15. marginal utility of consumption $\{\lambda^C\}$;
16. marginal disutility of labour hours $\{\lambda^H\}$;

such that markets clear for:

1. labour hours;
2. capital;
3. primary energy use;
4. sectoral output; and
5. total output.

Log-linearising Equilibrium Conditions The last footnote suggests that I should have 40 linearized equations in this sub-section solving for 28 endogenous and 12 exogenous stochastic processes. I labelled these equations as S1, S2, ..., S28 for the endogenous variables (S29-S40 for the exogenous variables are already defined in the preceding sub-sections) implying that they are used in simulation and to distinguish them from other model equations that 'explain' them.

On the side of the households, combining (B.3), (B.4), and (B.10) yields the supply of labour hours as

$$\zeta H^{\omega} = \frac{W}{(C - \iota C_{-1})^{\epsilon}} \tag{B.41}$$

which when log-linearized becomes

$$\widehat{H} = \frac{1}{\omega}\left(\widehat{W} - \widehat{\zeta} - \frac{\epsilon}{1-\iota}\left(\widehat{C} - \iota\widehat{C}_{-1}\right)\right) \tag{S1}$$

Consumption Euler equation is

$$\frac{\tau}{(C - \iota C_{-1})^{\epsilon}} = \beta R \mathbb{E} \frac{\tau_{t+1}}{(C_{t+1} - \iota C_t)^{\epsilon}} \tag{B.42}$$

which is obtained by combining (B.3) and (B.11). Log-linearising yields

$$\widehat{C} = \frac{1}{1+\iota}\widehat{C}' + \frac{\iota}{1+\iota}\widehat{C}_{-1} + \frac{1-\iota}{\epsilon(1+\iota)}\left(\widehat{\tau} - \widehat{\tau}' - \widehat{R}\right) \tag{S2}$$

I obtain the investment Euler equations for the two types of investment goods by combining (B.3), (B.12), and (B.14) to get

$$\begin{aligned}\left(1+\psi_e\left(\frac{K_e}{K_{e,-1}}-1\right)\right) &= \beta\mathbb{E}\frac{\tau'}{\tau}\frac{\mathsf{Z}_e}{\mathsf{Z}_e'}\frac{(C'-\iota C)^{-\epsilon}}{(C-\iota C_{-1})^{-\epsilon}}\left\{1-\frac{\delta_{e1}U_e'^{\mu_e}}{\mu_e}(1-\mu_e)\right. \\ &\left. -\delta_{e0} - 0.5\psi_e\left(\frac{K_e'}{K_e}-1\right)^2 + \psi_e\left(\frac{K_e'}{K_e}-1\right)\frac{K_e'}{K_e}\right\}\end{aligned} \tag{B.43}$$

and by combining (B.3), (B.13), and (B.15) to get

$$\begin{aligned}\left(1+\psi_n\left(\frac{K_n}{K_{n,-1}}-1\right)\right) &= \beta\mathbb{E}\frac{\tau'}{\tau}\frac{\mathsf{Z}_n}{\mathsf{Z}_n'}\frac{(C'-\iota C)^{-\epsilon}}{(C-\iota C_{-1})^{-\epsilon}}\left\{1-\frac{\delta_{n1}U_n'^{\mu_n}}{\mu_n}(1-\mu_n)\right. \\ &\left. -\delta_{n0} - 0.5\psi_n\left(\frac{K_n'}{K_n}-1\right)^2 + \psi_n\left(\frac{K_n'}{K_n}-1\right)\frac{K_n'}{K_n}\right\}\end{aligned} \tag{B.44}$$

Log-linearising (B.43) and (B.44) yields the following two expressions

$$\begin{aligned}&\widehat{\tau} - \widehat{\mathsf{Z}}_e - \frac{\epsilon}{1-\iota}\left(\widehat{C} - \iota\widehat{C}_{-1}\right) + \psi_e\left(\widehat{K}_e - \widehat{K}_{e,-1}\right) \\ &= \tau' - \mathsf{Z}_e' - \frac{\epsilon}{1-\iota}\left(\widehat{C}' - \iota\widehat{C}\right) + \beta\delta_{e1}u^{\mu_e}(\mu_e - 1)\widehat{U}_e' + \beta\psi_e\left(\widehat{K}_e' - \widehat{K}_e\right)\end{aligned} \tag{S3}$$

$$\begin{aligned}&\widehat{\tau} - \widehat{\mathsf{Z}}_n - \frac{\epsilon}{1-\iota}\left(\widehat{C} - \iota\widehat{C}_{-1}\right) + \psi_n\left(\widehat{K}_n - \widehat{K}_{n,-1}\right) \\ &= \tau' - \mathsf{Z}_n' - \frac{\epsilon}{1-\iota}\left(\widehat{C}' - \iota\widehat{C}\right) + \beta\delta_{n1}u^{\mu_n}(\mu_n - 1)\widehat{U}_n' + \beta\psi_n\left(\widehat{K}_n' - \widehat{K}_n\right)\end{aligned} \tag{S4}$$

Also, log-linearising the laws of motion for capital accumulation, (B.5) and (B.6), leads to

$$\widehat{K}_e = (1-\delta u_e)\widehat{K}_{e,-1} - \delta_{e1}u^{\mu_e}\widehat{U}_e + \frac{i_e}{k_e}\left(\widehat{\mathsf{Z}}_e + \widehat{I}_e\right) \tag{S5}$$

$$\widehat{K}_n = (1-\delta u_n)\widehat{K}_{n,-1} - \delta_{n1}u^{\mu_n}\widehat{U}_n + \frac{i_n}{k_n}\left(\widehat{\mathsf{Z}}_n + \widehat{I}_n\right) \tag{S6}$$

Moving on to the production side, log-linearized versions of the production technologies (B.17) and (B.18) are

$$\widehat{Y}_e = \widehat{\mathsf{A}}_e + (1-\alpha_e)\,\widehat{H}_e + \frac{\alpha_e}{1+\frac{1-\theta_e}{\theta_e}\left(\frac{e_e}{k_e}\right)^{-\nu_e}}\left(\widehat{U}_e + \widehat{K}_{e,-1}\right) + \frac{\alpha_e}{1+\frac{\theta_e}{1-\theta_e}\left(\frac{e_e}{k_e}\right)^{\nu_e}}\left(\widehat{\mathsf{O}}_e + \widehat{E}_e\right) \quad \text{(S7)}$$

$$\widehat{Y}_n = \widehat{\mathsf{A}}_n + (1-\alpha_n)\,\widehat{H}_n + \frac{\alpha_n}{1+\frac{1-\theta_n}{\theta_n}\left(\frac{e_n}{k_n}\right)^{-\nu_n}}\left(\widehat{U}_n + \widehat{K}_{n,-1}\right) + \frac{\alpha_n}{1+\frac{\theta_n}{1-\theta_n}\left(\frac{e_n}{k_n}\right)^{\nu_n}}\left(\widehat{\mathsf{O}}_n + \widehat{E}_n\right) \quad \text{(S8)}$$

Further, log-linearising first-order conditions (B.19)-(B.24) gives (noting that I have merged (B.12) with (B.21) and (B.13) with (B.22))

$$\widehat{H}_e = \widehat{P}_e + \widehat{Y}_e - \widehat{W} \quad \text{(S9)}$$

$$\widehat{H}_n = \widehat{P}_n + \widehat{Y}_n - \widehat{W} \quad \text{(S10)}$$

$$\widehat{U}_e = \frac{\widehat{P}_e + \widehat{Y}_e + \widehat{\mathsf{Z}}_e + \left(\frac{\nu_e}{1+\frac{1-\theta_e}{\theta_e}\left(\frac{e_e}{k_e}\right)^{-\nu_e}} - \nu_e - 1\right)\widehat{K}_{e,-1} + \frac{\nu_e}{1+\frac{\theta_e}{1-\theta_e}\left(\frac{e_e}{k_e}\right)^{\nu_e}}\left(\widehat{\mathsf{O}}_e + \widehat{E}_e\right)}{\mu_e + \nu_e - \frac{\nu_e}{1+\frac{1-\theta_e}{\theta_e}\left(\frac{e_e}{k_e}\right)^{-\nu_e}}} \quad \text{(S11)}$$

$$\widehat{U}_n = \frac{\widehat{P}_n + \widehat{Y}_n + \widehat{\mathsf{Z}}_n + \left(\frac{\nu_n}{1+\frac{1-\theta_n}{\theta_n}\left(\frac{e_n}{k_n}\right)^{-\nu_n}} - \nu_n - 1\right)\widehat{K}_{n,-1} + \frac{\nu_n}{1+\frac{\theta_n}{1-\theta_n}\left(\frac{e_n}{k_n}\right)^{\nu_n}}\left(\widehat{\mathsf{O}}_n + \widehat{E}_n\right)}{\mu_n + \nu_n - \frac{\nu_n}{1+\frac{1-\theta_n}{\theta_n}\left(\frac{e_n}{k_n}\right)^{-\nu_n}}} \quad \text{(S12)}$$

$$\widehat{E}_e = \frac{\widehat{P}_e + \widehat{Y}_e - \widehat{\mathsf{Q}} + \frac{\nu_e}{1+\frac{1-\theta_e}{\theta_e}\left(\frac{e_e}{k_e}\right)^{-\nu_e}}\left(\widehat{U}_e + \widehat{K}_{e,-1}\right) + \left(\frac{\nu_e}{1+\frac{\theta_e}{1-\theta_e}\left(\frac{e_e}{k_e}\right)^{\nu_e}} - \nu_e\right)\widehat{\mathsf{O}}_e}{\nu_e + 1 - \frac{\nu_e}{1+\frac{\theta_e}{1-\theta_e}\left(\frac{e_e}{k_e}\right)^{\nu_e}}} \quad \text{(S13)}$$

$$\widehat{E}_n = \frac{\widehat{P}_n + \widehat{Y}_n - \widehat{\mathsf{Q}} + \frac{\nu_n}{1+\frac{1-\theta_n}{\theta_n}\left(\frac{e_n}{k_n}\right)^{-\nu_n}}\left(\widehat{U}_n + \widehat{K}_{n,-1}\right) + \left(\frac{\nu_n}{1+\frac{\theta_n}{1-\theta_n}\left(\frac{e_n}{k_n}\right)^{\nu_n}} - \nu_n\right)\widehat{\mathsf{O}}_n}{\nu_n + 1 - \frac{\nu_n}{1+\frac{\theta_n}{1-\theta_n}\left(\frac{e_n}{k_n}\right)^{\nu_n}}} \quad \text{(S14)}$$

The following linearized forms are written for the first-order conditions relating to international trade, (B.28)-(B.30) and (B.33)-(B.34)

$$\widehat{D}_e = \varsigma\left(\widehat{P} - \widehat{P}_e\right) + \widehat{D} \tag{S15}$$

$$\widehat{IM} = \phi\widehat{P} + \widehat{D} \tag{S16}$$

$$\widehat{IM}_e = -\eta\widehat{\mathsf{P}}_e^{im} + \widehat{IM} \tag{S17}$$

$$\widehat{EX} = -\phi_w\widehat{P} + \widehat{\mathsf{D}}^w \tag{S18}$$

$$\widehat{EX}_e = \eta_w\left(\widehat{P} - \widehat{P}_e\right) + \widehat{EX} \tag{S19}$$

Log-linearized real exchange rate (B.31) is

$$\widehat{P} = \sigma\left(\frac{p_e}{p}\right)^{1-\varsigma}\widehat{P}_e + (1-\sigma)\left(\frac{p_n}{p}\right)^{1-\varsigma}\widehat{P}_n \tag{S20}$$

Definitions of aggregate variables (B.9, B.35, B.36, B.37) and sectoral (B.38), current account (B.39), and economy-wide (B.40) constraints give the remaining eight conditions I need for model simulation as

$$\widehat{I} = \frac{i_e}{i}\widehat{I}_e + \frac{i_n}{i}\widehat{I}_n \tag{S21}$$

$$\widehat{Y} = \frac{y_e}{y}\widehat{Y}_e + \frac{y_n}{y}\widehat{Y}_n \tag{S22}$$

$$\widehat{H} = \frac{h_e}{h}\widehat{H}_e + \frac{h_n}{h}\widehat{H}_n \tag{S23}$$

$$\widehat{E} = \frac{e_e}{e}\widehat{E}_e + \frac{e_n}{e}\widehat{E}_n \tag{S24}$$

$$\widehat{Y}_e = \frac{d_e}{y_e}\widehat{D}_e + \frac{ex_e}{y_e}\widehat{EX}_e - \frac{im_e}{y_e}\widehat{IM}_e \tag{S25}$$

$$\frac{pex}{e}\left(\widehat{P} + \widehat{EX}\right) - \frac{im}{e}\widehat{IM} = \widehat{\mathsf{Q}} + \widehat{E} \tag{S26}$$

$$\widehat{Y} = \frac{c}{y}\widehat{C} + \frac{i}{y}\widehat{I} + \frac{\mathsf{g}}{y}\widehat{\mathsf{G}} \tag{S27}$$

$$\widehat{Y} = \widehat{D} \tag{S28}$$

Steady State The log-linear form above reveals that I can only solve the model when I have given values to the vector of parameters, $\mathfrak{p}$, and the vector of variables in steady state, $\mathfrak{v}$, summarised by

$$\mathfrak{p} = \begin{bmatrix} \beta \\ \iota \\ \omega \\ \epsilon \\ \alpha_e \\ \alpha_n \\ \nu_e \\ \nu_n \\ \theta_e \\ \theta_n \\ \mu_e \\ \mu_n \\ \psi_e \\ \psi_n \\ \delta_{e1} u^{\mu_e} \\ \delta_{n1} u^{\mu_n} \\ \varsigma \\ \phi \\ \eta \\ \phi_w \\ \eta_w \\ \sigma \end{bmatrix}, \mathfrak{v} = \begin{bmatrix} \delta u_e \\ \delta u_n \\ \frac{e_e}{k_e} \\ \frac{e_e}{k_e} \\ \frac{p_e}{p} \\ \frac{p_n}{p} \\ \frac{i_e}{i} \\ \frac{i_n}{i} \\ \frac{y_e}{y} \\ \frac{y_n}{y} \\ \frac{h_e}{h} \\ \frac{h_n}{h} \\ \frac{e_e}{e} \\ \frac{e_n}{e} \\ \frac{d_e}{y_e} \\ \frac{ex_e}{y_e} \\ \frac{im_e}{y_e} \\ \frac{pex}{e} \\ \frac{im}{e} \\ \frac{c}{y} \\ \frac{i}{y} \\ \frac{\mathrm{g}}{y} \end{bmatrix} \tag{B.45}$$

The main text provides sufficient writing on the calibration and estimation of the vector of parameters. Here, I focus mostly on the computation of the deterministic steady state of the model. That is, the elements of $\mathfrak{v}$. To compute the steady state, I normalise the errors to unity and I employ the normalization that $U_e = U_n = 1$. As is standard in the literature, I target labour hours worked using microeconomic data on the U.S. time use survey from the Bureau of Labour Statistics (BLS). This gives $H = 0.279$, $H_e = 0.115$, and $H_n = 0.164$, where the aggregate labour hours is in the ballpark of figures found in the literature [see, for example, McGrattan et al. (1997) who used 0.27, and Dhawan and Jeske (2008) who used 0.3]. Then, the steady state representations of the model variables can be obtained recursively.

The steady state of the relative price of bonds, R, comes from the Euler equation for consumption, (B.42)

$$R = \frac{1}{\beta} \tag{B.46}$$

By combining the Euler equations for the two capital stocks, (B.14) and (B.15), with the respective equations that determine equality between the marginal user costs and marginal user benefits of capital, (B.12) and (B.13), and evaluating them in the steady state I obtain:

$$R_e = \frac{1}{\beta} - 1 + \delta u_e \tag{B.47}$$

$$R_n = \frac{1}{\beta} - 1 + \delta u_n \tag{B.48}$$

Combining (B.21) and (B.23) in the steady state and using (B.47) yields an expression for the energy-capital ratio in the energy intensive sector as

$$\frac{e_e}{k_e} = \underbrace{\left(\frac{1-\theta_e}{\theta_e}\frac{1-\beta\left(1-\delta u_e\right)}{\beta \mathsf{Q}}\right)^{\frac{1}{1+\nu_e}}}_{\mathfrak{E}_o} \tag{B.49}$$

$$\Rightarrow e_e = \mathfrak{E}_o k_e$$

Combining (B.22) and (B.24) in the steady state and using (B.48) yields an expression for the energy-capital ratio in the non-energy intensive sector as

$$\frac{e_n}{k_n} = \underbrace{\left(\frac{1-\theta_n}{\theta_n}\frac{1-\beta\left(1-\delta u_n\right)}{\beta \mathsf{Q}}\right)^{\frac{1}{1+\nu_n}}}_{\mathfrak{N}_0} \tag{B.50}$$

$$\Rightarrow e_n = \mathfrak{N}_0 k_n$$

Using (B.21), I can write an expression for steady state capital in the energy intensive sector as

$$\begin{aligned} k_e &= \left(\frac{\beta\alpha_e\theta_e p_e}{1-\beta\left(1-\delta u_e\right)}\left(h_e\right)^{1-\alpha_e}\underbrace{\left(\theta_e+\left(1-\theta_e\right)\mathfrak{E}_0^{-\nu_e}\right)}_{\mathfrak{E}_1}^{-\frac{\alpha_e+\nu_e}{\nu_e}}\right)^{\frac{1}{1-\alpha_e}} \\ &= h_e\underbrace{\left(\frac{\beta\alpha_e\theta_e p_e}{1-\beta\left(1-\delta u_e\right)}\mathfrak{E}_1^{-\frac{\alpha_e+\nu_e}{\nu_e}}\right)^{\frac{1}{1-\alpha_e}}}_{\mathfrak{E}_2} \\ &= \mathfrak{E}_2 h_e \end{aligned} \tag{B.51}$$

Applying the same procedure to (B.22) yields the expression for steady state capital in the non-energy intensive sector as

$$k_n = \mathfrak{N}_2 h_n \tag{B.52}$$

From the laws of motion for the accumulation of the two capital stocks, (B.5) and (B.6), in the steady state and the steady state solutions for the capital stocks, (B.51) and (B.52), steady state values for the two investments are given by

$$i_e = \delta u_e k_e = \delta u_e \mathfrak{E}_2 h_e \tag{B.53}$$

$$i_n = \delta u_n k_n = \delta u_n \mathfrak{N}_2 h_n \tag{B.54}$$

Substituting (B.49) and (B.51) into the energy intensive sector production function, (B.17), in the steady state gives

$$y_e = (h_e)^{1-\alpha_e} \underbrace{(k_e)}_{\mathfrak{E}_2 h_e}^{\alpha_e} \underbrace{\left(\left(\theta_e + (1-\theta_e)\,\mathfrak{E}_o^{-\nu_e}\right)\right)}_{\mathfrak{E}_1}^{-\frac{\alpha_e}{\nu_e}} \tag{B.55}$$
$$= h_e \underbrace{\mathfrak{E}_1^{-\frac{\alpha_e}{\nu_e}} \mathfrak{E}_2^{\alpha_e}}_{\mathfrak{E}_3}$$
$$= \mathfrak{E}_3 h_e$$

Likewise, substituting (B.50) and (B.52) into the non-energy intensive sector production function, (B.18), in the steady state gives

$$y_n = \mathfrak{N}_3 h_n \tag{B.56}$$

Then, the above sector related variables sums to give the aggregate steady state values

$$\begin{aligned} e &= e_e + e_n \\ i &= i_e + i_n \\ y &= y_e + y_n \end{aligned} \tag{B.57}$$

Further, using (B.29), the real exchange rate in the steady state, noting that $y = d$, is

$$p = \left(\frac{1}{1-\kappa}\frac{im}{y}\right)^{\frac{1}{\phi}} \tag{B.58}$$

where $\frac{im}{y}$ is taken from the data. Then, from (B.28) the price of energy intensive goods in the steady state is

$$p_e = \left(\frac{1}{\sigma}\frac{d_e}{y}\right)^{-\frac{1}{\varsigma}} p \tag{B.59}$$

where $\frac{d_e}{y}$ is taken from the data. I obtain the steady state price of non-energy intensive goods as

$$p_n = \left(\frac{p^{1-\varsigma} - \sigma \left(p_e\right)^{1-\varsigma}}{1-\sigma} \right)^{\frac{1}{1-\varsigma}} \tag{B.60}$$

Using (B.26) and (B.40), consumption-output ratio is derived as

$$\frac{c}{y} = 1 - \frac{i}{y} - \frac{\mathrm{g}}{y} \tag{B.61}$$

where $\frac{i}{y}$ is obtained from (B.57) and $\frac{\mathrm{g}}{y}$ is taken from the data. Combining (B.29) and (B.30), the steady state of imported energy intensive goods can be written as

$$im_e = \chi \left(1 - \kappa\right) p^{\phi} y \tag{B.62}$$

Finally, combining (B.33) and (B.34) gives the export of energy intensive goods in the steady state as

$$ex_e = \chi_w \left(1 - \kappa_w\right) \left(p_e\right)^{-\eta_w} p^{\eta_w - \phi_w} \tag{B.63}$$

It is easy to see from the above derivations that some parameters only work to pin down the steady state of variables and are not used in the dynamic model simulation. Hence, steady state representation is not worked out (by hand) for every single variable.

Appendix C

Supplementary Notes: Chapter 4

C.1 Data Construction

All series are defined as in Chapter 2 except domestic absorption, D_t. Also, I have six extra variables relating to the rest of the world to be defined.

Domestic absorption

Model variable: D_t.

Data: $d_t = C_t + I_t + G_t$ (Taken from Table 1.1.5. Gross Domestic Product).

Government spending

Model variable: G_t.

Data: This is government consumption expenditures and gross investment (Taken from Table 1.1.5. Gross Domestic Product).

Real price of energy

Model variable: Q_t.

Data: Q_t is the nominal dollar price per barrel of crude oil proxied by the crude oil domestic first purchase price (Taken from Table 9.1: Crude Oil Price Summary) divided by the consumer price index (CPI).

Foreign bonds

Model variable: F_t.

Data: This is taken to be the ratio of nominal net foreign assets (NNFA) to nominal GDP (NGDP), $F_t = \frac{NNFA}{NGDP}$, where $NNFA = Total\ Assets - Total\ Liabilities$.

Foreign interest rate

Model variable: r_t^f.

Data: Calculated as the weighted average of the interest rate for the G7 countries taken from the International Financial Statistics (IFS).

World demand

Model variable: D_t^w.

Data: This is measured as world trade less the U.S. imports taken from the International Financial Statistics (IFS).

Price of imported energy intensive goods

Model: $\mathsf{P}_{e,t}^{im}$.

Data: This is the price of the U.S. imported manufactures from the rest of the world taken from the International Financial Statistics (IFS).

C.2 Technical Appendix

In this section, I summarise the derivations of the equilibrium conditions in Chapter 3. The model is the same as in the previous chapter, but with the addition of capital account. Essentially, this introduces an additional first-order condition on the household's side:

the uncovered interest parity (UIP) condition and both the balance of payment (BOP) account and the economy-wide resource constraint are extended to include the capital account. Further, note that more shocks are added as already explained in the main text, and for this reason the first-order conditions on the firm and trader's side are altered.

This way, the sequential budget constraint becomes

$$
\begin{aligned}
& B_t + \frac{F_t}{P_t} + C_t + T_t + \frac{K_t^e}{\mathsf{Z}_t^e} + \frac{K_t^n}{\mathsf{Z}_t^n} + 0.5\psi_e \left(\frac{K_t^e}{K_{t-1}^e} - 1 \right)^2 \frac{K_{t-1}^e}{\mathsf{Z}_t^e} \\
& + 0.5\psi_n \left(\frac{K_t^n}{K_{t-1}^n} - 1 \right)^2 \frac{K_{t-1}^n}{\mathsf{Z}_t^n} + \frac{0.5\psi_f}{P_t} \left(F_t - f \right)^2 = \left(1 + r_{t-1} \right) B_{t-1} \\
& + \left(1 + \mathsf{r}_{t-1}^f \right) \frac{F_{t-1}}{P_t} + \left(R_t^e U_t^e + \frac{1 - \delta_{e0} - \frac{\delta_{e1} (U_t^e)^{\mu_e}}{\mu_e}}{\mathsf{Z}_t^e} \right) K_{t-1}^e \\
& + W_t H_t + \left(R_t^n U_t^n + \frac{1 - \delta_{n0} - \frac{\delta_{n1} (U_t^n)^{\mu_n}}{\mu_n}}{\mathsf{Z}_t^n} \right) K_{t-1}^n + \Pi_t
\end{aligned}
\tag{C.1}
$$

Hence, on the household side, the first-order conditions are

$$C_t\colon\ \lambda_t = \frac{\tau_t}{\left(C_t - \iota C_{t-1} \right)^{\epsilon}} \tag{C.2}$$

$$H_t\colon\ \lambda_t W_t = \tau_t \zeta_t H_t^{\omega} \tag{C.3}$$

$$B_t\colon\ \lambda_t = \beta \left(1 + r_t \right) \lambda_{t+1} \tag{C.4}$$

$$F_t\colon\ \frac{\lambda_t}{P_t} \left[1 + \psi_f \left(F_t - f \right) \right] = \beta \left(1 + \mathsf{r}_t^f \right) \frac{\lambda_{t+1}}{P_{t+1}} \tag{C.5}$$

$$U_t^e\colon\ R_t^e U_t^e \mathsf{Z}_t^e = \delta_{e1} \left(U_t^e \right)^{\mu_e} \tag{C.6}$$

$$U_t^n\colon\ R_t^n U_t^n \mathsf{Z}_t^n = \delta_{n1} \left(U_t^n \right)^{\mu_n} \tag{C.7}$$

$$K_t^e\colon \left(1+\psi_e\left(\frac{K_t^e}{K_{t-1}^e}-1\right)\right)=\beta\mathbb{E}_t\frac{\mathsf{Z}_t^e}{\mathsf{Z}_{t+1}^e}\frac{\lambda_{t+1}}{\lambda_t}\left\{R_{t+1}^e U_{t+1}^e \mathsf{Z}_{t+1}^e - 0.5\psi_e\left(\frac{K_{t+1}^e}{K_t^e}-1\right)^2\right. \tag{C.8}$$

$$\left. +1-\delta_{e0}-\frac{\delta_{e1}\left(U_{t+1}^e\right)^{\mu_e}}{\mu_e}+\psi_e\left(\frac{K_{t+1}^e}{K_t^e}-1\right)\frac{K_{t+1}^e}{K_t^e}\right\}$$

$$K_t^n\colon \left(1+\psi_n\left(\frac{K_t^n}{K_{t-1}^n}-1\right)\right)=\beta\mathbb{E}_t\frac{\mathsf{Z}_t^n}{\mathsf{Z}_{t+1}^n}\frac{\lambda_{t+1}}{\lambda_t}\left\{R_{t+1}^n U_{t+1}^n \mathsf{Z}_{t+1}^n - 0.5\psi_n\left(\frac{K_{t+1}^n}{K_t^n}-1\right)^2\right. \tag{C.9}$$

$$\left. +1-\delta_{n0}-\frac{\delta_{n1}\left(U_{t+1}^n\right)^{\mu_n}}{\mu_n}+\psi_n\left(\frac{K_{t+1}^n}{K_t^n}-1\right)\frac{K_{t+1}^n}{K_t^n}\right\}$$

The problem of the firms is to

$$\max \Pi_t = \underbrace{P_t^e Y_t^e + P_t^n Y_t^n}_{\text{Value of output}} - \underbrace{[(W_t+\xi_t^e)H_t^e}_{\text{Cost of production}} \tag{C.10}$$

$$\underbrace{+(W_t+\xi_t^n)H_t^n+(R_t^e+\vartheta_t^e)U_t^e K_{t-1}^e+(R_t^n+\vartheta_t^n)U_t^n K_{t-1}^n+\mathsf{Q}_t E_t^e+\mathsf{Q}_t E_t^n]}_{\text{Cost of production}}$$

subject to

$$Y_t^e = \mathsf{A}_t^e\left(H_t^e\right)^{1-\alpha_e}\left(\theta_e\left(U_t^e K_{t-1}^e\right)^{-\nu_e}+(1-\theta_e)\left(\mathsf{O}_t^e E_t^e\right)^{-\nu_e}\right)^{-\frac{\alpha_e}{\nu_e}} \tag{C.11}$$

$$Y_t^n = \mathsf{A}_t^n\left(H_t^n\right)^{1-\alpha_n}\left(\theta_n\left(U_t^n K_{t-1}^n\right)^{-\nu_n}+(1-\theta_n)\left(\mathsf{O}_t^n E_t^n\right)^{-\nu_n}\right)^{-\frac{\alpha_n}{\nu_n}} \tag{C.12}$$

Relevant F.O.Cs are

$$H_t^e\colon \frac{(1-\alpha_e)\,Y_t^e}{H_t^e}=\frac{W_t+\xi_t^e}{P_t^e} \tag{C.13}$$

$$H_t^n\colon \frac{(1-\alpha_n)\,Y_t^n}{H_t^n}=\frac{W_t+\xi_t^n}{P_t^n} \tag{C.14}$$

$$U_t^e K_{t-1}^e\colon \frac{\alpha_e\theta_e Y_t^e\left(U_t^e K_{t-1}^e\right)^{-\nu_e-1}}{\left(\theta_e\left(U_t^e K_{t-1}^e\right)^{-\nu_e}+(1-\theta_e)\left(\mathsf{O}_t^e E_t^e\right)^{-\nu_e}\right)}=\frac{R_t^e+\vartheta_t^e}{P_t^e} \tag{C.15}$$

$$U_t^e K_{t-1}^n\colon \frac{\alpha_n \theta_n Y_t^n \left(U_t^n K_{t-1}^n\right)^{-\nu_n - 1}}{\left(\theta_n \left(U_t^n K_{t-1}^n\right)^{-\nu_n} + (1-\theta_n)\left(\mathsf{O}_t^n E_t^n\right)^{-\nu_n}\right)} = \frac{R_t^n + \vartheta_t^n}{P_t^n} \tag{C.16}$$

$$E_t^e\colon \frac{\alpha_e (1-\theta_e) Y_t^e \left(\mathsf{O}_t^e E_t^e\right)^{-\nu_e - 1} \mathsf{O}_t^e}{\left(\theta_e \left(U_t^e K_{t-1}^e\right)^{-\nu_e} + (1-\theta_e)\left(\mathsf{O}_t^e E_t^e\right)^{-\nu_e}\right)} = \frac{\mathsf{Q}_t}{P_t^e} \tag{C.17}$$

$$E_t^n\colon \frac{\alpha_n (1-\theta_n) Y_t^n \left(\mathsf{O}_t^n E_t^n\right)^{-\nu_n - 1} \mathsf{O}_t^n}{\left(\theta_n \left(U_t^n K_{t-1}^n\right)^{-\nu_n} + (1-\theta_n)\left(\mathsf{O}_t^n E_t^n\right)^{-\nu_n}\right)} = \frac{\mathsf{Q}_t}{P_t^n} \tag{C.18}$$

The problem of the domestic trader is to

$$\max \left\{ P_t \underbrace{\left(\sigma^{\frac{1}{\varsigma}} \gamma_t \left(D_t^e\right)^{\frac{\varsigma-1}{\varsigma}} + (1-\sigma)^{\frac{1}{\varsigma}} \left(D_t^n\right)^{\frac{\varsigma-1}{\varsigma}}\right)^{\frac{\varsigma}{\varsigma-1}}}_{D_t \text{ aggregate by type of goods}} - P_t^e D_t^e - P_t^n D_t^n \right. \tag{C.19}$$

$$+ P_t \underbrace{\left(\kappa^{\frac{1}{\phi}} \left(D_t^d\right)^{\frac{\phi-1}{\phi}} + (1-\kappa)^{\frac{1}{\phi}} \varpi_t \left(IM_t\right)^{\frac{\phi-1}{\phi}}\right)^{\frac{\phi}{\phi-1}}}_{D_t \text{ aggregate by location of production}} - P_t^d D_t^d - IM_t$$

$$\left. + \underbrace{\left(\chi^{\frac{1}{\eta}} \varphi_t \left(IM_t^e\right)^{\frac{\eta-1}{\eta}} + (1-\chi)^{\frac{1}{\eta}} \left(IM_t^n\right)^{\frac{\eta-1}{\eta}}\right)^{\frac{\eta}{\eta-1}}}_{\text{Split of import bundle, } IM_t, \text{ by type of goods}} - \mathsf{P}_{e,t}^{im} IM_t^e - \mathsf{P}_{n,t}^{im} IM_t^n \right\}$$

Relevant F.O.Cs are

$$D_t^e\colon D_t^e = \sigma \gamma_t^{\varsigma} \left(\frac{P_t^e}{P_t}\right)^{-\varsigma} D_t \tag{C.20}$$

$$IM_t\colon IM_t = (1-\kappa) \varpi_t^{\phi} \left(\frac{1}{P_t}\right)^{-\phi} D_t \tag{C.21}$$

$$IM_t^e\colon IM_t^e = \chi \varphi_t^{\eta} \left(\mathsf{P}_{e,t}^{im}\right)^{-\eta} IM_t \tag{C.22}$$

where given D_t aggregate by type of goods, the domestic CPI/ real exchange rate is defined as a function of the two sectoral relative prices as[1]

$$P_t = \left(\sigma\gamma_t^{\varsigma}\left(P_t^e\right)^{1-\varsigma} + (1-\sigma)\left(P_t^n\right)^{1-\varsigma}\right)^{\frac{1}{1-\varsigma}} \tag{C.23}$$

The problem of the foreign trader as conceived[2] by the domestic trader is to

$$\max \left\{ \underbrace{\left(\kappa_w^{\frac{1}{\phi_w}}\left(D_t^f\right)^{\frac{\phi_w-1}{\phi_w}} + (1-\kappa_w)^{\frac{1}{\phi_w}}\varpi_t^w\left(EX_t\right)^{\frac{\phi_w-1}{\phi_w}}\right)^{\frac{\phi_w}{\phi_w-1}}}_{\mathsf{D}_t^w \text{ aggregate by location of production}} - P_t^f D_t^f - P_t EX_t \right. \tag{C.24}$$

$$\left. + P_t \underbrace{\left(\chi_w^{\frac{1}{\eta_w}}\varphi_t^w\left(EX_t^e\right)^{\frac{\eta_w-1}{\eta_w}} + (1-\chi_w)^{\frac{1}{\eta_w}}\left(EX_t^n\right)^{\frac{\eta_w-1}{\eta_w}}\right)^{\frac{\eta_w}{\eta_w-1}}}_{\text{Split of export bundle, } EX_t\text{, by type of goods}} - P_t^e EX_t^e - P_t^n EX_t^n \right\}$$

Relevant F.O.Cs are

$$EX_t\colon\ EX_t = (1-\kappa_w)\left(\varpi_t^w\right)^{\phi_w}\left(P_t\right)^{-\phi_w}\mathsf{D}_t^w \tag{C.25}$$

$$EX_t^e\colon\ EX_t^e = \chi_w\left(\varphi_t^w\right)^{\eta_w}\left(\frac{P_t^e}{P_t}\right)^{-\eta_w} EX_t \tag{C.26}$$

The government budget constraint is

$$\mathsf{G}_t = T_t + B_t - (1+r_{t-1})\,B_{t-1} \tag{C.27}$$

The remaining aggregate variables and market clearing conditions are

$$Y_t = Y_t^e + Y_t^n \tag{C.28}$$

$$H_t = H_t^e + H_t^n \tag{C.29}$$

$$E_t = E_t^e + E_t^n \tag{C.30}$$

[1] See Obstfeld and Rogoff (1996, p. 227) for details of the derivations.
[2] We assume that the problem is symmetric.

$$I_t = I_t^e + I_t^n \tag{C.31}$$

$$Y_t^e = D_t^e + EX_t^e - IM_t^e \tag{C.32}$$

$$F_t = \left(1 + \mathsf{r}_{t-1}^f\right) F_{t-1} + P_t EX_t - IM_t - \mathsf{Q}_t E_t \tag{C.33}$$

$$Y_t = C_t + I_t + \mathsf{G}_t + EX_t - IM_t - \mathsf{Q}_t E_t \tag{C.34}$$

The log-linearized equations that solve for the endogenous variables I am interested in are reproduced below where each has been normalised for a variable. Thus, given a sequence of 22 exogenous stochastic processes $\{\mathsf{a}_t^e,\ \mathsf{a}_t^n,\ \mathsf{d}_t^w,\ \varphi_t,\ \varphi_t^w,\ \gamma_t,\ \mathsf{g}_t,\ \zeta_t,\ \mathsf{o}_t^e,\ \mathsf{o}_t^n,\ \mathsf{p}_{e,t}^{im},\ \mathsf{q}_t,\ \mathsf{r}_t^f,\ \tau_t,\ \vartheta_t^e,\ \vartheta_t^n,\ \varpi_t,\ \varpi_t^w,\ \xi_t^e,\ \xi_t^n,\ \mathsf{z}_t^e,\ \mathsf{z}_t^n\}_{t=0}^{\infty}$, and the initial conditions $c_{-1},\ b_{-1},\ f_{-1},\ k_{-1}^e,\ k_{-1}^n$, a competitive equilibrium is a sequence of 29 endogenous stochastic processes $\{c_t,\ h_t,\ h_t^e,\ h_t^n,\ f_t,\ i_t,\ i_t^e,\ i_t^n,\ u_t^e,\ u_t^n,\ k_t^e,\ k_t^n,\ y_t,\ y_t^e,\ y_t^n,\ e_t,\ e_t^e,\ e_t^n,\ d_t,\ d_t^e,\ im_t,\ im_t^e,\ ex_t,\ ex_t^e,\ w_t,\ r_t,\ p_t,\ p_t^e,\ p_t^n\}_{t=0}^{\infty}$ satisfying the following equations[3]

$$c_t = \frac{1}{1+\iota} c_{t+1} + \frac{\iota}{1+\iota} c_{t-1} + \frac{1-\iota}{\epsilon\,(1+\iota)} \left(\tau_t - \tau_{t+1} - \beta r r_t\right) \tag{L\_L1}$$

$$h_t = \frac{h^e}{h} h_t^e + \frac{h^n}{h} h_t^n \tag{L\_L2}$$

$$h_t^e = p_t^e + y_t^e - \frac{w}{1+w} w_t - \frac{1}{1+w} \xi_t^e \tag{L\_L3}$$

$$h_t^n = p_t^n + y_t^n - \frac{w}{1+w} w_t - \frac{1}{1+w} \xi_t^n \tag{L\_L4}$$

$$f_t = \left(1 + \mathsf{r}_{t-1}^f\right) f_{t-1} + \frac{ex}{y} \left(p_t + ex_t\right) - \frac{im}{y} im_t - \frac{e}{y} \left(\mathsf{q}_t + e_t\right) \tag{L\_L5}$$

$$i_t = \frac{i^e}{i} i_t^e + \frac{i^n}{i} i_t^n \tag{L\_L6}$$

$$i_t^e = \frac{k_t^e - \left(1 - \delta u^e\right) k_{t-1}^e + \delta_{e1} u^{\mu_e} u_t^e - \frac{i^e}{k^e} \mathsf{z}_t^e}{\frac{i^e}{k^e}} \tag{L\_L7}$$

$$i_t^n = \frac{k_t^n - \left(1 - \delta u^n\right) k_{t-1}^n + \delta_{n1} u^{\mu_n} u_t^n - \frac{i^n}{k^n} \mathsf{z}_t^n}{\frac{i^n}{k^n}} \tag{L\_L8}$$

[3] Note that λ_t, R_t^e, and R_t^n have all been substituted out.

$$u_t^e = \frac{p_t^e + y_t^e + \frac{\mathsf{z}_t^e}{1+\frac{1}{\delta_{e1} u^{\mu_e}}} + \left(\frac{\nu_e}{1+\frac{1-\theta_e}{\theta_e}\left(\frac{e^e}{k^e}\right)^{-\nu_e}} - \nu_e - 1\right) k_{t-1}^e + \frac{\nu_e}{1+\frac{\theta_e}{1-\theta_e}\left(\frac{e^e}{k^e}\right)^{\nu_e}}\left(\mathsf{o}_t^e + e_t^e\right) - \frac{\vartheta_t^e}{1+\delta_{e1} u^{\mu_e}}}{\frac{1}{1+\frac{1}{\delta_{e1} u^{\mu_e}}}\left(\mu_e - 1\right) + \nu_e + 1 - \frac{\nu_e}{1+\frac{1-\theta_e}{\theta_e}\left(\frac{e^e}{k^e}\right)^{-\nu_e}}} \tag{L\_L9}$$

$$u_t^n = \frac{p_t^n + y_t^n + \frac{\mathsf{z}_t^n}{1+\frac{1}{\delta_{n1} u^{\mu_n}}} + \left(\frac{\nu_n}{1+\frac{1-\theta_n}{\theta_n}\left(\frac{e^n}{k^n}\right)^{-\nu_n}} - \nu_n - 1\right) k_{t-1}^n + \frac{\nu_n}{1+\frac{\theta_n}{1-\theta_n}\left(\frac{e^n}{k^n}\right)^{\nu_n}}\left(\mathsf{o}_t^n + e_t^n\right) - \frac{\vartheta_t^n}{1+\delta_{n1} u^{\mu_n}}}{\frac{1}{1+\frac{1}{\delta_{n1} u^{\mu_n}}}\left(\mu_n - 1\right) + \nu_n + 1 - \frac{\nu_n}{1+\frac{1-\theta_n}{\theta_n}\left(\frac{e^n}{k^n}\right)^{-\nu_n}}} \tag{L\_L10}$$

$$\begin{aligned} k_t^e &= \frac{\frac{\epsilon}{1-\iota}\left(c_t - \iota c_{t-1}\right) - \frac{\epsilon}{1-\iota}\left(\mathbb{E}_t c_{t+1} - \iota c_t\right) + \mathbb{E}_t \tau_{t+1} - \tau_t - \mathbb{E}_t \mathsf{z}_{t+1}^e}{\psi_e\left(1+\beta\right)} \\ &\quad \frac{+\mathsf{z}_t^e + \beta \delta_{e1} u^{\mu_e}\left(\mu_e - 1\right)\mathbb{E}_t u_{t+1}^e + \psi_e\left(\beta \mathbb{E}_t k_{t+1}^e + k_{t-1}^e\right)}{\psi_e\left(1+\beta\right)} \end{aligned} \tag{L\_L11}$$

$$\begin{aligned} k_t^n &= \frac{\frac{\epsilon}{1-\iota}\left(c_t - \iota c_{t-1}\right) - \frac{\epsilon}{1-\iota}\left(\mathbb{E}_t c_{t+1} - \iota c_t\right) + \mathbb{E}_t \tau_{t+1} - \tau_t - \mathbb{E}_t \mathsf{z}_{t+1}^n}{\psi_n\left(1+\beta\right)} \\ &\quad \frac{+\mathsf{z}_t^n + \beta \delta_{n1} u^{\mu_n}\left(\mu_n - 1\right)\mathbb{E}_t u_{t+1}^n + \psi_n\left(\beta \mathbb{E}_t k_{t+1}^n + k_{t-1}^n\right)}{\psi_n\left(1+\beta\right)} \end{aligned} \tag{L\_L12}$$

$$y_t = \frac{y^e}{y} y_t^e + \frac{y^n}{y} y_t^n \tag{L\_L13}$$

$$y_t^e = \mathsf{a}_t^e + \left(1-\alpha_e\right) h_t^e + \frac{\alpha_e}{1+\frac{1-\theta_e}{\theta_e}\left(\frac{e^e}{k^e}\right)^{-\nu_e}}\left(u_t^e + k_{t-1}^e\right) + \frac{\alpha_e}{1+\frac{\theta_e}{1-\theta_e}\left(\frac{e^e}{k^e}\right)^{\nu_e}}\left(\mathsf{o}_t^e + e_t^e\right) \tag{L\_L14}$$

$$y_t^n = \mathsf{a}_t^n + \left(1-\alpha_n\right) h_t^n + \frac{\alpha_n}{1+\frac{1-\theta_n}{\theta_n}\left(\frac{e^n}{k^n}\right)^{-\nu_n}}\left(u_t^n + k_{t-1}^n\right) + \frac{\alpha_n}{1+\frac{\theta_n}{1-\theta_n}\left(\frac{e^n}{k^n}\right)^{\nu_n}}\left(\mathsf{o}_t^n + e_t^n\right) \tag{L\_L15}$$

$$e_t = \frac{e^e}{e} e_t^e + \frac{e^n}{e} e_t^n \tag{L\_L16}$$

$$e_t^e = \frac{p_t^e + y_t^e - \mathsf{q}_t + \frac{\nu_e}{1+\frac{1-\theta_e}{\theta_e}\left(\frac{e^e}{k^e}\right)^{-\nu_e}}\left(u_t^e + k_{t-1}^e\right) + \left(\frac{\nu_e}{1+\frac{\theta_e}{1-\theta_e}\left(\frac{e^e}{k^e}\right)^{\nu_e}} - \nu_e\right)\mathsf{o}_t^e}{\nu_e + 1 - \frac{\nu_e}{1+\frac{\theta_e}{1-\theta_e}\left(\frac{e^e}{k^e}\right)^{\nu_e}}} \tag{L\_L17}$$

$$e_t^n = \frac{p_t^n + y_t^n - \mathsf{q}_t + \frac{\nu_n}{1+\frac{1-\theta_n}{\theta_n}\left(\frac{e^n}{k^n}\right)^{-\nu_n}}\left(u_t^n + k_{t-1}^n\right) + \left(\frac{\nu_n}{1+\frac{\theta_n}{1-\theta_n}\left(\frac{e^n}{k^n}\right)^{\nu_n}} - \nu_n\right)\mathsf{o}_t^n}{\nu_n + 1 - \frac{\nu_n}{1+\frac{\theta_n}{1-\theta_n}\left(\frac{e^n}{k^n}\right)^{\nu_n}}} \tag{L\_L18}$$

$$d_t = \frac{c}{d}c_t + \frac{i}{d}i_t + \frac{\mathsf{g}}{d}\mathsf{g}_t \tag{L\_L19}$$

$$d_t^e = \varsigma\gamma_t + \varsigma\left(p_t - p_t^e\right) + d_t \tag{L\_L20}$$

$$im_t = \frac{\frac{c}{y}c_t + \frac{i}{y}i_t + \frac{\mathsf{g}}{y}\mathsf{g}_t + \frac{ex}{y}ex_t - \frac{e}{y}\mathsf{q}_t - \frac{e}{y}e_t - y_t}{\frac{im}{y}} \tag{L\_L21}$$

$$im_t^e = \eta\varphi_t - \eta\mathsf{p}_{e,t}^{im} + im_t \tag{L\_L22}$$

$$ex_t = \phi_w\varpi_t^w - \phi_w p_t + \mathsf{d}_t^w \tag{L\_L23}$$

$$ex_t^e = \frac{y_t^e - \frac{d^e}{y^e}d_t^e + \frac{im^e}{y^e}im_t^e}{\frac{ex^e}{y^e}} \tag{L\_L24}$$

$$w_t = \omega h_t + \zeta_t + \frac{\epsilon}{1-\iota}\left(c_t - \iota c_{t-1}\right) \tag{L\_L25}$$

$$r_t = \mathsf{r}_t^f + p_t - \mathbb{E}_t p_{t+1} - \psi_{b^f} b^f b_t^f \tag{L\_L26}$$

$$p_t = \frac{im_t - d_t}{\phi} - \varpi_t \tag{L\_L27}$$

$$p_t^e = \varphi_t^w + p_t + \frac{ex_t - ex_t^e}{\eta_w} \tag{L\_L28}$$

$$p_t^n = \frac{p_t - \sigma\left(\frac{p^e}{p}\right)^{1-\varsigma}\left(\varsigma\gamma_t + p_t^e\right)}{\left(1-\sigma\right)\left(\frac{p^n}{p}\right)^{1-\varsigma}} \tag{L\_L29}$$

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