THE ECONOMIC IMPACT OF FUSION POWER IN THE UK'S 2050 ENERGY MIX

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DECLARATION

The University of Reading is in receipt of the sole submission of this thesis and it has not been submitted to any other institution for a research award.

I confirm that this is my own work and the use of all material from other sources has been properly and fully acknowledged.

Edward Anyaeji
February 2017

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LIST OF ABBREVIATIONS

ADF	Augmented Dickey-Fuller
AIC	Akaike information criterion
ARDL	Autoregressive distributed lag
ARIMA	Autoregressive integrated moving average
ARMA	Autoregressive moving average
ARMAX	ARMA with exogenous inputs
BEIS	Department for Business, Energy and Industrial Strategy
CCC	Committee on Climate Change
CCCEP	Centre for Climate Change and Economic Policy
CCFE	Culham Centre for Fusion Energy
CCS	Carbon, capture and storage
CES	Constant elasticity of substitution
CET	Constant elasticity of transformation
CFD	Contracts for Difference
CGE	Computable general equilibrium
CIEMAT	Centro de Investigaciones Energéticas Medioambientales y Tecnológicas (Centre for Energy, Environment and Technology)
CPF	Carbon price floor
CRC	Carbon Reduction Commitment
CUSUM	Cumulative sum
CUSUMSQ	Cumulative sum of squares
DECC	Department for Energy and Climate Change
DEFRA	Department for Environment, Food and Rural Affairs
DEMO	Demonstration fusion power plant
DF-GLS	Dickey-Fuller Generalised Least Squares
DOE	United States Department of Energy
DOLS	Dynamic ordinary least squares
DTI	Department of Trade and Industry
DUKES	Digest of the United Kingdom Electricity Statistics
EC	European Commission
ECM	Error correction model
EEC	European Economic Community

EFDA	European Fusion Development Agreement
EKC	Environmental Kuznets Curve
ELG	Export-led growth
EPA	Environmental Protection Agency
EPS	Emissions Performance Standard
EREC	European Renewable Energy Council
ERM	Exchange Rate Mechanism
ETSAP	Energy Technology Systems Analysis Program
EU-ETS	European Union Emissions Trading Scheme
EURATOM	European Atomic Energy Community
GDP	Gross domestic product
GHG	Greenhouse gases
IAEA	International Atomic Energy Agency
ICE	Internal combustion engines
IEA	International Energy Agency
IFMIF	International Fusion Materials Irradiation Facility
ILG	Import-led growth
IPCC	International Panel on Climate Change
ITER	International Thermonuclear Experimental Reactor
JET	Joint European Torus
KWh	Kilowatt - hour
LCOE	Levelised Cost of Electricity
MAC	Marginal abatement cost
MAE	Mean absolute error
MAPE	Mean absolute percentage error
MARKAL	Market allocation energy model
MeV	Megaelectron volt
ML	Maximum likelihood
$MtCO_2e$	Million tonnes of carbon dioxide equivalent
MTOE	Million tonnes of oil equivalent
MWe	Megawatt - electrical power
MWh	Megawatt - hour
NGO	Non-governmental organisation
NPS	National Policy Statement

OECD	Organisation for Economic Cooperation and Development
OLS	Ordinary least squares
ONS	Office of National Statistics
PLANELEC-PRO	Planning model for electricity system expansion
PPF	Production Possibility Frontier
PROTO	Prototype fusion power plant
R&D	Research and Development
RCUK	Research Councils United Kingdom
RFP	Reversed Field Pinch
RMSE	Root mean squared error
SIC	Schwarz information criterion
ST	Spherical Tokamak
TIMES	The Integrated MARKAL-EFOM System
TWh	Terawatt - hour
UKAEA	United Kingdom Atomic Energy Authority
UNFCCC	United Nations Framework Convention on Climate Change
VAR	Vector autoregression
VECM	Vector error correction model
WBCSD	World Business Council for Sustainable Development
WWF	World Wildlife Fund

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ABSTRACT

Access to a safe and inexpensive source of energy is one of society's essential needs that helps to support economic growth and development. Yet, there are a number of current challenges in the developed world that pose a threat to its energy security such as the high import dependency in Europe from politically unstable regions and the long term environmental risks from greenhouse gas (GHG) emissions. Based on scientific estimates from the United Kingdom Atomic Energy Authority's (UKAEA) fusion research and development site, fusion power could generate high volumes of decarbonised electricity that could begin to replace electricity sources from oil, gas and coal during the middle and latter half of this century. However, fusion power currently exists in a non-commercialised state and so the use of robust techno-economic and econometric models are required in order to estimate the role that fusion power could play within the context of a future energy mix.

The single equation, autoregressive distributed lag (ARDL) model of cointegration analysis is used to estimate the nuclear fission-GDP-CO_2 nexus. Nuclear fission is used as the guide for fusion power due to the similarities in energy-releasing nuclear reactions and complex power plant technology. A comparative analysis between nuclear fission and environmental taxes is performed within a multivariate framework. The UK Government's 2050 Energy Calculator is subsequently recalibrated in order to generate projections of the future energy mix with fusion power included. Multiequation econometric analyses are performed using Johansen's maximum likelihood (ML) estimator of cointegration analysis and the vector error correction model (VECM), with the latter used to estimate projections of economic variables to 2050. The 2050 estimates are fed into a computable general equilibrium (CGE) model and shocks from the different energy mix pathways are applied to the CGE model, with policy response adjustments and wider economic implications estimated for future policy consideration.

It was found that environmental taxes have a stronger long run relationship with CO_2 emissions abatement than electricity generated from nuclear fission, with the implication that commercialised fusion power would need a consistent and safe level of electricity generation in order for it to have a strong long run correspondence to CO_2 emissions abatement. The next empirical chapter finds that a configuration of the UK's future energy mix that includes fusion power is able to meet the 80% emissions reduction target in 2050 based on 1990 levels, while providing a cheaper cost of the entire energy system than the expert pathways that were developed by multinational organisations. Finally, it was found that the shocks on aggregate capital investment in the CGE model from the Fusion Pathway and the respective policy response adjustments produce a more stable economic environment in 2050 than the shocks and policy response adjustments from a competing expert pathway, with the latter producing distortionary increases in overall prices, indirect taxes and its environmental tax constituent.

CHAPTER 1

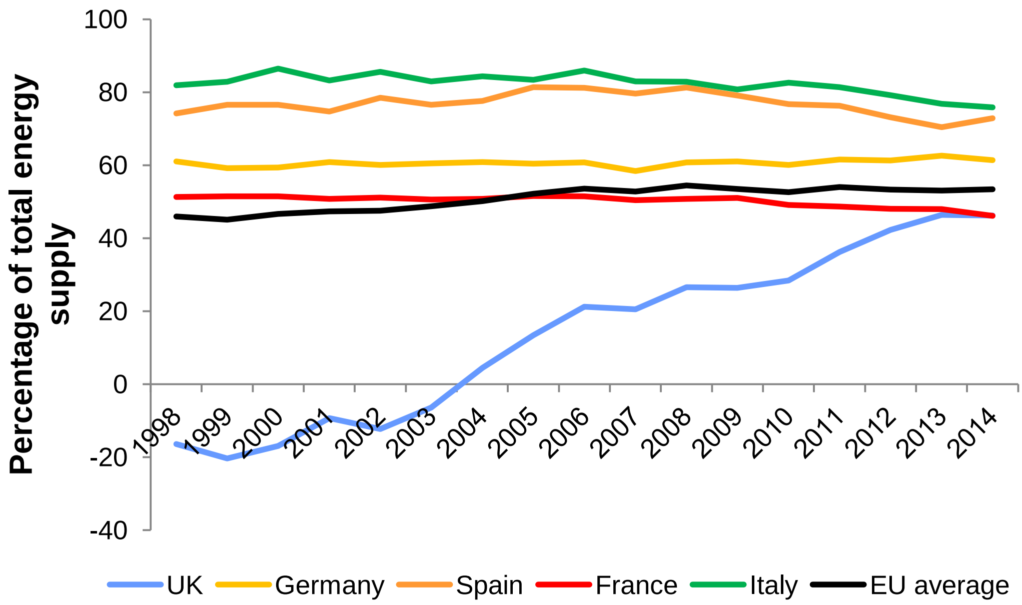
INTRODUCTION

1.1 Global challenges within the energy system and the role of fusion power

Access to a safe, inexpensive and stable source of energy supply is vital for the sustenance of human development and economic growth. The harnessing and use of energy has been an ongoing development over the centuries, with its early use in the preparation of food and production of metallic tools to the generation of heat for winter protection. Substantial improvements in primary energy extraction in the 19th century coincided with reciprocal advances in the distillation of crude oil. Innovations in the development of the internal combustion engine (ICE) and power plant in the late 19th and early 20th century led to the development of car assembly lines for mass car production and enhanced electricity distribution systems for industrial, business and household consumption. Yet, the seemingly unending dependence on finite hydrocarbon fuels in the post-World War II era has posed a threat to the energy security of net energy importers in the developed world. This presents an energy sustainability challenge to national governments and the myriad of stakeholders within the global energy system.

Within the European Union, a major energy security issue comes in the form of its long-term dependence on energy imports. The EU is the world's largest net importer of energy products, with the majority of its imports being oil and gas. The European Commission indicated that in 2012, 53.3% of the EU's energy supply came from imports, which was a higher figure than in 2010 due to the increasing demand for solid fuels and crude oil for refined petroleum products. A disturbing fact is that during the same period, 65.8% of the EU's gas supply and a historic high of 86.4% of its oil supply came from imports (EC, 2014). A significant proportion of these supplies were from nations that the EU generally regards as politically unstable regions. Figure 1.1 shows the extent of import dependency for the UK, the EU's four largest energy consumers and the EU average:

Figure 1.1: Percentage of energy supply made up of net imports for the UK, the EU's four largest energy consumers and the EU average



Source: ONS (2016)

From an economic perspective, theory suggests that volatile increases in the price of oil in global commodity markets have a negative effect on a developed economy. The effect is especially prominent in net energy importers such as the UK where the ripple effects are felt in the oil supply channels and the supply of goods and services. Demand for petroleum products is inelastic, which means that changes to prices are unable to affect consumer purchasing habits, especially in the short run[1]. As consumers are unaware of the length of time of an oil price increase, many lower and middle-income earners would make adjustments by reducing their expenditure on goods and services in order to maintain their expenditure on fuel for daily essential uses. Any increases in expenditure on net oil imports through price hikes would be transferred abroad and do not count towards GDP, so the overall effect of price hikes in net oil imports is reduced household consumption and reduced GDP.

The problems with energy security, sustainability and volatile oil prices are compounded by the urgent need to mitigate greenhouse gas (GHG) emissions that result from energy generation, industrial production and consumption. The International Panel on Climate Change 4th Assessment Report suggested that in order to stabilise GHG emissions to an

[1] Kilian and Murphy (2013) used a structural vector autoregression (SVAR) to estimate the short-run price elasticity of oil demand to be -0.2, which took into account the role of oil inventories in the smoothing of oil consumption. The result was even higher than traditional estimates that do not account for oil price endogeneity.

average of 2 ^{o}C (3.6 ^{o}F) above pre-industrial levels, GHG emissions would need to be halved by 2050 in comparison to the 2005 level (IPCC, 2007a). However, the World Energy Outlook report from the International Energy Agency indicated that at the current rate of relatively insignificant emissions abatement, fossil fuels would remain the dominant global source of primary energy by 2040 (IEA, 2014).[2] Global fossil fuels consumption would account for 80% of total primary energy consumption in the "Current Policies Scenario", with coal consumption more than 50% higher in 2040 than in 2012.

Based on the IPCC's recommendation for a significant level of GHG emissions abatement in developed countries, the European Council in 2009 supported the EU goal for an 80-95% reduction in GHG emissions relative to 1990 levels. The European Parliament also endorsed an 80% reduction target by 2050, with a medium-term target of a 25-40% GHG emissions reduction relative to 1990 levels by 2020 (EC, 2011a). These policies had filtered through to a national level with the Conservative-led coalition government reiterating its commitment to the 2050 decarbonisation target in 2012 through its Annual Energy Statement (DECC, 2012). There's an even more ambitious target that was established at an EU level by 2020: The British government has aligned itself with this target by committing to the actualisation of a "*20% overall share of renewable energy in the EU and a 10% share for renewable energy in the transport sector*" by 2020 (European Commission, 2009).

It is clear that the process by which the UK meets the 80% emissions abatement target would be the through the decarbonisation of electricity generation. In their Energy Roadmap 2050 report, the European Commission stated that "*Electricity will play a central role in the low carbon economy. The analysis shows that it can almost totally eliminate CO_2 emissions by 2050, and offers the prospect of partially replacing fossil fuels in transport and heating*" (EC, 2011b). The Committee on Climate Change, which was created under the Climate Change Act 2008 to advise the British government on its legal requirement towards the 2050 decarbonisation target, echoed the sentiments towards full electrification at a European level while indicating major investments were needed in order to achieve this. They stated that these investments would create an "*opportunity for the UK to start building a decarbonised electricity generation system. Seizing this opportunity is vital, especially given the likelihood*

[2] Asian countries are the main drivers of this growth. However, the projected growth towards 2030 is slower than in the World Energy Outlook 2008 due to the impact of the global economic meltdown caused by the sovereign debt and financial crisis.

that electricity will play an increasing role in energy use beyond 2020, particularly in surface transport and heating" (Committee on Climate Change, 2008).

The former Chief Scientific Advisor to the UK's Department of Energy and Climate Change, Sir David MacKay assessed the move towards full electrification on behalf of the UK Government and recommended different scenarios that would enable the UK's 2050 decarbonisation target to be met (MacKay, 2012). From a supply-side perspective, this would involve a significant growth in electricity generated from nuclear fission and renewable sources (especially offshore wind) as well as the commercial introduction of nascent decarbonised electricity generation sources such as carbon, capture and storage (CCS). This must be weighed against the future retirement of oil and coal-fired power plants (excluding those fitted with CCS technology) and electricity imports through the interconnectors with France and the Netherlands. From a demand-side perspective, the recommendation was for a significant growth in the electrification of industrial processes, increased electrification of commercial and residential appliances, and shifts towards plug-in hybrid and zero emission vehicles

However, the variability of electricity supply from renewable sources, the pre-development status of CCS and public perceptions of the hazards from nuclear waste that were highlighted by OECD (2010) means that other sources of electricity supply are required for the 2050 decarbonisation target. When considering the 2050 period, nuclear fusion could be regarded as the most significant potential new source of high volume electricity. Nuclear fusion involves the 'forcing together' of atoms, which is the process that takes place inside the sun. Fusion reactions are possible between certain elements but the easiest fusion reactions use deuterium and tritium, which are both hydrogen isotopes (Ongena and van Oost, 2006). The fusion process is the opposite of fission, which involves the splitting of atoms to create energy. Fusion creates even more heat, light and energy and promises an almost limitless source of energy for the earth as deuterium is abundant in the world's oceans. Fusion power could therefore gradually replace fossil fuels as a global, high volume source of electricity if commercialisation takes place during the middle and latter half of this century.

The €13bn International Thermonuclear Experimental Reactor (ITER) project in Cadarache, France has been hailed as the world's most important fusion reactor project for the creation of fusion power. The ITER fusion reactor is situated in a central area within the Cadarache site where a giant magnetic field will be formed to create a container for the fusion reactions to take place. The magnetic field is the only known entity that could physically contain the internally generated plasma with a temperature of up to 150 million degrees Celsius, the highest man-made temperature in world history and 10 times hotter than the sun's core (ITER, 2014). A smaller reactor, the Mega Amp Spherical Tokamak (MAST) had 10 times less volume than ITER and was developed at the UK Atomic Energy Authority's CCFE laboratory in Culham, Oxfordshire. From a technological perspective, ITER would seek to demonstrate that fusion could produce almost limitless electricity that is clean, safe and emissions-free. From an economic perspective, the potential future roll-out of fusion power plants may provide a major catalyst for towards economic growth and development.

1.2 Research objectives, methodology and contribution

The central objective of the research involves the estimation of the potential environmental and economic impact of commercialised fusion power. The assessment is estimated for the 2050 period, which represents the British Government's target date for an 80% reduction in GHG emissions, based on 1990 levels. The research takes into account the econometric and techno-economic energy models used for estimation, the role of punitive government action in emissions abatement, the total cost of different energy mixes and the wider economic impact of commercialised fusion power on areas such as trade and consumption.

While Chapter 2 provides a detailed review of the empirical literature and modelling techniques that underpins this thesis, the first empirical section of this thesis begins in Chapter 3. The single equation, multivariate econometric analysis in Chapter 3 provides the basis of our understanding of the potential role of fusion power, using nuclear fission (henceforth, nuclear) as a benchmark within the theoretical frameworks of the long run energy-economic-environment nexus and the environmental Kuznets curve (EKC).

The effect of nuclear energy on CO_2 emissions abatement would also be of interest to the myriad of stakeholders in fusion power research and development due to a number of similarities. The two energy sources generate decarbonised electricity from nuclear reactions and both are capital intensive with comparatively low fuel costs. Both also require long lead times from the construction of power plants to the commencement of commercial electricity generation due to the complex engineering works that are undergone during the plant development process. The similarities inevitably end there as nuclear energy produces long-lived radioactive waste and has a potential proliferation risk due to the use of fissile materials for nuclear weapons whereas fusion power has a much lower impact on the environment and a far greater abundance of primary fuel from deuterium, which is contained in seawater. Nevertheless, nuclear energy could provide an interesting guideline of the relationship between CO_2 emissions and electricity generated from power plants that have long development periods.

Chapter 3 therefore uses the single equation, autoregressive distributed lag (ARDL) / bounds test method of cointegration analysis (Pesaran, Shin and Smith; 2001) to assess the long run equilibrium and short run dynamic relationships within the nuclear-GDP-CO_2 nexus. Global action on climate change has necessitated the need for GHG emissions to be considered as part of the long-run, energy-economic-environment nexus study. Only three known sources of literature had seriously considered this area: Baek and Pride (2014) used a cointegrated vector autoregression (CVAR) to model the long run relationship between nuclear electricity generation, CO_2 emissions and per capita GDP in six countries. On the other hand, Baek and Kim (2013) and Iwata et al (2010) used the ARDL-bounds testing method of cointegration analysis with similar variables solely for South Korea and France respectively.

There is limited evidence in the literature of a comprehensive use of the ARDL-bounds test method of cointegration for the energy-economic-environment nexus in the UK. This thesis therefore fills this gap by providing a significant contribution to the empirical literature that concerns the short and long run relationships between British nuclear energy, GHG emissions abatement and economic growth, represented by gross domestic product (GDP). The nuclear-GDP-CO_2 elasticities would also provide a future guide for the UK's fusion power programme concerning the expected estimates of any future elasticities for fusion power within a multivariate framework.

This chapter also assesses this relationship through the estimation of Granger causality tests. It is remarkable that only Iwata et al (2010) had considered CO_2 emissions as an additional variable within the Granger causality test of the nuclear-GDP nexus. This thesis therefore provides an empirical contribution to this area through the inclusion of CO_2 emissions as a variable within a multivariate framework that includes nuclear electricity production, GDP and other economic variables for the UK. An additional empirical contribution would come through a comparison of the results between the Wald test from a standard multivariate Granger causality estimation and the modified Wald (MWald) test proposed by Toda and Yamamoto (1995). The MWald tests are included as it provides a more statistically robust estimation than the standard Wald test through its adherence to a chi-squared (χ^2) distribution.

The following research questions are addressed in Chapter 3:

(a) What does the econometric modelling of nuclear fission tell us about (1) the environmental impact of electricity generation in conjunction with other economic variables and (2) the potential future impact of fusion power?
(b) What additional information could we gain if we include an additional variable that enables a comparative analysis of the effect on CO_2 emissions abatement between punitive government action and nuclear electricity generation?
(c) While taking nuclear electricity generation into consideration, is there a point during the sample period where the ratio of CO_2 emissions to GDP declines?

The empirical analysis in Chapter 4 takes into account the modelling frameworks that were used by the UK Government and other organisations in its projection of the long-term energy mix scenarios to 2050. The general view from the energy projections of non-governmental organisations (NGOs) and energy sector associations is that electricity consumption will need to increase dramatically in 2050 from 1990 levels based on the shift in primary energy inputs used in electricity production (WWF, 2007; Eurelectric, 2010; Greenpeace, 2010; WBCSD, 2010). DECC (2009) described how the UK's final energy consumption of electricity increased in 1978 from 19.3 million tonnes of oil equivalent (Mtoe) to 29.4 Mtoe in 2008, an increase of 52.3%. No other major type of final energy consumption has achieved such growth within this 30-year period. The energy stakeholders had also factored in an increase in the decarbonisation of power generating facilities, increased renewable energy sources, increased carbon capture and storage (CCS) and moves towards transport electrification.

It is clear from these policy objectives that commercialised fusion power could potentially contribute to mitigating some of the disadvantages that these organisations have noted in their energy projections towards 2050 such as the impact on the economy, land availability for bioenergy, the future of fossil fuels and the role of nuclear energy. Chapter 4 therefore provides a contribution to the energy modelling literature for 2050 by including fusion power for the first time into the Department of Energy and Climate Change (DECC) 2050 Energy Calculator.[3] This techno-economic energy model would require a unique recalibration in order to integrate fusion power within the UK's 2050 energy mix. Projections of economic variables include the costs of capital expenditure, operations and fuel inputs as well as projections of emissions, energy demand and energy supply.

The following research questions are addressed in Chapter 4:

(a) What are the demand, supply and economic assumptions for the "Fusion Pathway" that underpins the recalibration of the 2050 Energy Calculator?
(b) How does the policy objectives from the output of the Fusion Pathway compare with the policy objectives from other multinational organisations that have used the 2050 Energy Calculator to model the UK's future energy mix?

The post-Kyoto Protocol global agenda on climate change mitigation saw a flurry of literature that sought to determine the effects of policy instruments on GHG emissions abatement while assessing the overall impact to the economy. Gottinger (1998), Zhang (1998), Rose and Oladosu (2002), O'Ryan et al (2005), Schaefer and Jacoby (2005) and Böhringer and Löschel (2006) were among a number of studies that addressed this area by using computable general equilibrium (CGE) models to estimate the macroeconomic impact of carbon emissions permits and/or carbon taxes, albeit at various permit pricing and carbon tax regimes. The post-financial crisis era of 2007-08 had increasingly seen CGE models used in conjunction with bottom-up, partial equilibrium projections of the 2050 energy mix in order to assess the future macroeconomic impact of differing energy and environmental policies.

Chapter 5 therefore consists of a multiequation analysis, which initially involves the estimation of five theoretical relationships of economic and fiscal variables using Johansen's maximum likelihood estimator of cointegration analysis (Johansen; 1988, 1991) and the vector error correction model. Forecast evaluations and projections are then made towards 2050, with the projections acting as inputs into a CGE model that uses the Salter-Swan theoretical

[3] Since July 2016, the Department for Energy and Climate Change has merged into a new Department for Business, Energy and Industrial Strategy (BEIS). The 2050 Energy Calculator still retains its original name as at December 2016.

framework. The estimates from the Fusion Pathway and competing energy mix pathways from the previous chapter then act as shocks to specific areas of the British economy's 2050 projections. Policy response adjustments are subsequently applied to variables such as environmental taxes (through the indirect tax variable), which enables the wider economic impact to be determined from the competing energy mixes. This particular modelling route provides a major thrust to the thesis' overall contribution as no existing studies had used the multiequation route to estimate the economic impact of a fusion pathway and other energy mix scenarios for 2050. The study that provides the nearest methodology to this particular chapter is Moore (2011), who used the Salter-Swan CGE framework to model the economic impact of two climate change scenarios on projected economic and environmental data for 2050

The following research questions are addressed in Chapter 5:

(a) How does the five theoretical relationships encapsulate the UK's economic activity?
(b) Would the estimated econometric projections towards 2050 enable reasonable inferences of the British economy to be made?
(c) What is the extent of the policy response adjustments of the competing energy mix scenarios for 2050 and what are the wider economic impacts of these adjustments on the projected economic variables?

1.3 Overview of the thesis

Chapter 2 provides a literature review of the role of fusion power from a technical, historical and economic perspective. The econometric results from the assessments of the current energy mix are highlighted with a special emphasis on the use of cointegration analysis, vector error correction modelling and Granger causality in order to estimate the role of nuclear energy within a multivariate framework. A review is given on the partial equilibrium, techno-economic energy models that were used in the literature to generate projections of the UK's energy mix to 2050, the target year for the 80% emissions reduction over 1990 levels. The energy policy objectives for the 2050 target year are also provided from a number of European organisations. Finally, the wider economic impacts of differing emissions abatement scenarios are considered through the use of computable general equilibrium models, with the literature focusing on the historical and empirical application of these models.

Chapter 3 uses the ARDL-bounds test method of cointegration analysis to estimate the long and short run elasticities of the energy-economic-environment nexus, with nuclear energy used for benchmark purposes. The multivariate model includes an environmental tax variable as it would offer a comparative analysis of the effect on CO_2 emissions abatement between punitive government action and nuclear electricity generation. Further assessments include tests of the turning point on the environmental Kuznets curve and two methods of Granger causality analysis.

Chapter 4 provides a unique recalibration of the UK government's 2050 Energy Calculator, which adds fusion power into the energy mix. The new "Fusion Pathway" consists of a configuration of the energy mix with professional estimates of fusion capital and operating costs. Projections from the Fusion Pathway are made towards 2050, which are compared to two existing expert pathways that were estimated by National Grid plc and Friends of the Earth. Estimates include projections of greenhouse gas emissions, measured in metric tonnes of CO_2 equivalent as well as energy supply, energy demand and costs of the energy system.

Chapter 5 uses multiequation econometric methods to project estimates of economic variables towards 2050. A CGE model that follows the Salter-Swan framework then considers the comparative impact of the Fusion Pathway and Friends of the Earth Pathway on the projected estimates of the UK's economy in 2050, with the National Grid Pathway acting as the reference pathway.

Chapter 6 provides a summary of the main findings and a synthesis of the conclusions, which have implications for policy decision makers. The limitations within the thesis are summarised and recommendations for future research are offered.

CHAPTER 2

LITERATURE REVIEW

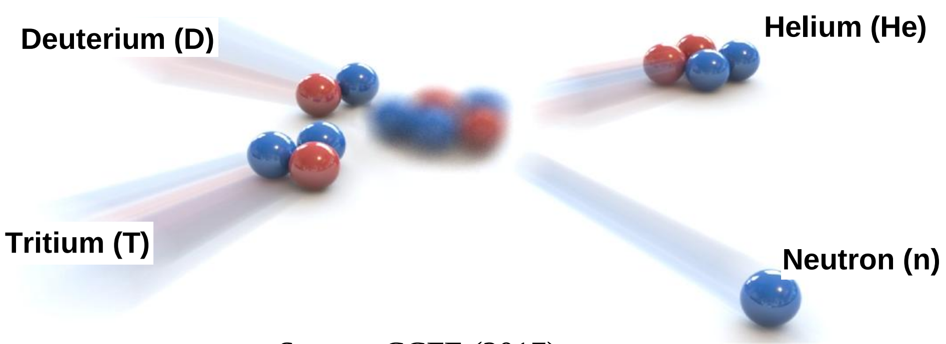
2.1 Introduction

2.1.1 Review of fusion power

Nuclear fusion is a fundamental energy reaction that is present in the sun and all of the stars of the universe. Fusion reactions involve the forcing together of atoms in order to produce extraordinarily high temperatures, which result in the release of vast amounts of energy. This process is the opposite of nuclear fission, which involves the splitting of atoms for the release of energy. The United Kingdom Atomic Energy Authority (UKAEA) currently owns and operates the UK's pioneering national laboratory for fusion power research, the Culham Centre for Fusion Energy (CCFE). Fusion power research in the UK and worldwide seeks to reproduce this naturally occurring stellar process here on earth for the production of unprecedented quantities of fusion power that are free from greenhouse gas emissions.

CCFE (2012a) describes the easiest method of achieving a fusion reaction on earth through the fusion of deuterium and tritium, each being heavy forms of hydrogen. The deuterium-tritium fusion process produces a helium and high-speed neutron nucleus, with both elements carrying energy. The higher-energy neutrons carry kinetic energy that are decelerated by a blanket of dense material to produce electricity in a fusion power plant (CCFE, 2012b).

Figure 2.1: Schematic of the deuterium - tritium fusion reaction

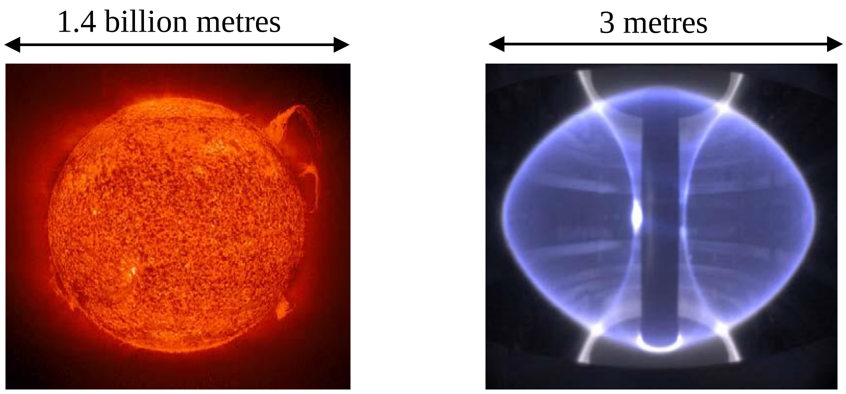


Source: CCFE (2017)

Deuterium is a naturally occurring, non-radioactive hydrogen isotope that can be extracted from seawater and all of the world's oceans. Approximately 35g of deuterium for every cubic metre of seawater can be extracted while tritium can be produced from lithium (an abundant light metal), which is subsequently recycled backed into the fusion power plant as fuel (EURATOM, 2004). CCFE (2012a) provides a window into the enormous efficiency of fusion power by explaining that the lithium contained in one laptop battery in conjunction with half a bath of seawater would provide energy for 200,000 kW hours of electricity, approximately 70 tonnes of coal. This is equivalent to the UK's per capita electricity consumption for around 30 years.

Fusion reactions naturally occur within the sun with temperatures of around 6,000 ^{o}C on the surface and 15 million ^{o}C at the core. According to ITER (2014), the temperature of the sun combines with its density at its core to form the necessary conditions for the generation of fusion reactions. The earth's gravity is far too weak in comparison so a different technique is required to generate fusion power at much higher temperatures than the sun's core. In fact, the temperatures in a fusion reactor must reach around 150 million ^{o}C or 10 times the temperature of the core of the sun in order to achieve the fusion reaction process on earth.

Figure 2.2: Hot plasma naturally occurs in the sun and man-made at CCFE



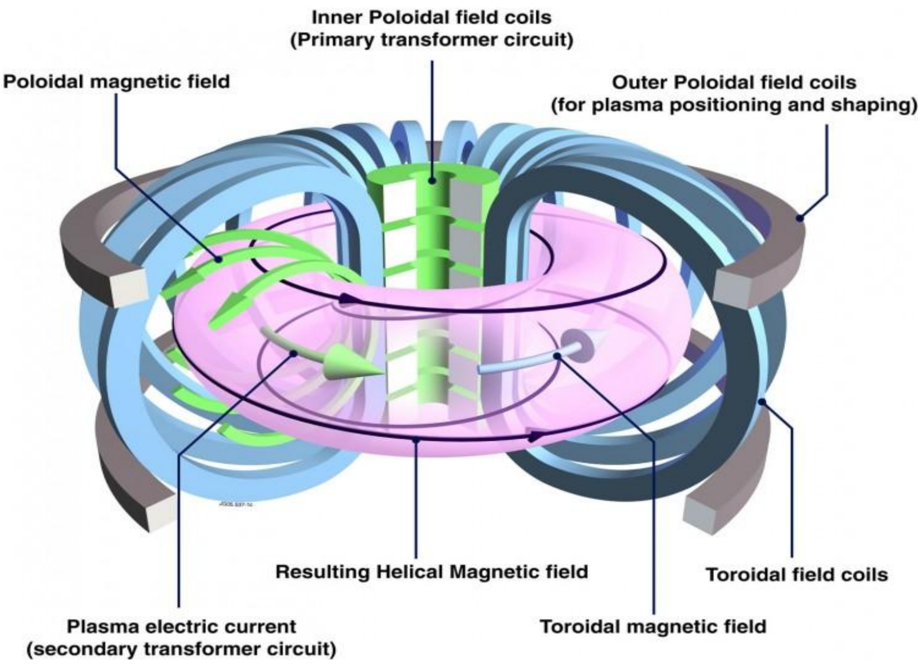
Source: CCFE (2010)

2.1.2 Technology used in fusion power production

Plasma is one the four states of matter with the other three states being solid, liquid and gas. General Atomics (2001) describes the properties of plasma as a "*gaseous soup of positively and negatively charged particles*" which result from atoms that are heated to very high temperatures. In a fusion reaction, the plasma becomes exceptionally hot and fragile and must therefore be contained in a magnetic confinement system. The tokamak is currently the world's most advanced magnetic confinement system and is the basis of future confinement system designs across the world[4]. Tokamaks contain a vacuum vessel, which creates the plasma by driving a current through a small puff of gas. The hot plasma would be contaminated and cooled if it came into contact with any surfaces so it is confined within the Tokamak by toroidal and poloidal magnetic coils (CCFE, 2014).

The heating of the plasma is provided by a transformer but it only provides a portion of the heat. Additional heating is required in order to raise the temperature of the plasma up to 150 million ^{o}C. This is provided by a high speed injection of beams of energised hydrogen atoms. As they collide with the plasma, they transfer their energy to the plasma, providing the additional heat in the process (Fusion for Energy, 2014). The UK is fortunate to host the world's largest magnetic confinement system, the Joint European Torus (JET), which has achieved all of its research objectives, including a world record 16 MW of generated fusion power[5] (EC, 2004). Figure 2.3 provides a general layout of the JET nuclear fusion reactor:

Figure 2.3: Electromagnetic coil set up of JET



Source: Eurofusion (2005)

[4] Tokamak is a transliteration of the Russian acronym TOKAMAK, which stands for “Toroidal chamber with magnetic coils”

[5] The input power for the 16MW world record was 24MW, providing a net gain of 0.7. However, a net gain of 1 is required in order to breakeven and higher net gains with minimal input power are required in order to achieve sustainable fusion power.

JET is based on the tokamak design and is the only experiment that is capable of using tritium and special materials for the lining of the inner tokamak walls such as beryllium (EFDA, 2012). JET research is the main focal point of the European Atomic Energy community (EURATOM) and is managed by UKAEA under a contract with EURATOM. Research is carried out on JET by British scientists, scientists from other EURATOM laboratories and scientists from non-European laboratories (UKAEA, 2007).

The EURATOM fusion power programme consists of a collaboration between member states and associated states (currently Switzerland) in order to pool scientific and technological expertise together for the eventual realisation of commercial fusion power. The European Commission (2014) describes the objectives of EURATOM, which focus on a variety of activities such as scientific exploitation of experimental fusion reactors, plasma physics, diagnostic studies, tritium breeding blanket research and advanced materials testing. Most EURATOM institutions operate with the tokomak model as the scientific advancements and performance of the tokamak were evident as early as 1968 (see Braams and Scott, 2001; ITER, 2008; Meade, 2011). However, some institutions use two alternative magnetic confinement models: the stellarator and reverse field pinch (RFP) devices. Table 2.1 shows a summary of the main experimental fusion reactors at the EURATOM network of laboratories and the heating power for the plasma:

Table 2.1: Devices within the EURATOM network of fusion power laboratories

Name	Device	Organisation	Location	Operation year	Heating (MW)	Plasma volume (m^3)
ASDEX Upgrade	T	IPP	Garching, Germany	1991 - present	27	13
COMPASS-D	T	IPP	Prague, Czech Republic	2006 - present	0.6	U
EXTRAP-T2R	RFP	NFR	Stockholm, Sweden	1994 - present	3	0.4
FTU	T	ENEA	Frascati, Italy	1990 - present	9.2	U
ISTTOK	T	IST	Lisbon, Portugal	1991 - present	1	0.06
JET	T	UKAEA	Culham, UK	1984 - present	38	100
MAST	ST	UKAEA	Culham, UK	1999 - 2013	5	8
RFX	RFP	ENEA	Padua, Italy	1992 - present	40	8
TCV	T	CRPP	Lausanne, Switzerland	1992 - present	4.5	1.47
TEXTOR	T	FZJ	Julich, Germany	1983 - 2013	9	7
TJ-II	S	CIEMAT	Madrid, Spain	1997 - present	2	1.1
TORE SUPRA	T	CEA	Cadarache, France	1988 - present	20	25
Wendelstein 7-X	S	IPP	Greifswald, Germany	2015 - present	14	30

T = Tokamak, ST = Spherical Tokamak, RFP = Reversed Field Pinch, S = Stellarator and U = Unavailable data

Source: European Commission (2013)

Stellarators are similar to tokamaks as they operate with the toroidal configuration but differ from tokamaks in that the toroid is helically wound i.e. spiral (Braams and Scott, 2002). Escande et al (2000) indicated that tokamaks and RFP share similar axisymmetric properties in terms of the shape of the magnetic surfaces around the torus but differ in that the toroidal field is produced by external magnetic coils in the tokamak while the toroidal field is generated by the plasma in the RFP. Escande et al (2000) further indicates that a significant issue with the RFP is that the plasma's role in generating the toroidal field tends to create magnetohydrodynamic instabilities in the plasma ring, which ruptures the torrodial symmetry of the magnetic field.

Magnetohydrodynamic disturbances in RFP devices also causes turbulence in the magnetic field lines, which diminishes energy containment. On the other hand, Helander et al (2012) argues that there are a number of advantages and disadvantages between the stellarator and tokamak including greater magnetohydrodynamic stability for the stellarator and stronger neoclassical energy confinement in the tokamak. Nevertheless, the greater plasma physics advancements of the tokamak means that stellarators are less well understood, technically more complex and have a greater number of degrees of freedom in order to find the most suitable configuration of the magnetic field (Wolf et al, 2013).

2.1.3 The International Thermonuclear Experimental Reactor (ITER)

ITER is an international scheme that is currently in the development process in Cadarache, South of France with the aim of demonstrating the technical feasibility of fusion power. ITER (2014a) points out that the scheme constitutes the largest scientific project in the world with the participating countries representing more than half of the world's population. The participating countries are the United States, the EU, China, Japan, Russia, India and South Korea.

The ITER agreement was signed in 2006 by ministers from the 7 ITER members[6] at Elysée Palace in Paris. The establishment of the ITER organisation took place in 2007 and site preparation and construction began in 2007 and 2010 respectively (ITER, 2014b). At the heart of the ITER project lies the €13bn tokamak fusion reactor, whose design is based on the JET

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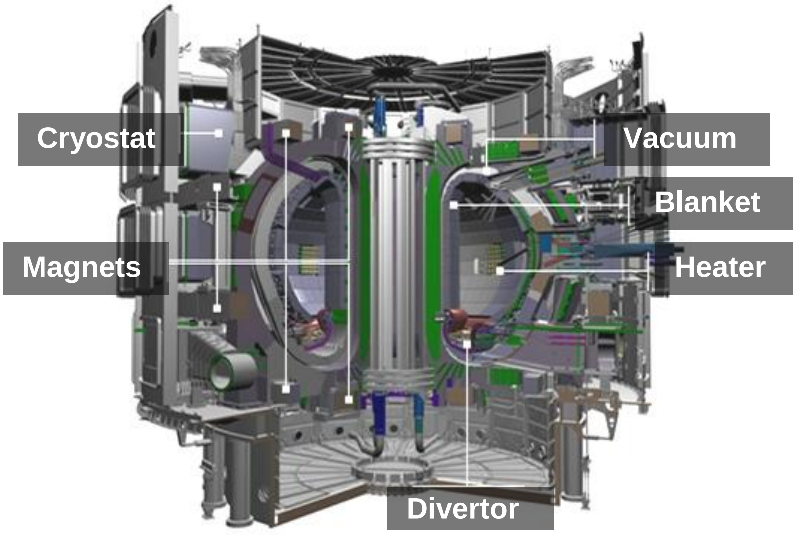
[6] The UK is expected to become the 8th ITER member in its own right after its eventual exit from the EU following the June 2016 referendum vote to leave the bloc.

facility at CCFE but double the size. The design of the ITER reactor is based on the success achieved by a wide variety of fusion experiments in Europe and around the world as well as successes in theoretical and modelling work (CCFE, 2012a). ITER (2014a) describes the dimensions and output of its tokamak, with a weight of 23,000 metric tonnes, height and width of 30 metres, Plasma volume of $840m^3$, plasma core temperature of 150 million ^{o}C and fusion power of 500MW. A number of new technologies will be tested at ITER such as superconducting coils, remote maintenance and tritium breeding blankets that absorb the energy from neutrons. Figure 2.4 shows a cross section of the ITER conceptual design:

Figure 2.4: ITER nuclear fusion reactor



Source: ITER (2013)

2.1.4 Historical and current status of fusion power

The science of fusion was already understood during the first half of the 20^{th} Century. Eddington (1919) understood that a fusion process of hydrogen into helium was responsible for a star's release of energy while Hendry (1987) describes how sufficient advancements in research had been made in the 1930s such as the discovery of deuterium and neutrons, which enabled scientists to contemplate the development of a controlled nuclear fusion device. However, the story of the tokamak fusion reactor starts with Oleg Lavrentiev, a Soviet Union soldier who drew the attention of the Soviet government to controlled thermonuclear reactions. His letters were passed onto two nuclear weapons scientists, Igor Tamm and Andrei Sakharov, who subsequently conceived the design for their reactor which they called "tokamak" in 1950 (Meade, 2011).

Braams and Scott (2001) describes how fusion power stepped into the international limelight at Geneva in 1958 during the 2nd UN International Conference on the Peaceful Uses of Atomic Energy. At the time, the UN International Atomic Energy Agency (IAEA) seized the initiative by organising a series of conferences on controlled fusion and plasma physics as well as publishing the journal *Nuclear Fusion* in 1960. The 1968 IAEA conference in Novosibirsk also established the tokamak's performances in the eyes of the West. An expedition from Culham's UKAEA were left in no doubt about the spectacular performance of the Russian-designed reactors and a number of fusion power experimental reactors were built in the Soviet Union, Europe, the United States and Japan during the 1970s, This early work laid the foundation for the modern designs of the JET and ITER tokamaks.

A recurring issue with fusion power research and development is the seemingly long timescales that have been given for commercialisation. EURATOM was established alongside the European Economic Community (EEC) as part of Article 163 of the Treaty of Rome in 1957 (Treaty of Rome, 1957), with the main purpose of pooling together resources for the development and civilian use of nuclear energy (Europa, 2007). By the 1960s, it was nuclear fission and not nuclear fusion that set the pace as the commercialisation of nuclear fission went underway in the US, Europe and the Soviet Union.

Rowberg (2000) describes how the United States Congress constantly probed the fusion programme officials in the 1960s on the timescales to fusion power commercialisation while advising them to focus on concepts that would save money and accelerate development progress. The United States Congress Joint Committee on Atomic Energy (JCAE) responded by officially declaring that fusion power would be demonstrated within a 10 to 11 year period from 1967. However, Rowberg (2000) further highlights that the JCAE received a report in 1976 that fusion would not be ready for at least another 40 years and in 1984, the US Department of Energy indicated that commercial fusion power was around 40 - 50 years away due to insufficient scientific progress.

A number of studies such as D’haeseleer (2003) concluded that the commercialisation phase of fusion power might come in the early part of the second half of this century i.e. after 2050.

However, one of the recent themes in fusion power R&D is the so-called "fast-track" approach towards commercialisation, which is further incentivised by the UK and EU-wide 80% decarbonisation target by 2050. The King Report (2001) assessed the ITER-DEMO-PROTO route to commercialisation and concluded that ITER and IFMIF (International Fusion Materials Irradiation Facility) should be parallel projects. The report also concluded that the post-ITER stages of DEMO (demonstration power plant) and PROTO (prototype power plant) should be combined into a single step. Dr David Ward, Head of Power Plant Technology Unit at CCFE modelled three scenarios for a fast track option, with "Case 1" showing that an ambitious construction of DEMO after the completion of the ITER/IFMIF build is the riskiest but most financially rewarding scenario, with a potential time to commercialisation of 25 years (Ward et al, 2004). Furthermore, a group of scientists from the EURATOM/UKAEA Fusion Association concluded that the first commercial power plant could potentially be in operation 43 years after the decision to proceed with ITER and IFMIF i.e. 2006. They mentioned that the inclusion of buttresses to reduce overall risk would shave 4 years off the commercialisation date, giving 2045 as the year when the commercialisation of fusion power could take place (Cook et al, 2005). These fast-track routes had necessitated the need for modelled scenarios that would assess the contribution of fusion power as a green, sustainable energy source towards the UK's 2050 decarbonisation target.

Global optimism in the fusion R&D programme has evidently increased with the development work that is currently taking place at ITER. The UK is part of the European Fusion Development Agreement (EFDA) and the 2012 "Roadmap" stipulates their aim to achieve market penetration of fusion power by 2050 with a 30% market of electricity production by 2100 (EFDA, 2012). Despite the global ITER collaboration, EFDA specifically names China as embarking on an "*aggressive programme aimed at fusion electricity production well before 2050*", which they say, should drive Europe to focus its efforts and keep up the pace (EFDA, 2012). A brief summary of the EFDA 2012 Roadmap is as follows:

Stage 1 Construction of the 500 MW International Thermonuclear Reactor (ITER) currently underway at Cadarache, south of France with completion scheduled for 2020. Seeks to demonstrate tritium breeding and extraction. Full exploitation to be carried out from 2020 until 2040.

Stage 2 Development of the JT-60SA tokamak. This Europe-Japan joint venture is scheduled to have a 6-year assembly and commissioning period. The JT-60SA is based in Naka, Japan with first plasma production expected by 2019. The main purpose of JT-60SA would be to support and complement the work of ITER.

Stage 3 The International Fusion Materials Irradiation Facility (IFMIF) is a facility whose construction is currently underway in conjunction with ITER. This facility seeks to test materials that would be used for ITER, DEMO and future fusion power plants. Design and prototyping were carried out by agreement between Europe and Japan.

Stage 4 Construction of the demonstration fusion power plant (DEMO) to begin in the early 2030s with full tritium breeding capability.

There are challenges highlighted by the EFDA 2012 Roadmap that must be faced by DEMO prior to the realisation of commercial fusion power such as tritium self-sufficiency, maintenance of plasma at high temperatures and the development of strong materials that are able to tolerate the high-speed onslaught of 14MeV neutrons. The recommendation at the DEMO stage is for industry to gradually shift its focus from materials and components suppliers to drivers in innovation and fusion power development. Stork (2009) questions the sustainable nature of fusion power if it is dependent on helium and urges the DEMO planners to pursue the development of high-temperature superconducting magnets that do not require helium cooling. Bradshaw et al (2011) also expressed reservations about the "virtually limitless" energy term often given to fusion power as the reactors currently rely on the rare beryllium metal as an interior wall coating for neutron multiplication. They suggest that other neutron multiplier options should be sought for commercial fusion power plants.

2.1.5 The costs and potential benefits of fusion power

During the early 1980s, the United States Congress supported fusion power R&D at the expense of renewables R&D. Rowberg (2000) describes how the administration of Ronald Reagan chose to reduce federal funding of R&D budgets that they felt the private sector could handle. The first Reagan budget for fusion power in FY1982 was USD460m and USD241.7m for renewable energy. This contrasted sharply with the FY1981 budget of USD396m for fusion power and USD654.4m for renewable energy. Relatively slow scientific progress impacted the fusion power budget five years into the Reagan administration to USD333m, a 27.6% decrease from the FY1982 budget.

The past, present and future costs from the global fusion R&D programme are highlighted in Table 2.2, with data from the "Current Status" publication by the European Parliament (2003). On assessment, the EU's 5th Framework budget (1999-2002) has an average annual fusion R&D expense that is less than the 4th Framework budget (1995-1999) and is in line with the decline in R&D spending on fusion in the United States. However, despite EURATOM (2004) classifying fusion power research as a "Priority Thematic Area", the 6th EU Framework budget (2002-2006) for fusion power declined from €788m to €750m. Among the major costs of global fusion expenditure is ITER, which had a budget of €4.6bn in 2004 (EC, 2004). However, as at 2011, the project costs of ITER were nearly triple the 2004 estimate at €13bn (ITER, 2014a), drawing stinging criticism about its "exorbitant" costs from the German government's Federal Ministry of Education and Research (EUobserver, 2011). From a UK perspective, spending on fusion power research is carried out by the Research Councils via the RCUK Energy Programme. DECC (2013) highlighted UK fusion power budget of £31.9m in 2011/12, which is relatively modest in comparison to other leading fusion power developers. However, this represents a £2.1m decline from the 2010/11 RCUK fusion power budget (House of Lords, 2011) and leaves open the question of what the most appropriate level of UK Research Council and EURATOM funding that is required for the implementation of the fast track objective of commercial fusion power by 2050.

Table 2.2: Historical and future expenditure on fusion power research and development

Fusion power expenditure	**Total spent (€)**
OECD fusion power spending from 1974 - 1998	30bn
Amount spent on fusion R&D in the EU up to the late 1990s	10bn
Annual investment in fusion power R&D (as at the late 1990s)	1.4bn
Annual EU spend on fusion power R&D from 1995-1999	470m
US Dept of Energy (DOE) request for fusion R&D budget (2001)	249m
Planned fusion power budget for Germany in 2001	116m
"5th Framework" 3 year EU budget for fusion R&D (1999-2002)	788m
Investment in ITER	13bn
Investment in IFMIF (vital prerequisite for DEMO)	600m
Scheduled investment in DEMO (1,000 MW fusion power plant)	8bn
Estimated global R&D spending up to the point of future fusion electricity generation	60 - 80bn

Source: Data cited in the European Parliament (2003)

In relation to fusion electricity costs, the levelised cost of electricity (LCOE) methodology was used in a number of studies to determine the estimated discounted costs of producing fusion electricity per kWh. For example, in their study of the deployment options for fusion power plants, Sheffield et al (2000) highlighted the decline in the estimated fusion LCOE relative to the capacity of a future proposed power plant. They described LCOE ranges for two proposed power plant models of $0.038 to $0.055/kWh based on the power plant capacity range of 4000MWe to 1000MWe and an LCOE range of $0.055 to $0.087/kWh for an alternative proposed power plant model with a similar capacity range. Furthermore, EFDA (2005) found that the estimated LCOE in four different conceptual fusion power plants ranged from 5 to 9 Eurocents/kWh, dropping down to 3 to 5 Eurocents/kWh when taking into account technological maturity in power plant physics and engineering.

In terms of benefits, scientists from the EURATOM/UKAEA Fusion Association at CCFE and the EURATOM/CIEMAT Fusion Association at Madrid carried out a socioeconomic analysis of commercialised fusion power and used probabilistic decision analysis to assess its overall future value (Ward et al, 2005). The costs and benefits were then discounted to provide an NPV of the fusion power programme. Their calculations indicated a total discounted development cost of between USD 10-20bn in 50 years from 2005 with an overall discounted future benefit of USD 400-800bn based on a 10-20% market share. The market share calculation is consistent with Gnansounou and Bednyagin (2007), who used a probabilistic electricity simulation model, PLANELEC-Pro and concluded that commercialised fusion power may potentially capture up to 20% of the global energy market.

2.2. Modelling the current energy mix

2.2.1 Growth of energy as a commodity

The accelerated growth of global energy consumption finds its roots in the transition from the more traditional agricultural economy where land was used for farming and housing to a more industrial economy. Innovations during the Industrial Revolution such as the steam engine marked the major acceleration of coal as a primary source of fuel over wood fuels. The post-World War II oil and gas boom of the mid 20th century accompanied the socio-economic and political changes that were taking place around the world as oil and gas dominated the landscape for transportation fuels, heating, lighting and manufacturing.

The International Energy Agency highlighted the continued strength of demand for oil in 2014 with global demand estimated to increase by 1.3 million barrels per day (mb/d) to 92.6 mb/d, while 9 of the world's top 10 consumers of oil are projected to increase their demand from 2013 levels (IEA, 2014). Despite the rapid progress that developed nations have made in reducing their carbon emissions after the Kyoto Protocol, BP plc (2016) estimated that global oil (including biofuels) and coal consumption between 2014 and 2035 would increase on average by 1.02% and 0.48% per annum respectively, with non-OECD consumption growth driving demand. Their more significant 2011-2035 energy consumption projections came from renewables at 15.66% p/a, nuclear energy at 2.37% p/a and hydroelectric power at 2.14% p/a.

However, these projections contrast with the Shell (2011) future energy scenarios where global coal consumption is expected to double between 2000 and 2030. The so-called "scramble" to cheap coal is envisaged because of the expected pressure from national governments to encourage energy independence, even in the face of strong opposition from environmental groups and non-governmental organisations. Renewables (including biofuels) are also projected to have a greater share of global fuel consumption in 2030 than the BP plc (2016) projections. The contrasting projections between two of the world's largest energy companies raises the question: which modelling techniques produce the best forecasts and projections of the UK's energy mix and what are the relative merits of each technique?

It is arguable that there is no model that could accurately forecast the future scenarios for either the UK or global energy mix as Box and Draper (1987) famously stated that "*all models are wrong, but some are useful*". However, the role of energy as one of the dominant drivers of the global economy as well as the strong projected growth in primary energy consumption and power generation has warranted the use of a variety of sophisticated econometric and techno-economic energy models. These models have greatly helped policy makers, energy producers and investors to have an idea of the direction of the future energy mix in order to develop a strategy that helps them to maximise their benefits from the energy sector.

2.2.2 Energy models

There are general features that are common among energy models. For example, energy models should be a reflection of economic theory and should use suitable energy and economic explanatory variables that have some form of causal influence on the dependent variable such as energy price. Energy models can be classified in many ways such as static versus dynamic, bottom-up versus top-down, univariate versus multivariate or they could be classified by energy type such as oil, gas, coal, solar and nuclear. The energy type may determine the type of energy model used for forecasting or scenarios projections e.g. oil may use an autoregressive model for forecasting price. On the other hand, future energy sources such as fusion power could benefit from a bottom-up, partial equilibrium energy model as this source of energy has yet to be commercialised, which means that estimates of the price of future inputs, such as materials, are a contributory factor on the projection of electricity demand and supply scenarios.

The purpose of the energy model may also determine the modelling technique. For example, Sftetsos (2002) provides a typical scenario where wind speeds are modelled as wind energy load is a factor of wind speed, while Chen et al (2011) builds on the significant literature on the forecasting of photovoltaic power production by using a hybrid model that captures the hourly solar irradiation and air temperature levels of a region. The structural form of the energy model should be developed based on an understanding of the following:

(1) What is the purpose of the energy model (e.g. demand forecasting, price prediction, energy load factor analysis etc)?
(2) What theoretical assumptions are the energy models based on?
(3) Which types of models are best suited to adequately represent the different energy types and systems?
(4) Does the sample size of the data allow for sufficient inferences to be drawn from the model's estimates?
(5) What are the implications of the mathematical approach to the modelling technique?
(6) What is the wider impact of the results to the specific energy sector and economy?

A review is carried out on the models that were previously used to generate estimates and forecasts of the existing energy mix in order to understand the validity of the techniques against the different sources of energy. This assessment will form the basis of the modelling techniques that will act as a guide as to what to expect from fusion power.

Frey et al (2009) provides an example of a broad classification of energy price models into (a) times series models that study the statistical properties of energy data over time (b) financial models that model the relationships between spot and futures prices and (c) structural models that study causal relationships between economic and energy price data. However, the review in this section narrows down the classification as the econometrics literature on energy modelling is dominated by three techniques: (1) ARMA models (2) cointegration and the vector error correction (VECM) models and (3) Granger causality models.

2.2.3 Autoregressive moving average (ARMA) model

One of the earliest uses of the autoregressive (AR) family of univariate time series models in the 20th century came from Yule (1927) where he used an autoregressive process to model Wolfer's annual sunspot numbers, using data from 1749 to 1924. Slutsky (1927, 1937) extended the understanding of the moving average (MA) model, which he called a "*moving summation with weights of one kind or another*". However, the foundation of the ARMA model came from Wold (1938), whose "Wold decomposition" demonstrated that a stationary time series can be separated into a deterministic part and a moving average part. The Wold decomposition has come to play a central role in univariate time series analysis as it implies that the dynamic of the purely indeterministic part of a covariance-stationary process can be approximated by an ARMA process (Diebold, 2004).

The influential Box-Jenkins (1976, first edition 1970) approach for the autoregressive moving average model (ARMA) has come to set the benchmark for the estimation of univariate energy models and takes the following form:

$$y_t = \alpha_0 + a_1 y_{t-1} + \dots + a_p y_{t-p} + \varepsilon_t + \beta_1 \varepsilon_{t-1} + \dots + \beta_q \varepsilon_{t-q} \qquad (2.1)$$

Where p represents the lag lengths for the autoregressive part of the equation and q represents the lag lengths for the moving average part of the equation. In this methodology, a 3-stage process is carried out which involves: (a) model selection, with an examination of the autocorrelation and partial correlation functions, while ensuring that the variables are stationary; (b) parameter estimation and examination of the α and β coefficients; and (c) checking to confirm that the residuals display a white-noise process with constant mean and variance. In ARIMA models, the integrated element "I" denotes the order of integration of the differenced dependent variable.

The use of the Box-Jenkins methodology in forecasting grew as a result of influential studies such as Newbold and Granger (1974), who indicated that the Box-Jenkins method of forecasting performed better in a majority of time series samples than alternative methods such as the Holt-Winters and stepwise autoregression, especially over the short run. However, there were criticisms concerning the usefulness of the model, such as Makridakis et al (1979), who criticised the "accuracy" of the Box-Jenkins methodology despite the fact that forecasts can never truly be accurate and implied that exponential smoothing provides better forecasts than the Box-Jenkins method. Huss (1985) also indicated that the Box-Jenkins methods required repeated diagnostic runs and skilled judgment, which he felt was unnecessary as the forecast results should not be dependent on the forecaster's expertise.

One of the most important recent developments in the field of energy modelling is the development of hybrid models, which aim to combine the favourable aspects of the forecasting power of different modelling techniques. The literature on the combination of models for time series forecasts is well documented, with Newbold and Granger (1974) providing an early endorsement for such a modelling technique. ARIMA models can be successfully hybridised for electricity prices, with Conejo et al (2005) providing a typical example of a hybrid ARIMA model through the combination of an ARIMA and wavelet transform model to forecast day-ahead electricity prices in Spain. The wavelet transform converts a single electricity price series into multiple price series, which demonstrates a more stable variance due to the filtering effect of the wavelet transform. The ARIMA model is then applied to each of the constituent price series in order to provide hourly forecasts for a 24 hour day.

A more recent example of a hybrid ARMA model for day-ahead electricity prices is Bordignon et al (2013), who combined an ARMA exogenous (ARMAX) model, time-varying regressions models and Markov regime switching models, which capture fluctuations between normal and high price time series. Price data from the UK power exchange from April 2005 to September 2006 was used with 48 observations per day, based on the half hour intervals.

The results from the Conejo et al (2005) and Bordignon et al (2013) tests showed that univariate hybrid forecasts could produce more reasonable forecasts than the single model forecasts and provide less risk than the selection and prediction risk that could be inherent in individual models.

ARIMA models have been used to forecast primary sources of sustainable energy. However, the uniqueness of the primary sustainable energy type may contribute to the complexity of the forecasting problem, e.g. fluctuations in wind speed could impair the forecasting power of wind energy models. Early studies such as Hennesey (1978) had attempted to understand the wind speed forecasting challenge by comparing different distribution functions to model wind speed. Others such as Huang and Chalabi (1995) and Poggi et al (2003) had used conventional autoregressive models to successfully simulate wind speeds. Zhang et al (2012) continued the modern theme of model hybridisation through their development of a complex hybrid ARIMA model that was used to forecast day-ahead wind energy in China. Among the models that were aggregated include an ARIMA model, a group of univariate least squares support vector machine (LS-SVM) models and a group of multivariate LS-SVM models, with a fuzzy aggregator used to aggregate the results. The ARIMA hybrid model was compared with the individual models using forecast evaluation methods such as mean absolute percentage error, with the ARIMA hybrid showing a consistently stronger performance in forecasting short-term wind energy.

In the case of solar energy, Pedro and Coimbra (2012) chose a hybrid ARIMA model in order to capture the uncertainty from solar irradiance for a 1MW solar power plant in Merced, California. Exogenous variables were used to provide a number of different forecasts from an ARIMA model, two Artificial Neural Network model types and the persistent model. The persistent model is a simple forecasting model where calculations are performed for future values of a time series and are based on the assumption that weather conditions stay unchanged between time t and time $t + \Delta t$ (Δt can be 1 or 2 hours in this example). As is the case with most weather based models, the viability of estimates from the ARIMA hybrid model is predominantly dependent on the seasonal variability of sunlight.

2.2.4 Cointegration and elasticity studies

While the contribution from univariate time series modelling techniques such as the ARIMA is undoubted, the empirical contribution to the energy modelling literature in this thesis is predominantly focused on the estimation of multivariate time series models. Multivariate time series analysis is commonly used by econometricians to assess economic relationships between variables and there is a considerable amount of interest in the theoretical improvement and empirical extension of such techniques. The concept of cointegration was published by Engle and Granger (1987) and can be described as a long-run linear relationship between variables that are individually integrated of order *n*. For example, a stationary linear combination of nonstationary variables that are individually integrated of order one - $I(1)$, are said to be cointegrated. Johansen (1988, 1991) contributed significantly into the cointegration space with his maximum likelihood (ML) estimator circumventing the limitations of the two-step Engle-Granger approach.

On the other hand, a vector autoregression (VAR) is a system of equations that models linear interdependencies among lagged variables. Sims (1980) is generally viewed to be one of the early leading advocates of the VAR model as an alternative representation of multivariate simultaneous equation models that were used at the time. Since then, a number of VAR models were used to model the energy mix with Keng (1985) providing an early example of how causal energy and economic variables were used for a VAR model in order to generate forecasts for Canada's early-stage nuclear industry. However, a VAR model can only be fitted to cointegrating variables for energy elasticity studies if it is reparameterised into a vector error-correction model (VECM) as VARs fitted to $I(1)$ cointegrating variables exhibit misspecification errors.

Despite the recent strides in the use of cointegration and VECM for energy demand elasticity studies such as those connected to oil, the literature in the field of electricity demand elasticities based on aggregated primary energy is less prevalent. Notable studies of industrial electricity demand elasticities at a national and international level were conducted by Beenstock et al (1999), Stern (2000), Galindo (2005), Polemis (2007), Yuan et al (2008), Hatzigeorgiou (2011), Polemis and Dagoumas (2013), Lin and Ouyang (2014) and Lim et al (2014). In these studies, the long-run electricity demand elasticities in relation to industrial activity ranged from 0.85 to 1.44 with a short-run elasticity of 0.61 as in the case of Polemis

(2007). For price, the long-run electricity demand elasticities ranged from -0.25 to -0.85 and the short-run elasticities range from -0.08 to -0.35. The lack of general consensus in these studies comes as a result of the countries assessed, varying industrial sectors, model specification, data frequency and the length of time span. Yuan et al (2008) further points out that it would be unwise to expect consensus on industrial electricity demand elasticities due to the subject country's stage of economic development and its relative impact on the energy-economy nexus. Nevertheless, the price-inelastic nature of electricity demand runs in conjunction with the theoretical assumption that energy use is generally regarded as a necessity (Belke et al, 2011).

The UK and EU's action against GHG emissions, the volatility of oil and gas prices, and the geopolitical problems faced by fossil fuels-rich nations have led to an increasing emphasis on the role of nuclear fission within the future global energy mix. The current installed global nuclear fission energy capacity as at January 2015 is 373 GW (Nuclear Energy Institute, 2015). However, the International Energy Agency (IEA, 2010) put forward a powerful appeal for political backing and public acceptance towards the tripling of global nuclear capacity to 1,200 GW by 2050. This would generate nearly 10,000 TWh of annual electricity production with nuclear's share of global energy output reaching 24%. This projected increase in nuclear capacity is consistent at a UK level where the House of Lords (2011) urged the UK Government to make plans for the early decarbonisation of UK power generation and for nuclear capacity to increase from its current 12 GW of capacity to a potential high of 38 GW by 2050[7].

While the importance of nuclear fission for the world's sustainable energy future is undoubted, the literature that focuses specifically on the long-run modelling of elasticities between nuclear fission energy production / consumption and other variables is especially scarce with only a handful of available studies such as Apergis and Payne (2010), Lee and Chiu (2011) and Jobert et al (2013). These studies mainly had a multi-country focus and used different cointegration modelling techniques and data ranges to generate elasticities between nuclear fission energy and other variables such as GDP, CO_2 emissions and oil prices. Table 2.3 provides a summary of the energy-economic studies with nuclear electricity demand or supply variables modelled within a multivariate framework:

[7] The House of Lords also expressed their serious doubts about this target through their rebuke of the government's lack of "leadership and strategic thinking" and that UK's past strengths in nuclear R&D were diminishing as many experts were near retirement.

Table 2.3: Elasticity studies for nuclear fission electricity generation and demand

Literature	Country	Method	Data	Dep. variable	Estimates of elasticity	
Apergis and Payne (2010)	16 countries (incl. nuclear dependent France)	Panel cointegration	Panel data (annual) 1980 - 2005	GDP	Nuclear demand *LR*: 0.32%	Capital formation *LR*: 0.17%
Baek and Kim (2013)	South Korea	ARDL / Bounds test method of cointegration	Time series (annual) 1978 - 2007	CO_2 emissions (metric ton per capita)	Per capita GDP *LR*: 7.8%	Nuclear generation (% of total energy) *LR*: −0.45%
Baek and Pride (2014)	US, France, Japan, South Korea, Canada and Spain	Cointegrated VAR	Time series (annual) 1965/80 - 2007	CO_2 emissions (metric ton per capita)	Per capita GDP *LR*: 0.85% to -4.3%	Nuclear generation (% of total energy) *LR*: -0.5% to -1.8%
Iwata et al (2010)	France	ARDL / Bounds test method of cointegration	Time series (annual) 1960 - 2003	CO_2 emissions (metric ton per capita)	Per capita GDP *LR*: 3.1% to 37.21%	Nuclear generation (% of total energy) *LR*: -0.26% to -0.31%
Jobert et al (2013)	21 countries	Panel cointegration / DOLS	Panel data (annual) 1980 - 2009	Petroleum demand		Nuclear demand *LR*: -14.44
Lee and Chiu (2011)	Canada, France, Germany, Japan, UK and the US	Panel cointegration / DOLS	Panel data (annual) 1971 - 2006	Per capita nuclear demand	Oil prices *LR*: 0.12%	Per capita GDP *LR*: 0.89%

Key: *LR* = long-run elasticity, Dep. = dependent, DOLS = dynamic ordinary least squares, ARDL = autoregressive distributed lag

In summary, the Baek and Kim (2013) results for South Korea, the Baek and Pride (2014) results for six developed countries and the Iwata et al (2010) results for France show that electricity generated from nuclear fission within the nuclear-GDP-CO_2 nexus corresponds to the long run decarbonisation strategies of the subject countries. This is because a 1% increase in nuclear electricity generation corresponds to a -0.26 to -1.8% decrease in CO_2 emissions. From an economic perspective, there is a long run relationship between income/GDP growth and increases in nuclear energy demand in the estimates from Apergis and Payne (2010), and Lee and Chiu (2011). The results therefore provide the hypothetical foundation from which the long run estimates in the following chapter would be assessed.

2.2.5 Granger causality studies

One way to test causality between variables in a VAR is to assess whether the past value of an independent variable influences the current value of the dependent variable. Granger (1969) is credited with formulating the "Granger-causality" test, which is regarded as a straightforward and general method of causality testing. Quite simply, variable X is deemed to Granger-cause variable Y if, based on the past values of Y, past values of X are effective in predicting Y.

Apergis and Payne (2010) highlighted four hypotheses that concern the causal relationship between economic growth and energy consumption. The first is a growth hypothesis which proposes that energy consumption E influences economic growth G as well as labour and capital indirectly through the production process. The presence of a unidirectional causality in this instance would be from $E \rightarrow G$. The second is a conservation hypothesis which proposes that energy conservation policies will not have a negative impact on economic growth and the presence of unidirectional causality would be from $E \rightarrow G$. The third is a feedback hypothesis which proposes that economic growth and energy consumption are interlinked and the presence of bidirectional causality would be between $E \leftrightarrow G$. Here, E and G interdependently drive each other with the implication of negative growth if energy conservation policies are pursued. The fourth is a neutrality hypothesis, which proposes that energy consumption represents a small section of the economy with little or no effect on economic growth. In this instance, the absence of causality between $E\ and\ G$ supports this hypothesis and energy conservation policies might be pursued with minimal or no impact on economic growth.

Early causality studies such as Kraft and Kraft (1978) provided strong evidence of a unidirectional causal relationship from income to energy consumption. However, despite the format of the previously stated hypotheses, the literature concerning the causal relationship between nuclear energy and GDP is scarce, with only a handful of available studies for consideration. Furthermore, there is a lack of consensus concerning the causal relationship between GDP and the generation and/or consumption of nuclear energy with developed nations reporting a mixture of $Nuc \rightarrow G$, $G \rightarrow Nuc$ and $Nuc \leftrightarrow G$ causal relationships. Table 2.4 highlights the limited number of studies that had delved into the causal relationship between nuclear and other variables.

Table 2.4: Studies of Granger causality between nuclear energy and other variables

Literature	**Data**	**Country**	**Direction of causality**	**Number of variables**
Iwata et al (2010)	Time series (annual) 1960 to 2003	France	$GDP \rightarrow CO_2$ $NucG \rightarrow CO_2$	Bivariate
Yoo and Jung (2005)	Time series (annual) 1977 - 2002	South Korea	$NucC \rightarrow GDP$	Bivariate
Yoo and Ku (2009)	Time series (annual) Min: 1984 - 2005	South Korea France Switzerland	$NucC \rightarrow GDP$ $GDP \rightarrow NucC$ $GDP \leftrightarrow NucC$	Bivariate
Apergis and Payne (2010)	Panel data (annual) 1980 - 2005	16 countries	$NucC \rightarrow GDP$ $Cf \rightarrow GDP$ $Lab \rightarrow GDP$ $GDP \leftrightarrow NucC$	Multivariate
Lee and Chiu (2011)	Panel data (annual) 1971 - 2006	Japan Canada Germany UK	$Inc \rightarrow NucC$ $Inc \leftrightarrow NucC$ $Inc \leftrightarrow NucC$ $Inc \leftrightarrow NucC$	Multivariate
Wolde-Rufael (2010)	Time series (annual) 1971 - 2005	Canada Japan Netherlands Switzerland Sweden France Spain UK US	$GDP \rightarrow NucC$ $NucC \rightarrow GDP$ $NucC \rightarrow GDP$ $NucC \rightarrow GDP$ $GDP \rightarrow NucC$ $GDP \leftrightarrow NucC$ $GDP \leftrightarrow NucC$ $GDP \leftrightarrow NucC$ $GDP \leftrightarrow NucC$	Multivariate

Key: *NucC* = nuclear electricity consumption, *NucG* = nuclear electricity generation, *GDP* = gross domestic product, *Cf* = Real gross fixed capital formation, *Lab* = labour force, *Inc* = GDP per capita.

The results point to a mix of unidirectional and bidirectional causal relationships in a number of countries between nuclear electricity consumption and income/GDP growth as well as a unidirectional causal relationship running from nuclear electricity generation to CO_2 emissions in Iwata et al (2010). However, the main issue with the first three results from Iwata et al (2010), Yoo and Jung (2005) and Yoo and Ku (2009) is that they use the "pairwise" bivariate approach, which may result in omitted variable bias (Lutkepohl, 1982). An omitted variable bias scenario arises where the possible effect of other variables are not regarded within the nuclear-GDP link, which may lead to estimation results that are biased and inconsistent. The additional studies in Table 2.4 mitigated this risk with their multivariate approach to Granger causality analysis. Apergis and Payne (2010) provides an example of a successful application of a multivariate Granger causality test that used nuclear electricity consumption, GDP, capital formation and labour force variables.

2.3 Long run modelling of the future energy mix

2.3.1 Background to the energy scenario studies for 2050

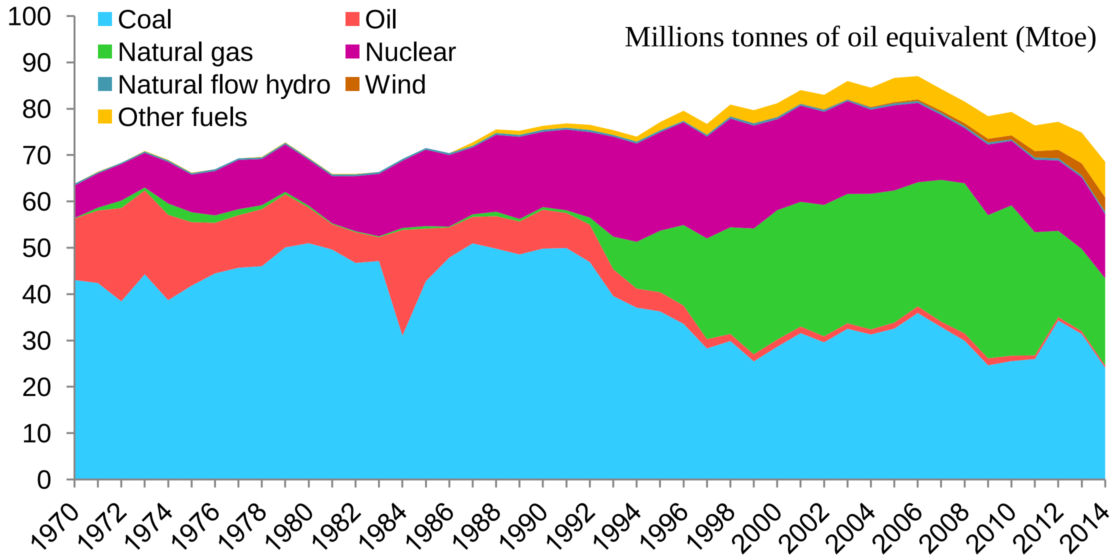
Climate change has been identified by scientists and governments in the last few decades as one of the most significant environmental risks that the world faces and this view led to the formation of the United Nations Framework Convention on Climate Change (UN, 1992). The 1997 Kyoto Protocol subsequently laid the foundation for most of the world's leading industrialised nations to set binding targets for the reduction of greenhouse gas emissions (GHG). IPCC (2007a) describes how the UN Environment Programme and the World Meteorological Organisation established the Intergovernmental Panel on Climate Change (IPCC) for the purpose of assessing the potential future risks from climate change. The IPCC's 4th Assessment Report was a thorough scientific report that concluded that climate change has a significant impact on a wide range of areas within the human and natural environment such as ecosystems, food security, human health, industry and human settlements (IPCC, 2007a).

The European Commission (2013a) highlighted the European Parliament climate commitment in 2008 for the legally binding 80% - 95% reduction in GHG emissions by 2050 in comparison to 1990 levels (base year). The result from the European Parliament climate commitment in the UK was the Climate Change Act (2008), which aligns the UK to the EU's 2050 GHG emissions target with an additional CO_2 emissions target of at least 26% below 1990 levels by 2020. This initiative was deemed necessary as part of the global GHG mitigation effort to limit the average temperature increase to no more than 2^oC compared to preindustrial levels and to prevent further lasting harm to the environment.

The Climate Change Act (2008) also set the institutional framework for the creation of the Committee on Climate Change (CCC), the provision of a carbon budgeting system as well as amendments to the Energy Act 2004 concerning the obligations towards renewable transport fuel. In their first report, the Committee on Climate Change (2008) developed long-term energy projections and suggested that the UK should move towards a near total electrification of light duty vehicles (cars and light vans) as well as other energy-need areas such as heating and lighting. However, Foxon (2013) criticised the incomplete nature of the modelled scenarios from the Committee on Climate Change, indicating that very little was discussed on the motivations of energy participants and that specific policy actions were required from energy stakeholders in order for the decarbonisation targets to be met.

The projection of energy scenarios to 2050 therefore present a challenge to econometric energy modellers as long term energy projections do not take into account many unknown future aspects such as developments in energy technology and changes in the mix of primary energy inputs. Forecasts and projections of energy demand and supply in 1970 would have yielded significantly different data to what we have today. For example, North Sea oil and gas production and nuclear energy were still at an early stage in 1970 yet the British government's Department of Energy and Climate Change (DECC) highlighted the nuclear industry's large share of total primary energy consumption at 19% as of 2012 (DECC, 2013). In 1970, wind energy was not commercialised but is now seen as a critical sustainable element in the energy mix for 2050. Coal and oil were also long established as the dominant sources of primary energy for electricity production but have seen a dramatic decline that accelerated sharply after the UK recession of the early 1990s. Figure 2.5 shows a breakdown of the dramatic changes in primary sources of electricity between 1970 and 2014[8]:

Figure 2.5: Breakdown of sources of electricity (1970 -2014)



Source (DECC, 2014)

[8] Data in the graph after 1987 are for all energy generating companies (public and private ownership). Before 1987 the data are solely for large power producers, industrial hydro, transport undertakings and nuclear power stations.

Despite the early stage nature of the 1970s British nuclear, gas and renewable energy sectors, their electricity production technologies were developed to an extent where long term projections could be made of their overall contribution to future energy mix. The UK Government's Parliamentary Office of Science and Technology (2012) suggested that many uncertainties relating to the future nature of these energy technologies at the time were somewhat mitigated by the desire of the UK Government to improve energy security and increase diversity of the energy resources that are used in the economy.

Unforeseen energy treaties in 1970 such as the Kyoto Protocol of 1997 had also contributed to the increased interest in renewable energy and would not have been picked up in any energy scenario projections that may have existed in 1970. Despite the environmental benefits and promise of long-term energy security, the entry of fusion power into the commercial energy space is deemed to be dependent on the technical feasibility of existing R&D activity and economic competitiveness of future power plants (Lechon et al, 2005). However, the technical progress of fusion is sufficient enough to warrant the creation of energy scenarios in 2050 with fusion power firmly included within the commercial energy mix.

2.3.2 Partial equilibrium modelling of long-term energy scenarios

IPCC (2014) classifies models that provide projections of varying energy scenarios as "bottom up" energy models. They are sometimes preferred to econometric models for long-term energy and GHG projections due to the highly disaggregated nature of the energy sector. Top-down modellers may use econometric techniques and macroeconomic theory on aggregated historical variables in order to generate relatively short-term forecasts of energy supply and demand. Lans and Rausch (2011) suggests that partial equilibrium energy models focus on energy generation at a microeconomic level with limited interactions at a macroeconomic level while top-down general equilibrium models assess economic and energy activities via aggregate production functions. IPCC (2014) indicated that bottom-up models are stronger for energy projections where long-term GHG mitigation policies and complex energy sector data require more detailed analyses. The focus of bottom-up models in this scenario lies with the technological energy-gains that manifest at a microeconomic level as well as analyses of the technical and economic consequences of energy-specific policy options.

Most bottom-up energy models use partial equilibrium analysis, which is based on the maximisation of total economic surplus. Loulou et al (2005) emphasises that partial equilibrium energy models simultaneously arrange the production and consumption of energy-related resources (such as primary fuels, materials and services) with their respective prices. The price of producing the energy-related commodity affects the demand and conversely, the demand of the commodity affects its price with an equilibrium market achieved when no producer desires to produce in excess of quantity q at price p and no consumer desires to buy less than q. Alongside the maximisation of economic surplus is the linearity concept based on outputs of an energy technology being a function of its inputs. Linear programming is therefore built into some partial equilibrium models as there is usually a minimum cost that must go into capital intensive energy projects (e.g. nuclear power plants) otherwise they cannot be implemented (Loulou et al, 2005).

Partial equilibrium energy models have a long history in the literature with Hotelling (1931) providing an early contribution to the literature with his focus on extractable energy resources. The Hotelling (1931) framework was extended by Dasgupta et al (1980), who demonstrated the impact of tax policy on resource extraction. Recent developments in partial equilibrium models have gone beyond the analysis of hydrocarbons and into the entire energy system. There are two major categories of technology-focused partial equilibrium models: the first category (e.g. MARKAL) use optimisation methods to calculate a minimum cost or maximum surplus pathway for the entire energy system; the second category such as the GHG mitigation model used by Jaccard et al (2003) consists of simulation models where investment decisions by producers and consumers are only partially based on profit maximisation. In the second category, sustainable energy technologies can still capture a small or significant share of the market even if their costs over their lifecycle exceed the costs of other energy technologies (Loulou et al, 2005). Some well-known partial equilibrium models are summarised below in order to determine the effectiveness in meeting the GHG emissions targets for 2050.

2.3.3 MARKAL model

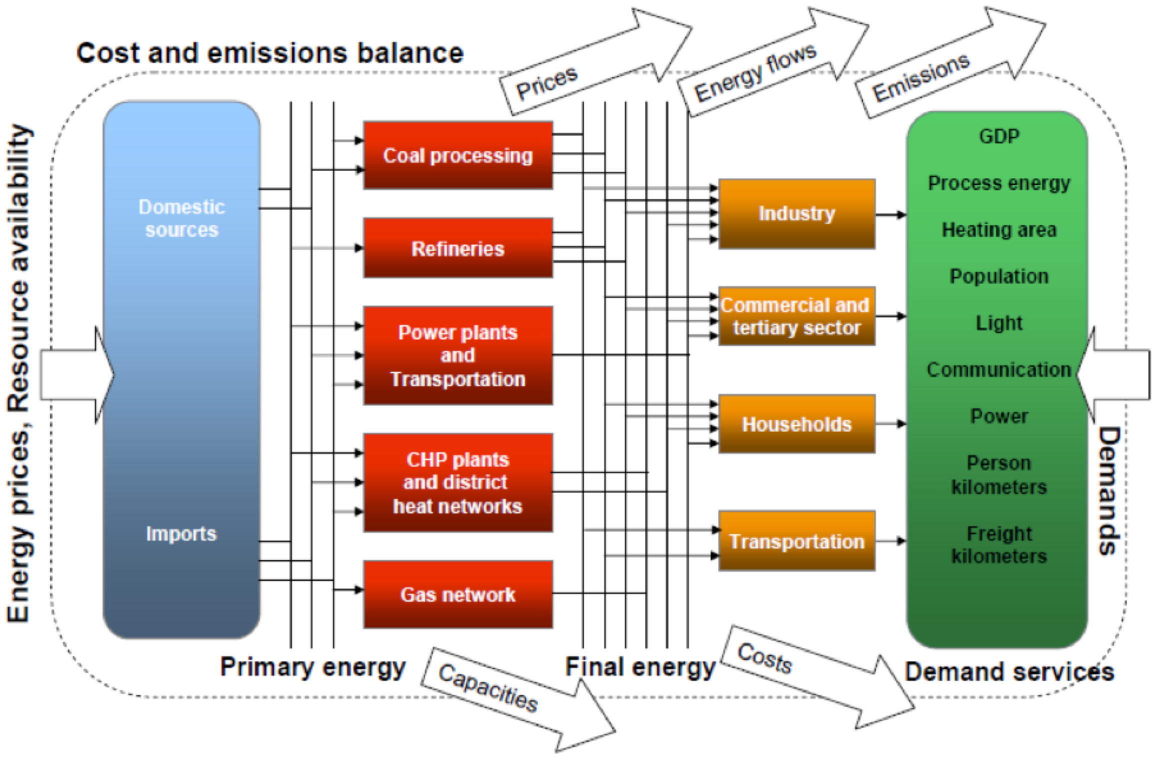
The MARKAL energy model (short for MARKet ALlocation) is a widely used optimisation model that applies linear programming methods to generate least cost scenarios from a list of energy technologies (Fishbone and Abilock, 1981). The model deals with an evolution of optimal costs energy systems, which is the key element of generalised variants that include the maximisation of economic utility and maximisation of energy producer and consumer parameters (Kannan and Strachan, 2009). Van Vliet et al (2011) explains how the energy production technologies in the model convert primary energy to final-use energy for consumers, with demand technologies converting final-use energy for the benefit of energy services companies. Additional drivers of the production-side of the model such as economic and population growth are expressed as demand for final-use energy. The in-built linear programming system then calculates a minimum discounted cost for the entire energy system, which is subject to change depending on factors such as the availability of new technologies. However, Lee et al (2013) identifies the main weakness of the MARKAL model through its preference for selecting the most cost effective energy route while ignoring other important factors in energy selection. The model also does not account for planning and construction costs in the lead time towards development for capital intensive energy projects (Kannan, 1875).

The UK Government funded the development of the original MARKAL model, with early results of the application of MARKAL published in Finnis (1980). The following decade saw a decline in the use of the MARKAL in the UK to the point where the Department of Energy was reported to had not made a "*comprehensive use of the MARKAL facility in recent years*" (Taylor et al, 2014). During the 1990s, the model was modified and updated and in 2000, the use of MARKAL improved due to climate change policy playing an important role in UK energy policy. The Royal Commission on Environmental Pollution (2000) published an influential report to the UK Government and used the MARKAL model to generate a number of scenarios for GHG emission mitigation towards 2050. The MARKAL model has been a core model for the UK Government's energy policy since the Royal Commission's report in 2000, with the DTI (2003) and DEFRA (2007) demonstrating it's important role in producing the UK's 2050 projections for GHG emissions mitigation.

2.3.4 TIMES model

The TIMES (The Integrated MARKAL-EFOM System) model is an energy model that was developed by the IEA under the Energy Technology Systems Analysis Program (ETSAP) agreement. Figure 2.6 shows the inputs and outputs from the TIMES model:

Figure 2.6: Schematic of TIMES inputs and outputs



Source: Remme et al (2001)

Labriet et al (2009) describes the TIMES energy model as being global in reach, driven by 42 energy demand areas in industry, residential, commercial, transport and agriculture. Remme et al (2001) stated that the TIMES model is based on a reference energy system that models the entire energy system of a country from the primary energy inputs to the conversion and distribution of energy to the end-users. The model uses an NPV approach for all energy-related costs in order to generate outputs such as energy prices, CO_2 emissions levels, investment levels and reductions in demand.

Similarly to its MARKAL predecessor, the TIMES model performs a partial equilibrium calculation based on the flows of energy types, materials and prices. The calculations are performed in order for the energy suppliers to produce energy at the price that consumers are prepared to buy i.e total economic surplus is maximised. The TIMES model has a long projection horizon from 2005 to 2100 and is able to capture seasonal and time-of-day variations. Model assumptions such as competitive energy markets with perfect foresight are held in the same way as the MARKAL model and linear programming is used to enable energy technology output to be a linear function of its inputs (Loulou et al , 2005).

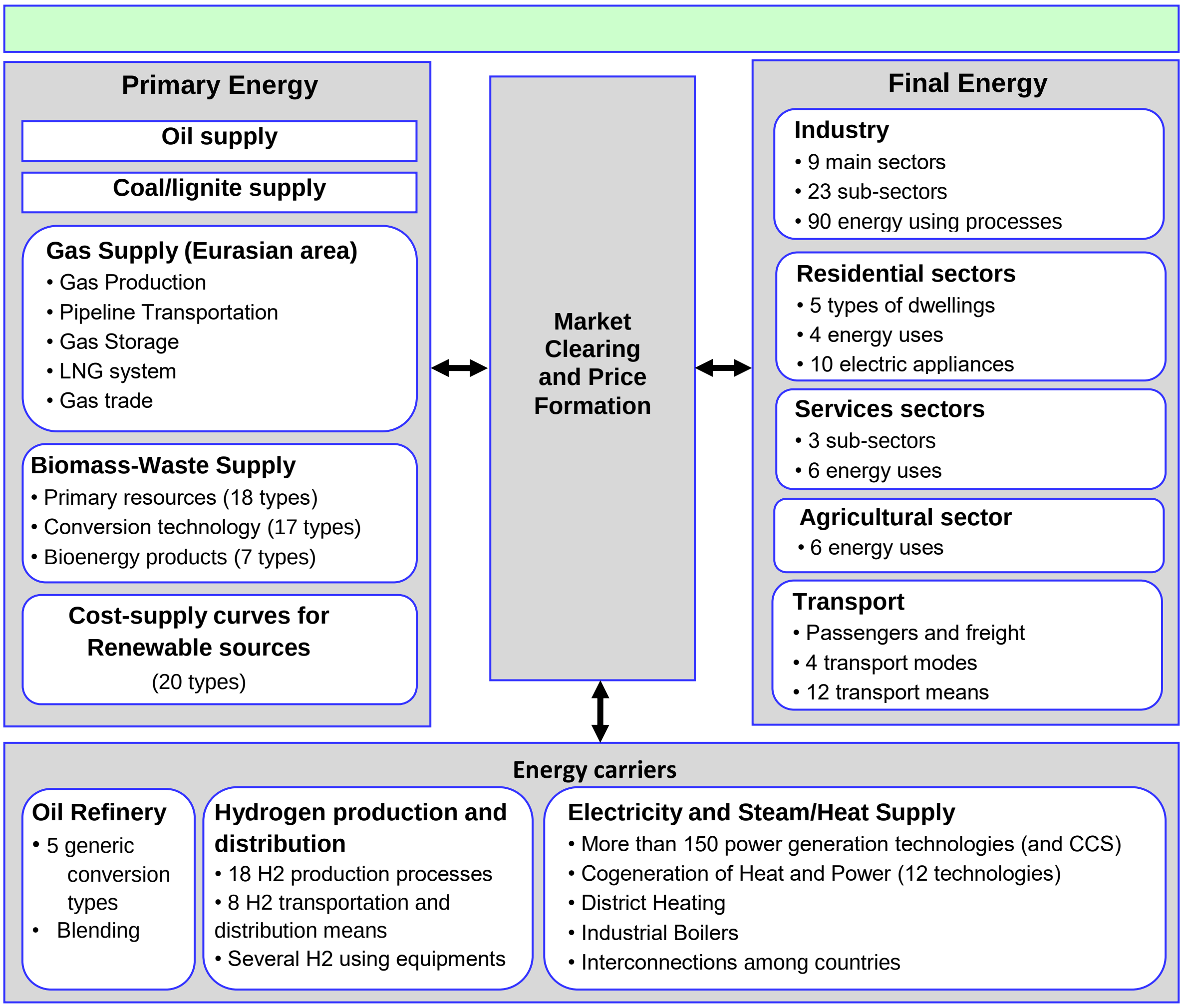
However, TIMES differs from MARKAL in that the length of time periods can be defined in a flexible way, unlike MARKAL which has fixed time periods. Investments in energy technology in MARKAL are also defined as fixed payments at any given time period whereas in the TIMES model, investments in the construction of energy projects follow a real situation in that they are staggered over a period of time until completion (Loulou et al , 2005). The model has been widely used to create projections of scenarios for the future energy mix and importantly, it has been used by Biberacher (2006) to model the future energy mix with fusion power included as a result of the dynamic structural nature of the model.

2.3.5 PRIMES model

The PRIMES energy model is a partial equilibrium model that simulates a market equilibrium situation for energy producers and consumers. The model was developed by the Energy-Economy-Environment modelling laboratory (E3Mlab) at the National Technical University of Athens. E3Mlab (2011) describes how the model is divided into sub-models with each sub-model representing the behaviour of an energy producer (price maker) and consumer (price taker). The modelling framework is based on the microeconomic foundation of maximisation of profit and utility under certain constraints such as technology and fuel availability. The model calculates GHG emissions from energy production and consumption based on GHG emissions and technology policies. Economic decision-making, capital formation and capital turnover are dynamic functions and the model is able to calculate projections for demand, supply and price variables in 5 year blocks up to 2050.

PRIMES has a number of advantages over alternative partial equilibrium models that were used to generate energy projections to 2050. Models such as MARKAL formulate single optimisation solutions that cover the entire energy production and supply system, with no consideration of energy price formation, whereas PRIMES performs individual objective functions per energy supplier and demander and creates detailed simulations of energy price formation (EM3lab, 2011). However, Capros (2011) points out that PRIMES cannot convey short-term projections and long-term projections are statistically independent from past data. The PRIMES model also lacks spatial information at a below-country level, which hampers its ability to comprehend areas such as energy distribution and transport infrastructure. Figure 2.7 shows the structure of the PRIMES model in terms of its primary energy inputs and final energy uses:

Figure 2.7: Modular Structure of the PRIMES model



Source: E3Mlab (2011)

2.3.6 The 2050 Energy Calculator

Mackay (2009) published an influential study that consisted of a variety of assumptions of a sustainable energy mix in 2050, with associated energy consumption options. The 2050 Energy Calculator model and energy pathways analysis were subsequently published the following year by the Department of Energy and Climate Change (DECC), using many of the assumptions highlighted in MacKay (2009). The UK Government's main objective for the 2050 Energy Calculator is to encourage national debate and dialogue concerning the UK's collective responsibility towards the reduction of GHG emissions (Allen and Chatterton, 2013). The key to its success lies in its ability to translate simple energy policy options into viable projections of a variety of technical, economic, energy and environmental variables into the long run.

Unlike the previous models discussed, the 2050 Energy Calculator does not automatically carry out an optimisation approach for the calculation of the least costly route to 2050. Instead, this model considers the feasibility of what could be delivered by each element of the energy sector under various scenarios. The underlying focus of the 2050 Energy Calculator is in meeting the UK's legally binding 80% decarbonisation target in 2050, based on the 1990 level. Other critical dimensions such as cost implications, land use impacts, technological risk, socioeconomic and environmental impacts are also important in determining the possible pathways to 2050 (HM Government, 2011). Essentially, the 2050 Energy Calculator must meet the government's GHG target by 2050 while ensuring that supply and demand needs are fully met.

Marginal abatement cost (MAC) curves had frequently been used by energy economists and policy makers to assess the options available for the mitigation of GHG emissions. However, Ekins et al (2010) demonstrates that there are weaknesses in MAC curves for GHG mitigations such as interdependences and intersectoral interactions. For example, a significant shift towards electric vehicles in 2050 would have the proportional effect of increasing GHG emissions if the primary fuel used in generating the electricity is not decarbonised. The 2050 Energy Calculator counters this weakness through its consideration of the dynamic interactions between demand, supply and across energy sectors.

However, HM Government (2010) implied that the model does not gather the positive or negative feedback effects from the economy that become apparent through the decarbonisation effort. The model might also be perceived to be less useful for business than it would be for government policy makers and non-government organisations (NGOs) due to cost minimisation not being its central focus (UKERC, 2013). The 2050 Energy Calculator would therefore suit the British fusion power R&D programme as it is currently implemented at a UK governmental level but there are no existing studies that explicitly show the application of fusion power within the model. However, despite the detailed nature of the 2050 Energy Calculator, it is flexible enough to permit adjustments for the purpose of generating GHG mitigation scenarios with fusion power added to the UK's 2050 energy mix.

2.3.7 Energy policy objectives of the 2050 decarbonisation target

Energy policy analysts have a significant interest in the 80% - 95% emissions reduction target for 2050, which is widely accepted by organisations and governments at a UK and EU level. However, European non-governmental organisation and global sustainable energy sector associations have developed policies that diverge, to varying degrees, from the UK Government and EU parliament's 2050 emissions target. Eurelectric (2010) set a target of a 75% reduction in CO_2 emissions in their modelling scenario, which was based on the Intergovernmental Panel on Climate Change (IPCC) target of a 70% - 80% reduction relative to 2005 emissions levels. The European Climate Foundation (2010) takes an aggressive decarbonisation approach in their modelling by declaring that "*it is virtually impossible to achieve an 80% GHG reduction across the economy without a 95 to 100% decarbonised power sector*". Business Europe (2010) takes a pro-growth approach by declaring that GHG emissions would need to be at least 50% in 2050 compared to 1990 while emphasising the need to prioritise investments in the industrial sector in order to protect future growth and employment. The World Business Council for Sustainable Development goes further by declaring their critical pathway for emissions in 2050 as 50% of 2005 levels with global action seen as necessary to meet this target (WBCSD, 2010).

Renewable energy sources have played an important role in the 2050 modelling scenarios of EU nations, NGOs and organisations. However, alongside the differences in opinion regarding the 2050 emissions scenarios comes the general lack of consensus on how to appropriately deploy energy technologies, primary energy sources and end-use energy sources within their modelling frameworks. The European Renewable Energy Council (2010) supports a 100% renewable energy system in the EU by 2050 while the "advanced scenario" of Greenpeace (2010) sees 92% of heating and 97% of electricity generated from renewables. On the other end of the spectrum, the WBCSD had modelled renewables with a 50% share of the energy mix in 2050 with fossil fuels having a future decarbonised role through carbon, capture and storage (CCS) technologies. Eurelectric (2010) had lowered their estimation of the share of renewables to 40.4% with nuclear at a relatively high 28.4% in 2050.

The high nuclear energy input for the scenarios of Eurelectric (2010) would cause issues for the policy frameworks of many modellers at a UK and EU level due to the perceived long-term hazards that are inherent in nuclear waste. WWF (2007) factored in a complete decommissioning of nuclear energy in their modelling work due to the potential environmental impact of radiotoxic emissions and the risks from nuclear proliferation. The Stockholm Environment Institute (SEI, 2009) and Friends of the Earth (2012) also take a hard line against nuclear in their 2050 energy scenarios, again due to similar concerns shared with WWF. There are also differences in opinion regarding the future role of biomass. Eurelectric (2010) envisages a lesser role for biomass due to limitations in the availability of land for energy crops. However, WWF (2007) seem to contradict their core values of the conservation of wild habitats and preservation of farmland for food crops with their recommendation for a "*rapid expansion of biomass energy*" towards 2050. Shell (2008) predictably concurs with this opinion by declaring that biomass would have a greater market share than gas in 2050 with as much as 15% of primary energy supply in the ‘scramble’ energy scenario.

2.4. Macroeconomic impact of the energy mix on the British economy

2.4.1 Background

Energy is a vital resource that is fundamental to the operations of the global economy. Energy is required by the primary production processes of industry and final consumers such as households and transport services. The interrelationship between energy use and economic activity means that factors that affect energy production such as price and government policy, directly have an impact on economic growth. Turton (2008) emphasised that the critical role that policy-makers play is to predict the impact of existing energy policies on socioeconomic and environmental security as good projections could enable the adoption of policy instruments via resource allocation.

One of the leading challenges faced by energy policy-makers over the last two decades are the potential future risks from climate change. A significant number of global environmental organisations such as the Intergovernmental Panel on Climate Change had followed the EU by producing a series of statistics that pushed this risk firmly into the public conscience (IPCC, 2007b). The central message is that the global economy must seriously reduce its emissions actions and Faehn et al (2013) was among a number of commentators who suggested that shifts in technological adaptation must accompany changes in industrial structures and consumption in order to directly confront the challenge of climate change. However, a group of British academics who were affiliated with the ESRC's Centre for Climate Change and

Economic Policy (CCCEP) found that increased CO_2 emissions from fossil fuels were positively correlated to increases in GDP in the United States between 1950 and 2007 with a similar but moderately less prominent pattern in the UK (Bowen et al, 2009). The European Commission took an opposing line and claimed that economic growth and GHG emissions reductions were not contradictory and produced a report showing GDP growth in the EU between 1990 and 2012 at 45% compared to -19% for GHG emissions (EC, 2014).

In order to manage these uncertainties, policy-makers require effective assessment tools that can consider a range of future energy and GHG emissions scenarios in order assess their impact on key macroeconomic variables. In the literature, two modelling approaches have dominated the long-term GHG mitigation scenarios for 2050: Bottom-up models are disaggregated models that focus on future energy technology scenarios and their corresponding GHG emissions at a microeconomic level, whereas top-down models are aggregated models that assess the interactions between the energy sector and the wider economy (IPCC, 1995). The latter category commonly use computable general equilibrium (CGE) models that aims to predict economic development levels, energy use and GHG emissions while factoring in resource constraints and energy activity at a microeconomic level (Faehn et al, 2013). Pezzy and Lambie (2001) emphasise that the essential feature of a CGE energy model is that it estimates the indirect sectoral impacts of potential GHG abatement policies on the economy that are caused by substitutable sources of energy.

2.4.2 History of computable general equilibrium modelling

The history of general equilibrium theory finds its roots in Leon Walras' (1874) contribution *Elements D'économie Pure, ou Théorie de la Richesse Sociale*. Walras represented the state of an economy as a system of simultaneous equations of the demand and supply of goods and services. The assumption was that consumers sought to maximise their utility and producers aimed to maximise their profit, with the equilibrium condition apparent where supply = demand in every market of an economy. Arrow and Debreu (1954) expanded the Walrasian equilibrium by developing an equilibrium solution that is defined by production levels and prices such that (a) demand = supply for all goods and services (b) income = expenditure and (c) the break-even of production activity happens at solution prices that conform to Walras's Law.

Johansen (1960) is credited with creating the first computable general equilibrium (CGE) model by using a system of linear equations based on economy-wide assumptions that identified the behaviours of different agents. The behaviours of agents included households that sought to maximise their utility based on their budget restrictions and industries that sought to minimise their expenditure due to their production-function restrictions. The outcome for the economy in Johansen's CGE model is decided by actions from agents harmonised through price adjustments that match supply and demand. Dixon and Rimmer (2010) recognised Johansen's pioneering work but indicated that the main early objection to Johansen's model in North America was that his linear solutions were derived from a linear depiction of the theory, which only gave approximate answers that result from "linearization error". Nevertheless, Johansen's CGE model was a major improvement on the previously dominant economy-wide assumptions of Leontief's (1936, 1941) input-output model, whose fixed coefficients did not permit important substitutable effects from an economy's production side.

Energy policy gave CGE models a new emphasis in the 1980s due to its role as one of the largest and most influential sectors in the global economy. Early applications of the CGE model to energy and economy-related issues came with Despotakis and Fisher (1988) through their assessment of the impact of oil price shocks to a sub-section of the US economy while Bergman (1988) considered the impact of changing energy conditions to economic welfare issues related to product and factor prices. The 1990s saw a major shift in CGE emphasis from energy-economy to energy-economy-environment with Jorgenson and Wilcoxen (1990) providing an insight into the negative economic impact to GDP from environmental regulations that were designed to mitigate pollution from energy companies, industries and consumers. Moreover, Perroni and Wigle (1994) found that international trade policies had a minor impact on environmental degradation and advocated the promotion of trade liberalisation to support greater efficiency in global resource management.

The post-Kyoto Protocol literature typically contains bottom-up, techno-economic energy models that take the GHG emissions, electricity cost and quantity impacts from the bottom-up model and effectively force them into the CGE model as external shocks. This process is easier with static than dynamic CGE models, as the latter requires an iterative process of adjustment between the bottom-up model and the CGE model. Messner and Schrattenholzer (2000) gives an example of an iterative approach with their MESSAGE-MACRO model and the iterative approach is also used by the International Energy Agency (IEA, 2008) in their global WEM-ECO model. However, most analyses that are apparent in the literature are usually based on static or "soft" link between the bottom-up and CGE model (Helgesen, 2013), which is also the basis of the latter empirical section of this thesis.

2.4.3 Outline of the CGE model

CGE models generally estimate the behaviours of producers and consumers in order to assess how differing policies will impact all sections of an economy in a way that runs consistent with economic theory. RTI International (2008) describes the circular flows that a CGE model considers within an economy based on households owning factors of production (such as capital and labour), which are supplied to firms in order to make income for households. Firms combine those factors of production with intermediate goods and services in order to generate output that is sold to consumers and other industries. International trade is also conducted through the export and import of goods and services. The general equilibrium element of the CGE model arises when all sectors of the economy and income equals consumer expenditure and all supply of commodities and factors of production equals demand.

Energy production technologies and energy commodities are generally defined using a constant elasticity of substitution (CES) functions, which explain how various types of inputs can be substituted for other inputs (Burniaux and Truong, 2002). The degree of substitution is determined by elasticities that manage the exchange among inputs. For example, rises in energy prices may cause energy companies to switch towards employing more labour as permitted by CES equations, which consequently enable firms to move towards energy production methods that are more energy efficient. For CGE energy-focused models, there are different substitution possibilities. Peterson (2011) describes substitution options such as between a primary factor and capital-energy composite and also inter-fuel options such (a) electricity and non-electricity (b) coal and non-coal and (c) between fossil fuels. The consumption of energy commodities by households is determined by their utility function, which shows the willingness of commodity consumers to substitute based on prices changes.

CGE models are generally viewed as an essential macroeconomic impact tool for many modellers and have many strengths, with one of the most important being that CGE models are robustly grounded on economic theory. The quantitative evaluation of general equilibrium effects are also an important aspect of CGE models and has proved to be an essential tool for evaluating climate policies and their impact on energy costs (Qi et al, 2004). The use of CGE models at the highest levels of government and business has cemented its status as one of the main macroeconomic policy models of choice. For example, Arora (2013) highlighted their wide use in energy-related US government departments such as the Department of Energy (DOE), Environmental Protection Agency (EPA) and the Department of Agriculture.

However, Allan et al (2007) sets out the weaknesses of the CGE model by indicating that CGE models were information intensive through its requirement of multi-sectoral accounts i.e. the social accounting matrix (SAM), as well as a significant number of behavioural connections and parameter values. Allan et al (2007) also criticised the supply-side rigidity of some of the assumptions such as cost minimisation for firms as there has been a growing contribution to literature such as Sorrell et al (2004) concerning barriers to acceptance of technologies that are energy efficient. Nonetheless, the CGE modelling framework will be a key tool in understanding the impact of commercialised fusion power operating in an equilibrium economy in 2050.

2.5 Concluding remarks

Continuous research and development within the fusion power programme has become a key energy policy objective over the last few decades in a number of OECD and non-OECD countries. The literature suggests that despite the significant levels of investment over the last few decades into the global fusion R&D programme, there appears to be no decline in the excitement that fusion power stakeholders feel towards the potential realisation of a near limitless source of high-volume decarbonised electricity. It is this view that motivates the selection of the modelling techniques that were highlighted in this chapter. The results from the econometrics literature for nuclear energy were intended to present a guideline for a future commercialised source of fusion power, based on the similar processes that are used in the generation of electricity. The range of nuclear energy elasticities for several different countries in section 2.2.4 offers a theoretical basis for understanding the role of nuclear energy within the energy-economic-environment nexus. This provides the foundation for a similar empirical study for the UK in the next chapter.

Furthermore, the energy policy objectives of several European organisations in section 2.3.7 demonstrates the lack of consensus concerning the optimal energy mix that should be pursued in their aim of meeting the 80% decarbonisation target by 2050, based on 1990 levels. The empirical literature highlights a wide spectrum of modelled energy scenarios, which range from the need to maintain economic growth in a limited decarbonisation effort to the need for full electrification of the energy system regardless of the economic consequences. A different approach is pursued in this thesis as it aims to provide modelled scenarios of fusion power's contribution towards the decarbonisation effort in 2050 while maximising the various economic benefits that could arise from its commercial introduction into the UK's future energy mix.

CHAPTER 3

SINGLE EQUATION MODELLING: COINTEGRATION ANALYSIS OF THE NUCLEAR-GDP-CO_2 NEXUS

3.1 Introduction

A number of studies in the previous chapter had used a variety of multivariate econometric methods to explore the relationship between energy production and economic growth. Furthermore, recent studies highlighted in the previous chapter saw the global decarbonisation agenda pushed more prominently into this relationship, which was spurred by the greenhouse gas (GHG) abatement policies that were highlighted in the 1992 UN Framework Convention on Climate Change (UNFCCC) and the 1997 Kyoto Protocol. This resulted in policy makers and researchers including CO_2 emissions in their analysis of the energy-economy nexus. The global combustion of fossil fuels is widely viewed as the principal human cause of CO_2 emissions and the UK Government's attention has increasingly been drawn towards the generation of electricity from decarbonised sources. As a potentially large future source of decarbonised electricity, fusion power can be viewed as an important counterbalance to fossil fuels in the UK's long-term fight towards the reduction of GHG emissions. Therefore, econometric models that draw plausible inferences from the fusion-GDP-CO_2 relationship could have an impact on the UK Government's long-term decarbonisation strategy.

In the case of fusion power, it would be impossible to estimate the long or short run econometric relationships between fusion power, CO_2 emissions and other economic variables based on past or present data. This is due to its current non-commercialised status and there are no hypothetical econometric studies in existence for fusion power. However, it is important to consider existing primary energy sources in terms of their trend from 1970 and compare them with the projected time path and market share of fusion power. This would help to determine a primary energy source that would provide a guideline of what to expect from fusion. A number of studies offer projected estimates of the market share of fusion power in the future energy mix. Konishi et al (2005) estimated that electricity generated from fusion could have a significant market share towards the latter half of this century of approximately 23% in Japan and 30% globally. This is consistent with the Lako et al (1998) report that was authorised by the European Commission where a steady projection of fusion power was estimated from a potential commercialisation point in the middle of this century up to 2100. Therefore, a guideline energy source would need to have a significant current market share of electricity generation based on a consistent trend over the long run.

UK energy statistics from DECC (2014) shows that oil had a 20.8% market share of total UK electricity generation in 1970 but declined sharply from the 1990-1991 recession to the point where it now has a 1% market share as at 2012. Coal was the dominant source of electricity generation in 1970 at 67.5% but declined due to action against CO_2 emissions and now occupies a 44.4% share of total electricity generation as at 2012. Gas had experienced a boom in recent years and enjoyed a 23.8% market share in 2012. However, its market share never rose above 4% in the 21 years from 1970 to 1991 and would not be suitable for guideline purposes. Of the four main primary sources of energy for electricity production, nuclear fission (henceforth, nuclear) has shown a trend that could be considered as the guideline in this chapter for the potential future growth curve of fusion power. Electricity generated from nuclear fission had steadily increased during the 42 years from 1970 to 2012, from 11% of total UK electricity generation in 1970 to 20% in 2012. Moreover, the Institute of Physics (2008) highlighted the similarities between fission and fusion in terms of the nuclear reactions for energy generation, the high power plant construction costs and complex power plant engineering.

Building on the above arguments, this chapter seeks to provide new evidence by extending the existing empirical literature through two lines of analysis: the greater part, which assesses the nuclear-GDP-CO_2 nexus in the UK as a guideline for fusion and the lesser section, which tests the environmental Kuznets curve (EKC) hypothesis. The autoregressive distributed lag (ARDL) method of cointegration analysis (Pesaran, Shin and Smith, 2001) is therefore the selected procedure for the nexus study. This chapter uses the unrestricted error correction form of the ARDL model to assess the long run elasticities of the variables prior to the application of a restricted error correction model (ECM) for the estimation of the short run elasticities. This method of cointegration analysis is well suited to handle variables that display different statistical profiles such as variables that have different orders of integration as well as variables that have endogenous properties. Multivariate Granger causality is subsequently applied to the variables using two comparative systems: the standard Wald test and the modified Wald test proposed by Toda and Yamamoto (1995).

Another long run form of the ARDL model is used to test the EKC hypothesis, which was first proposed by Grossman and Krueger (1992, 1995) and the World Bank (1992)[9]. EKC theory suggests that an inverted U-shaped relationship exists between environmental degradation (commonly measured by CO_2 emissions per capita) and economic growth (commonly measured by GDP per capita). During the earlier stages of economic development, the growth rate of a country's CO_2 emissions may disproportionately exceed the rate of economic growth. As a country's development stage reaches maturity, a turning point is reached, after which the rate of CO_2 emissions declines as a ratio of GDP growth.

Many feasible explanations were proposed for the inverted U-shaped curve and EKC turning point such as Stokey (1998), who suggested that poorer countries predominantly use the most polluting methods of production until they reach a GDP threshold where they turn towards cleaner technologies. Arrow et al (1995) supported this view by suggesting that high pollution is a tolerable part of the early stages in a country's economic development path but rising income leads to the promotion of national institutional reforms such as environmental protection and market-based incentives, which help to reduce environmental degradation. There is also a substantial debate as to whether the EKC hypothesis could be supported when considering the impact of energy variables. Examples such as Richmond and Kaufmann (2006) were unable to provide evidence to support the EKC hypothesis when considering total primary energy consumption in a number of OECD nations with small sample sizes. However, Balaguer and Cantavella (2016) supported the EKC hypothesis when considering oil prices in Spain and Ang (2007) supported the EKC hypothesis when considering commercial energy use in France.

As mentioned in the previous chapter, there is an acute scarcity of literature that analyses the econometric link between nuclear energy, GDP and CO_2 emissions. An important study of the effect of nuclear electricity generation on CO_2 emissions in France comes from the work of Iwata et al (2010) who included the rate of urbanisation, energy consumption and trade as additional variables within a multivariate framework. The results showed that those three

[9] The EKC hypothesis is a development of the original Kuznets curve hypothesis (Kuznets, 1955), which suggests that in the early stages of an economy's development, income inequality is higher but decreases as a nation undergoes industrialisation and populations shift from the rural agrarian communities to the cities.

additional variables had a statistically insignificant relationship with CO_2 emissions in the long run.

However, there are two reasons for considering a different approach to the Iwata et al (2010) study in the choice of appropriate variables for estimation purposes. The first argument is based on the mixing of 'share' variables such as *nuclear* (% of total electricity) with 'level' variables such as GDP per capita. Level variables are generally unbound without limitation but share variables have a different time series profile as they are bound between 0 and 1. Mixing share and level variables may result in estimations that lead to distorted inferences on the long run behaviour of nuclear electricity generation against the unbound variables. Therefore, *nuclear* in this chapter is changed from a share variable to kilowatt hours (kWh) of nuclear electricity generated per capita and *trade* is changed from a share variable (% of GDP) to British pounds (GBP) per capita.

The second argument is based on the total omission of the role of government action in the studies of the nuclear-GDP-CO_2 nexus. National governments and the agencies of government departments play a leading role in assuring the decarbonisation pathway through the implementation of legislation, regulation, enforcement and taxation. For example, the Electricity Market Reforms (EMR) stipulated in the Energy Act 2013 provides powerful incentives for investors to significantly participate in decarbonised electricity generation. This is mainly administered through (a) the Capacity Market (CM), which guarantees long-term, predictable revenues streams to electricity generators on the condition that certain electricity supply capacities are met and (b) Contracts for Difference (CFD), which the UK Government uses to stabilise revenues for electricity generators by paying them the difference between the 'strike price' – the market price of electricity and the 'reference price' – the cost of investing in decarbonised electricity generation. The Climate Change Act 2008 is another example of environmental legislation that spurred the UK Government to take a dominant position in the climate change debate within the European Union. This subsequently resulted in the successful lobbying of the EU to agree a landmark deal in October 2014 for a 40% reduction in GHG emissions across the EU by 2030 (European Council, 2014).

In light of the second argument, a suitable proxy variable for the UK Government's action against climate change would come in the form of environmental taxes. The potential effect of environmental taxes on environmental preservation was highlighted as far back as the early

20th century by Pigou (1920), who stated that "*the whole movement for conservation in the United States is based on this conviction. It is the clear duty of Government, which is the trustee for unborn generations as well as for its present citizens, to watch over, and, if need be, by legislative enactment, to defend, the exhaustible natural resources of the country from rash and reckless spoliation...either out of taxes, or out of State loans*". FT (2015) highlighted the powerful modern-day effects of environmental taxation by describing how high carbon taxes were blamed for the closure of two of the largest coal-fired power plants in the UK: the 2,000 MW plant in Ferrybridge, West Yorkshire and the 2,400 MW plant in Longannet, Scotland[10].

Further rationale for using environmental taxes as a proxy variable for UK Government action stems from its growing impact on the total government revenues from taxation. The Office of National Statistics described how the UK had seven different types of environmental tax at a total tax intake of £14.9bn in 1990, which represents the decarbonisation base year of the Kyoto Protocol (ONS, 1999). However, heavy government pressure on industry has seen the number of different environmental taxes rise to thirteen in 2014, with a tax intake triple the 1990 value at £44.6bn. This represents 7.5% of total UK Government revenues from taxation and is the 4th largest aggregate source of tax revenue after income tax, national insurance contributions (NIC) and value added tax (VAT)[11]. Therefore, an analysis of the comparative impact of environmental taxes against nuclear electricity generation on CO_2 emissions would provide an important new contribution to the empirical literature of the nuclear-GDP-CO_2 nexus and EKC hypothesis.

3.2 Description of environmental taxes

Environmental taxes have taken on an increasingly high profile in the UK's environmental policy in recent years. The Stern Review (2006) is the largest report generated for the UK Government on the effects of climate change and its findings provided the UK Government with the techno-economic and environmental rationale for the implementation of the 'double dividend' i.e. increasing the number of environmental taxes on the 'public bad' while allowing for a decrease in other disproportionate taxes. There are three categories of environmental taxes according to the Office of National Statistics' definition based on EU regulation

[10] This follows an overall trend in the closure of coal-fired power plants, whose capacity is expected to be reduced substantially before the end of the 3rd carbon budget of 2022.

[11] VAT and environmental taxes make up the majority of indirect taxes that are levied in the UK

691/2011: energy taxes, transportation taxes and pollution/resources taxes (ONS, 2015a). Table 3.1 shows the data for each of the three categories and a comparative summary between the environmental taxes paid in 1990 (base year of the Kyoto Protocol) and environmental taxes paid in 2014, in current prices:

Table 3.1: Environmental taxes in 1990 and 2014

Classification of environmental tax	Name of tax	Start year	End Year	Taxes paid in 1990 (£ million)	Taxes paid in 2014 (£ million)
Energy taxes	Tax on hydrocarbon oils	1928	→	9.335	27,094
	Climate Change Levy	2001	→	-	1,500
	Fossil Fuel Levy	1990	2012	875	-
	Gas Levy	1980	1998	291	-
	Hydro-Benefit	1992	2005	-	-
	Renewable Energy Obligations	2002	→	-	2,931
	Emissions Trading Scheme (EU-ETS)	2009	→	-	356
	Carbon Reduction Commitment	2012	→	-	618
Transport taxes	Air Passenger Duty	1994	→	-	3,154
	Car Tax	1973	1992	1,464	-
	Rail Franchise Premia	1996	→	-	1,417
	N. Ireland Driver Vehicle Agency	2007	→	-	16
	Motor vehicle excise duty Businesses	1920	→	1,134	958
	Motor vehicle excise duty Households	1920	→	1,837	5,029
	Boat Licenses	1987	2000	4	-
Pollution/Resources taxes	Landfill Tax	1996	→	-	1,146
	Fishing Licenses	1995	→	-	21
	Aggregates levy	2002	→	-	345
Total environmental taxes				14,940	44,585

Source: Data collated from ONS (1999) and the dataset of ONS (2015b)

The data shows that five of the eighteen individual energy and transportation taxes were retired by 2012. However, all environmental taxes have observations that fall within the period of the sample (1975 to 2014), so the aggregate environmental tax variable consists of data from the eighteen individual environmental taxes in Table 3.1. The following provides a brief description of the individual levies during the sample period that collectively make-up the aggregate environmental tax variable:

3.2.1 Energy taxes

Tax on Hydrocarbon oils – is a tax paid on petroleum products used by the majority of road vehicles. Petroleum products consist of diesel (standard and ultra-low sulphur), unleaded petrol (including super unleaded), leaded petrol, lead replacement petrol and ultra-low sulphur petrol). Ultra-low sulphur petroleum products attract higher tax incentives as their emissions release fewer particulates, thereby causing less adverse effects on the environment.

Climate Change Levy – is a tax paid on the supply of energy to industrial and commercial users of energy. Renewable energy supply is exempt from this tax and businesses could obtain discounts of 65% on fossil fuel supply and 90% on electricity supply if they enter into a voluntary Climate Change Agreement (CCA) to improve energy efficiency and reduce carbon emissions. The Climate Change Levy also consists of an additional tax called the Carbon Price Floor (CPF), which was included in 2013 for the purpose of encouraging investment in decarbonised energy generation.

Fossil Fuel Levy – was a tax paid for the supply of non-renewable sources of energy, which was essentially designed to raise funds for investment in renewable energy generation. The cost of this tax was borne by suppliers and by consumers through the inclusion of part of the tax in the energy bill.

Renewable Energy Obligations – is a tax whose commencement in 2002 coincided with the end of the fossil fuel levy. The central purpose of this tax is to encourage electricity generators to source an increasing proportion of their primary energy from renewable sources. This is in order for the UK to meet the EU legal obligation to source 15% of its energy consumption from renewable sources by 2020.

Gas Levy – was a tax on some of the profits that were amassed by the former British Gas Corporation (BGC), which arose from the surging price of gas that was bought by BGC under the petroleum revenue tax (PRT) exempt contracts prior to 1975. The rationale for this tax was based on HM Treasury under-recovering tax revenues from PRT exempt contracts at pre-1975 gas prices that had failed to keep up with the increase in oil prices.

Hydro-Benefit – was a tax on Scottish and Southern Energy (SSE), which was used to subsidise electricity distribution in the North of Scotland (Highlands and Islands). This was in order to prevent electricity customers in this sparsely populated region from paying disproportionately high electricity costs based on the region that they lived within the UK.

Emissions Trading Scheme (EU-ETS) – is an EU-wide scheme where national governments generate revenue by auctioning ETS allowances, which subsequently enable power stations and energy-intensive industries to release carbon emissions up to certain limit called a ‘cap’. If emissions are to exceed the cap, then further ETS allowances must be purchased from other companies within a trading environment, otherwise the company would be subject to heavy fines. If the company cuts its emissions, then they either sell their allowances to other companies or reserve the allowances for future needs.

Carbon Reduction Commitment (CRC) – is a mandatory scheme that encourages large companies and public sector organisations that are not energy intensive to reduce their carbon emissions and improve energy efficiency. Similarly to the EU-ETS, the UK Government would generate revenue by auctioning CRC allowances to large companies and organisations that do not generate enough emissions to pass the EU-ETS emissions threshold.

3.2.2 Transport taxes

Air Passenger Duty – is a tax that is charged for the transportation of passengers from airports in the UK and Isle of Man. Exemptions from this tax apply to light aircraft of less than 10 metric tons or aircraft with a seating capacity of less than 20 seats.

Car tax – was a tax that was exclusively applied to the purchase of cars. It ran for 20 years prior to its abolition in the early 1990s.

Rail Franchise Premia – is a premium paid to the Department for Transport (DfT) for the operation of a UK franchise for rail passengers.

Northern Ireland Driver Vehicle Agency – is an agency of the Department of the Environment (DOE) for Northern Ireland. It is responsible for the collection of vehicle excise duties for vehicles that are based in Northern Ireland.

Motor vehicle excise duties – are annual taxes that are payable by business and household drivers of vehicles that are used on public roads within Great Britain. This tax is administered by the Driving Vehicle and Licensing Agency (DVLA) who previously issued a tax disc for display on the vehicle's windscreen prior to the introduction of the digital system in 2014.

Boat Licence – was a charge for boat owners to use and park their boats on rivers and canals.

3.2.3 Pollution/Resources taxes

Landfill Tax – is a tax paid on the disposal of most types of waste that are dumped at registered landfill sites. Exemptions are given to waste cleared from mines and contaminated land. Landfill taxes are designed to lessen the environmental impact of waste disposal as well as encourage alternatives to waste disposal e.g. incineration and recycling.

Fishing License – is an annual charge that permits anglers to use a rod and line for fishing.

Aggregates levy – is a tax that is charged on sand, rock and gravel that is used for industrial and other purposes. The tax is charged on matter that is extracted from the ground (mainland and beneath UK's coastal waters) and on imports.

3.3 Statistical properties of the data

This chapter uses UK annual time series data, which consists of 40 observations spanning from 1975 to 2014. The length of the sample period was chosen subject to the availability of data. CO_2 emissions (co_2) are measured in metric tons (MT) per capita, real GDP (*gdp*) is measured as GDP per capita in constant 2010 British pounds, nuclear electricity generation (*nuc*) is measured as KWh of electricity produced per capita, environmental taxes (*entax*) are measured as environmental taxes per capita in constant 2010 British pounds, trade (*trade*) is measured as total imports and exports of products and services per capita in constant 2010 British pounds and industrial electricity consumption (*indelec*) is measured in MWh per capita

Data for CO_2 emissions and the UK population are obtained from the Sustainable Development Indicators of the Office of National Statistics (ONS, 2015b). Data for industrial electricity consumption and nuclear electricity generation are obtained from the Department of Energy and Climate Change (DECC, 2015). Data for GDP and environmental taxes are obtained from the United Kingdom National Accounts (the Blue Book), published by the Office of National Statistics (ONS, 1999). Lastly, data for trade are obtained from the World Development Indicators from the World Bank's 2015 database (World Bank, 2015). Table 3.2 shows the data prior to their conversation to natural logarithms for estimation purposes.

Table 3.2: Summary statistics of the data

Variable	Measurement	Obs.	Mean	Stan. deviation	Minimum	Maximum
co_2	MT per capita	40	9.66	1.20	6.53	12.02
gdp	2010 GBP per capita	40	£19,739.11	£4,616.22	£12,490.15	£26,218.33
nuc	KWh per capita	40	1,030.41	313.01	470.66	1,549.21
entax	2010 GBP per capita	40	£496.86	£125.01	£268.72	£648.15
trade	2010 GBP per capita	40	£10,559.75	£3,130.90	£6,404.02	£15,867.85
indelec	MWh per capita	40	1.65	0.20	1.31	1.96

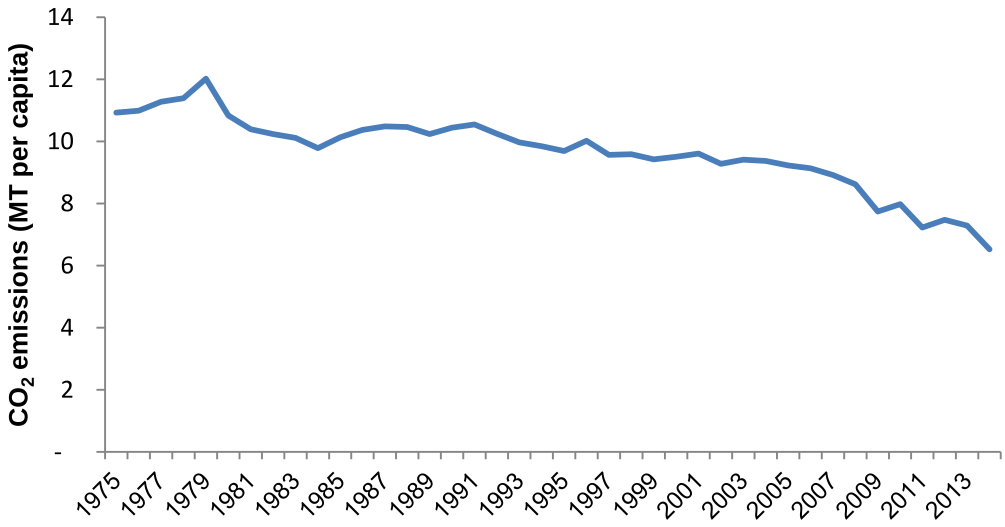
Note: co_2 is measured in MT per capita, *gdp*, trade and *entax* are measured in per capita 2010 British pounds (GBP), *nuc* is measured in KWh per capita and *indelec* is measured in MWh per capita. *Obs* represents the number of observations for each variable

The preceding sections saw the introduction of these variables and a justification was provided for their selection. In this section, graphs are generated for the variables in both their level and first difference in order to facilitate a visual survey of the trends. The variables are then subjected to testing and analysis of their orders of integration, with the augmented Dickey-Fuller (ADF) and the Dickey-Fuller Generalised Least Squares (DF-GLS) used to determine the presence of unit root processes. Finally, evidence of any significant structural breaks would render the time series subject to additional testing by means of the breakpoint unit root test, which is based on a conventional Dickey-Fuller unit root equation.

3.3.1 CO_2 emissions per capita

The Office of National Statistics (2015c) provides data on the UK's CO_2 emissions and human population in order to generate the CO_2 emissions per capita time series during the 40 years of the sample period. The following is a list of CO_2 emissions sources and their average percentage shares of total CO_2 emissions throughout the sample period: energy supply (39.5%), transportation (19.8%), business (19.4%), residential (14.6%) and miscellaneous emissions (6.7%). Figure 3.1 represents the graph for total CO_2 emissions in metric tons (MT) per capita.

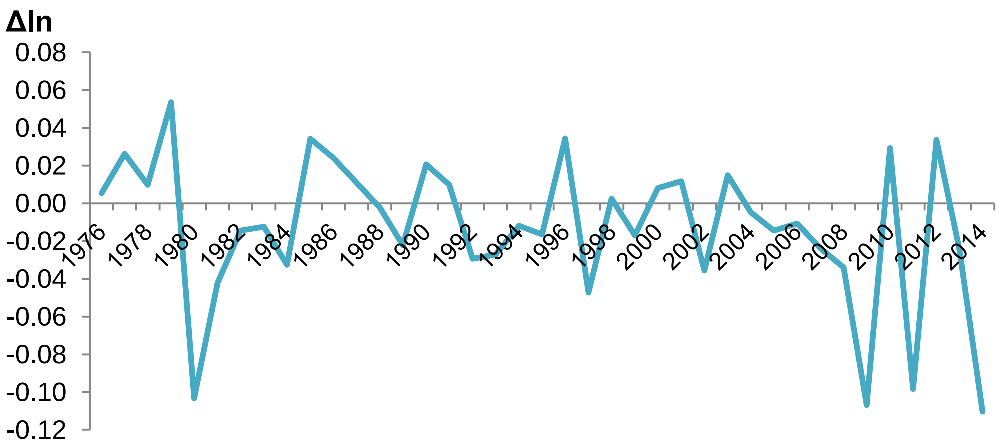
Figure 3.1: CO_2 emissions (metric tons per capita): 1975 - 2014



Source: ONS (2015c)

At a glance, the CO_2 emissions per capita curve seems to show a steady decline throughout most of the sample period. CO_2 emissions per capita peaked at 12.02 metric tonnes (MT) in 1979 followed by a fall of 9.8% to 10.84 MT in 1980. Apart from the 1979 peak, there seems to be little variation in the long-term downward trend. This downward trend is driven by a strong undercurrent of CO_2 emissions abatement in energy supply and business, the two sectors that had received the most pressure from the UK Government's decarbonisation agenda. The curve also displays a slight hint of a bow-shaped pattern from 1984 until the end of the sample period. Figure 3.2 represents the graph of the first difference, natural logarithm of CO_2 emissions per capita (MT).

Figure 3.2: First difference of the natural logarithm of CO_2 emissions: 1975 - 2014

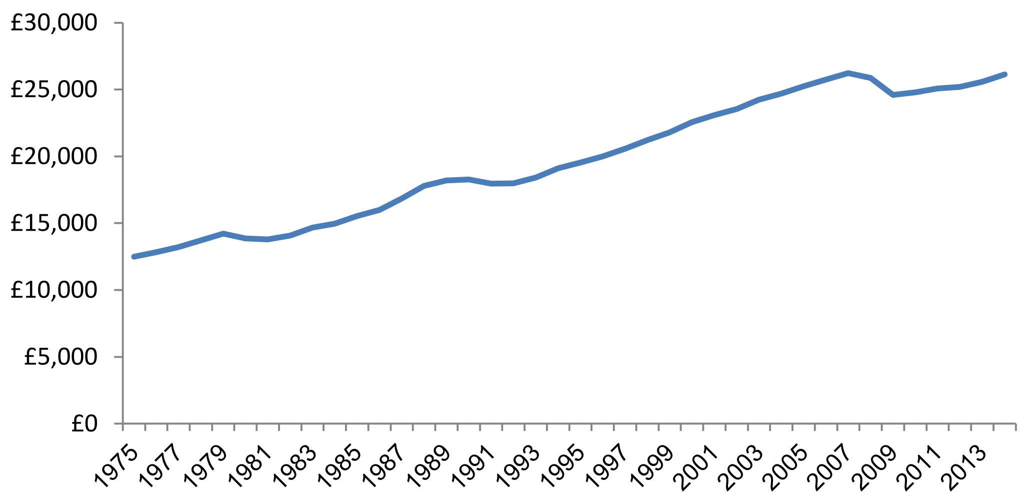


The first difference graph shows a general fluctuation above and below the zero level, with a pronounced dip in 1979. There are also more pronounced fluctuations during the last few years of the sample period, starting from 2008. It may be possible that the beginning of the dip in 2008 caused a structural break in the intercept as a result of the global financial crisis.

3.3.2 Gross Domestic Product per capita

The Office of National Statistics (2015c) provides data on the UK's real gross domestic product (GDP) via its annual publication of the United Kingdom National Accounts (the Blue Book). The data is based on the sum of all UK economic activity resulting from the production and provision of goods and services, represented in constant 2010 British pounds. Figure 3.3 represents the graph for total CO_2 emissions in metric tons (MT) per capita.

Figure 3.3: GDP per capita (constant 2010 GBP): 1975 – 2014

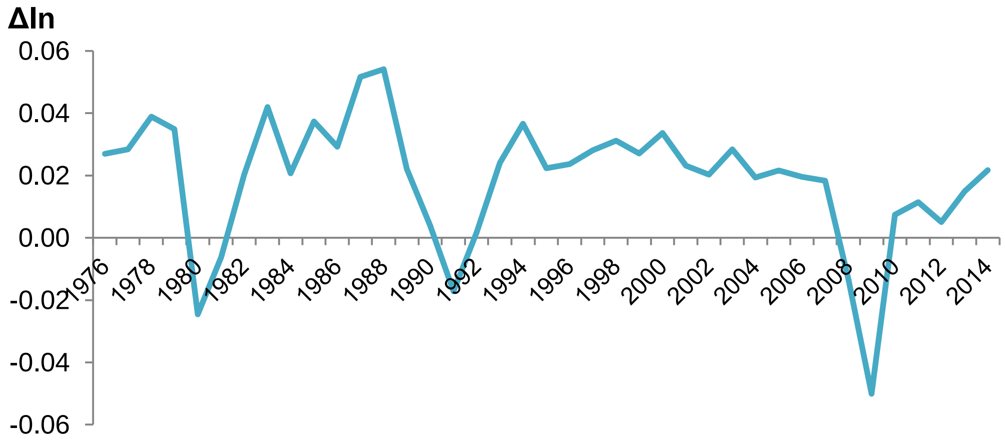


Source: ONS (2015c)

The real GDP per capita curve seems to show a steep rising trend throughout most of the sample period. The trend is smooth apart from three noticeable dips. The first dip in 1980 coincided with the end of the Winter of Discontent of 1978-79, a period that was marked by numerous public sector strikes, high inflation and high unemployment. This was followed by a steep decline in the manufacturing sector and increased unemployment during the early 1980s. The second dip marked the recession of 1990, which coincided with a general contraction of the British economy, high interest rates, high inflation and losses made through the UK's entry and abrupt exit from the European Exchange Rate Mechanism (ERM).

However, the most significant dip came in 2007-08 during the global financial crisis, which was triggered by the subprime mortgage crisis and subsequently led to widespread property repossessions, bank liquidity squeezes and bankruptcies of large corporations and small businesses. The graph indicates that this event is likely to have caused a structural break in the intercept of the data. Figure 3.4 represents the graph of the first difference, natural logarithm of GDP per capita:

Figure 3.4: First difference of the natural logarithm of real GDP per capita: 1975 - 2014

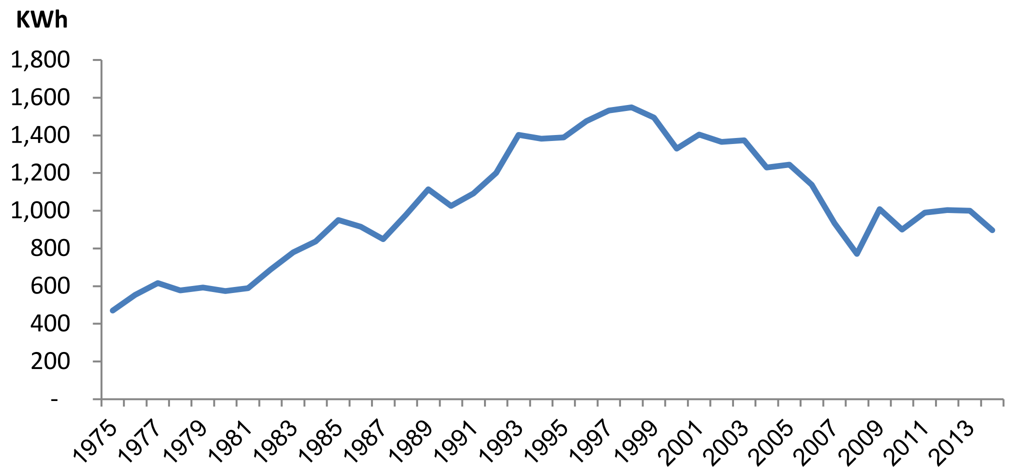


The first difference graph shows the curve mildly fluctuating above zero by approximately 2% throughout the sample period with the exception of three clearly defined recessionary periods. The 2007-08 financial crisis is prominently reflected as the steepest dip in the graph.

3.3.3 Nuclear electricity generation per capita

As in the case of industrial electricity consumption, DECC (2015) provides data on nuclear electricity generation during the sample period from its annual Digest of the United Kingdom Energy Statistics (DUKES). The time series averages approximately 19% of total electricity production throughout the sample period and forms the largest source of decarbonised electricity generation in the UK. Figure 3.5 represents the graph for nuclear electricity production in kilowatt hours (kWh) per capita:

Figure 3.5: Nuclear electricity production (kWh per capita): 1975 - 2014



Source: DECC (2015)

The nuclear electricity generation curve contains a number of volatile fluctuations throughout the sample period. The upward trend starts at 471 kWh per capita in 1975 and is punctuated by dips and peaks until it reaches a high point at 1,549 kWh per capita in 1998. The downward trend in nuclear electricity production starts at the end of 1999, which Bolton (2013) describes as caused by the cessation of nuclear power plant production in 1995. The steady decline from 1999 was also punctuated by a sharp dip during the financial crisis of 2007-08 and this period was marked by the complete closure of some power stations and a high number of unplanned outages at other power stations. Nuclear's electricity production experienced a jump during the 2008-09 period, which coincided with EDF's takeover of British Energy and its portfolio of eight nuclear power plants.

Figure 3.6: First difference of the natural logarithm of nuclear electricity production: 1975 - 2014

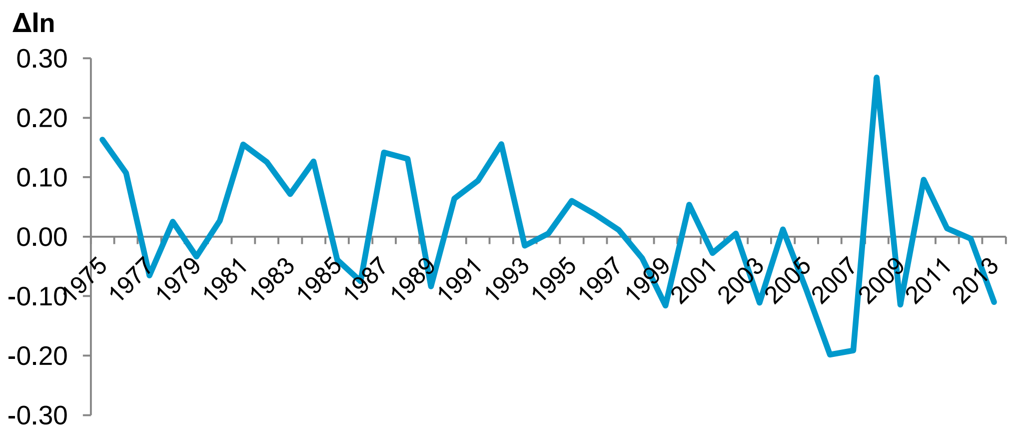
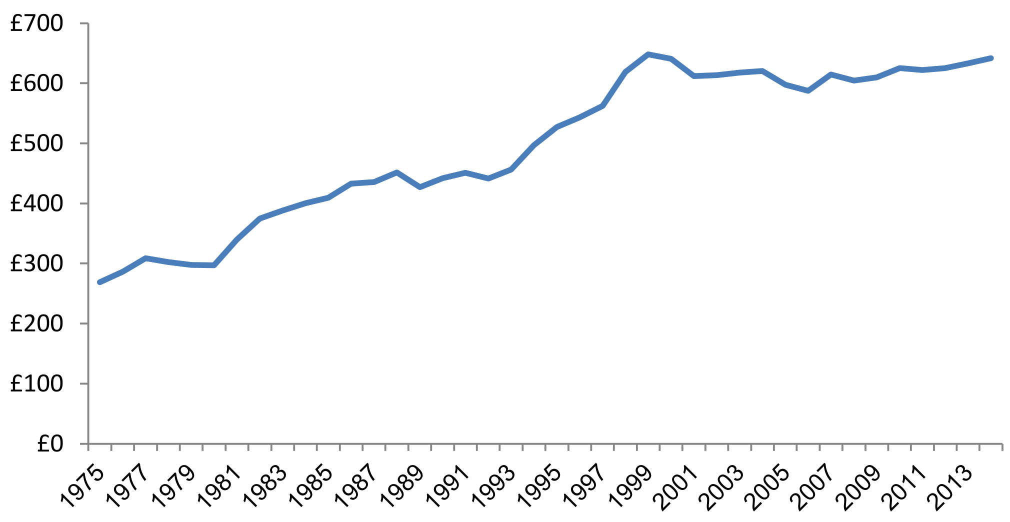


Figure 3.6 represents the graph of the first difference, natural logarithm of nuclear electricity production (kWh per capita). Despite the changing trends of the previous graph, the first difference graph shows a consistent volatile fluctuation of the curve above and below zero. Nevertheless, there are still some noticeable peaks such as the spike in 2009 after the financial crisis as well as dips such as the decline in 1998 after the cessation of investment in new power plants.

3.3.4 Environmental taxes per capita

The Office of National Statistics (2015c) provides data on environmental taxes from the United Kingdom National Accounts. The aggregate environmental tax curve is based on data highlighted in Table 3.1, which consisted of different energy taxes, transport taxes and pollution/resource taxes. Figure 3.7 represents the graph for environmental taxes per capita in constant 2010 British pounds:

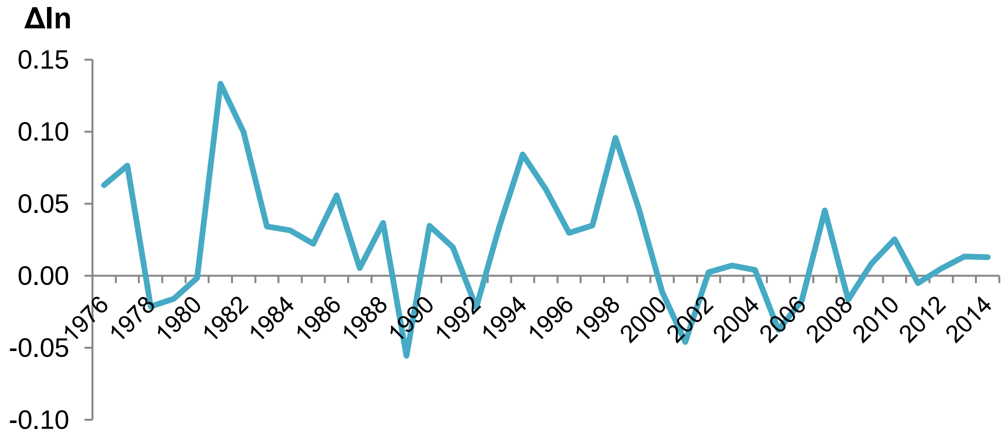
Figure 3.7: Environmental taxes per capita (constant 2010 GBP): 1975 - 2014



Source: ONS (2015c)

The environmental taxes per capita curve follows a predictable inclining trend that is punctuated by three minor dips during the sample period. The first dip period of 1977 was marked by a fall of 2.1%, caused by a moderate decline in the UK population and a relatively lower rate of environmental tax receipts between 1977 and 1979. The second dip period started in 1988 and coincided with the decline in environmental tax receipts from the fossil fuel levy as well as the stabilisation of vehicle excise duties paid by businesses. The third dip period started in 1999 and came a year after the end of the gas levy in 1998. Figure 3.8 represents the graph of the first difference, natural logarithm of environmental taxes per capita:

Figure 3.8: First difference of the natural logarithm of real environmental taxes per capita: 1975 - 2014

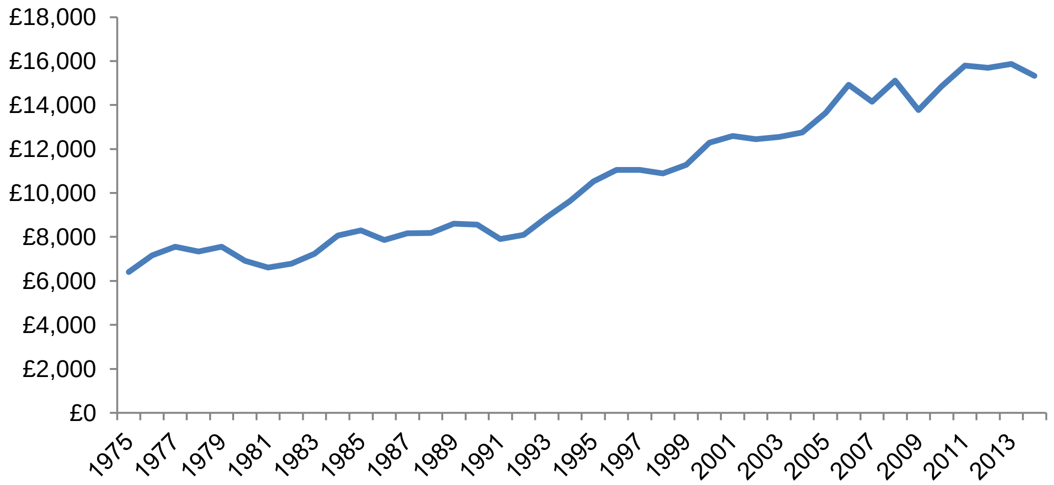


The first difference graph shows the curve predominantly hovering above zero. This reflects a consistent push by the British government to generate revenues through the penalisation of CO_2 emissions. The curve experiences irregular oscillations of peaks and dips during the sample period.

3.3.5 Total trade

The World Bank (2015) provides data on total British trade during the sample period. The data consists of total imports and exports of goods and services, which the World Bank produces through its annual publication of the World Bank Development Indicators. Figure 3.9 represents the graph for trade in constant 2010 British pounds:

Figure 3.9: Total trade per capita (constant 2010 GBP): 1975 - 2014



Source: World Bank (2015)

The curve displays an upward trend with dips that are consistent with the recessionary periods of the last 40 years. As in the case of the GDP curve, British trade was impacted by the economic downturn of the early 1980s where the decline in manufacturing and high inflation brought an end to the UK's surplus in the net trade in goods account by 1982. Trade picks up again due to the UK government's focus on strengthening services growth but experiences stagnation from 1986 that lasted until the recession of 1991. The UK Government's former Department of Business, Innovation and Skills (BIS, 2010) hinted at the pre-recession stagnation by indicating that the net trade in services surplus offset the deficit in net trade in goods from 1982 until 1987, which subsequently led to the overall long term deficit of the trade account. Trade picks up again in 1993 but there are areas of trade volatility that could be seen during the final 10 years of the sample period, especially during and after the global financial crisis of 2007-08.

Figure 3.10: First difference of the natural logarithm of trade per capita: 1975 - 2014

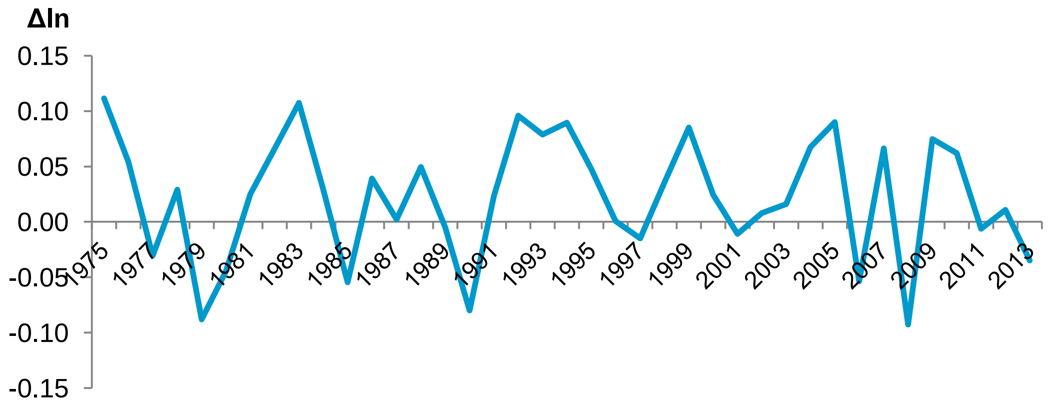
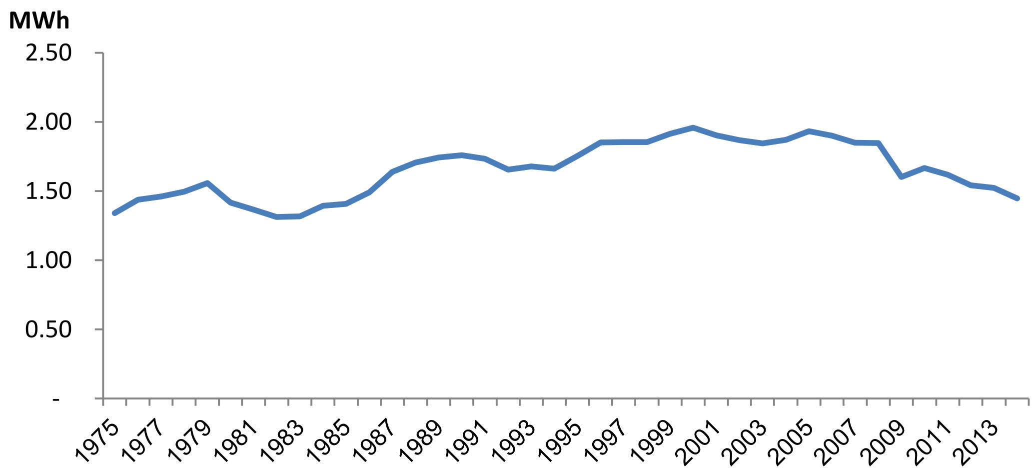


Figure 3.10 represents the graph of the first difference, natural logarithm of total trade per capita. The first difference graph shows a consistent volatile fluctuation of the curve above and below zero, with frequent periods of dips and peaks. Some dips are noticeable in the graph such as the commencement of the UK's trade deficit and the financial crisis of 2007-08.

3.3.6 Industrial electricity consumption per capita

The British Government's Department of Energy and Climate Change (DECC, 2015) provides data on industrial electricity consumption during the sample period. The time series averages approximately 34% of total electricity consumption during the sample period and forms a major subset of electricity consumption statistics obtained from its annual energy statistics publication, DUKES. Figure 3.11 represents the graph for industrial electricity consumption per capita in megawatt hours (MWh):

Figure 3.11: Industrial electricity consumption per capita (MWh): 1975 - 2014

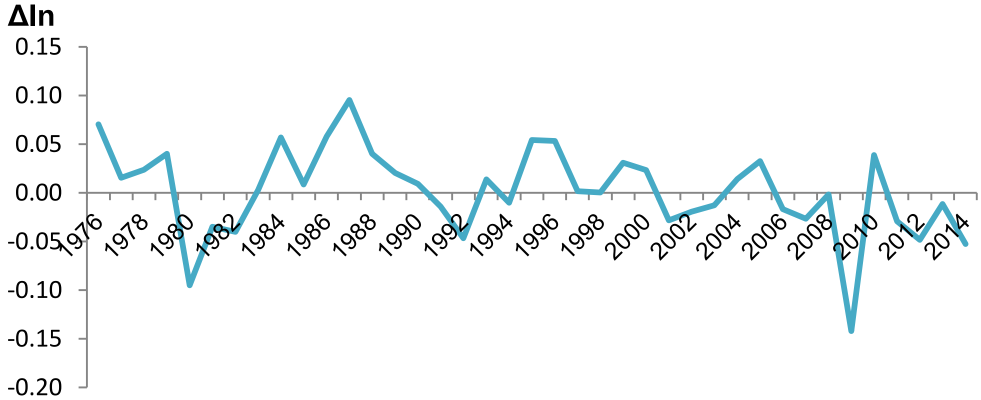


Source: (DECC, 2015)

Similarly to the CO_2 per capita curve, the industrial electricity consumption curve follows a bow-shaped pattern throughout the sample period but seems to assume a gradual cyclical pattern in terms of dips and peaks during the sample period. The first and biggest dip period coincided with the start of the Thatcher administration in 1979 and lasted until 1983. The dip in industrial electricity consumption coincided with the decline in manufacturing and heavy industries during the period of high inflation. The graph shows a slow recovery after this period that reaches its peak in 1990 followed by another dip.

The overall upward trend declines from 2001 and the most significance dip after 2001 coincided with the global financial crisis of 2007-08, which lasted for the final 7 years of the sample period. Figure 3.12 represents the graph of the first difference, natural logarithm of industrial electricity consumption per capita (MWh).

Figure 3.12: First difference of the natural logarithm of industrial electricity consumption per capita: 1975 - 2014



The first difference graph shows a general fluctuation of the curve above and below the zero level, with a dip that started in 1979. A dip could also be seen in 2008 but the graph quickly reverts back to a fluctuating stationary process.

3.4 Estimation methodology

3.4.1 Order of integration and unit root processes in time series data

Energy-economic variables that are used in time series analysis exhibit stochastic processes that model the transformation of a random variable over time. The transformation process is comprised of a random walk where the current value of a random variable consists of the previous value plus a white noise, which itself has a mean of zero. This is represented by the following equation:

$$y_t = y_{t-1} + \varepsilon_t \tag{3.1}$$

The issue with this process is that the current value of the random variable y_t is in fact the best forecast for the next period of y_{t+1}, which means that the random walk does not allow a predictive change between y_t and y_{t+1}. Therefore, a random walk without a predictive trend is known as a nonstationary process. Granger and Newbold (1974) demonstrated that regressions produced from unrelated nonstationary variables would generally produce spuriously significant relationships. The expected output from a spurious regression would consist of a high R-squared, low Durbin-Watson statistic and high t-statistic for the slope coefficient. On the other hand, a random walk with drift allows for the modelling of a stochastic trend process and consists of the following form:

$$y_t = \alpha + y_{t-1} + \varepsilon_t,\ \alpha \neq 0 \tag{3.2}$$

where α is the drift, which is also known as an intercept or constant. The stochastic trend model may have a tendency to move in an upward or downward direction and any random shock to the nonstationary process may increase or decrease the gradient of the stochastic trend. A third process involves the combination of the stochastic trend in equation (3.2) and a deterministic trend. This is represented by the following equation:

$$y_t = a + \beta t + y_{t-1} + \varepsilon_t \tag{3.3}$$

where βt is the time trend component of the deterministic trend $a + \beta t$ and $y_{t-1} + \varepsilon_t$ is the stochastic trend. While polynomial functions of time represent the most common deterministic trends, integrated processes such as those found in energy-economic variables represent the most common stochastic trends. The order of integration of an energy-economic variable should be determined from the outset as invalid statistical inferences can result from regression analyses that use nonstationary variables. As such, a variable that is stationary at 'level' is integrated of order zero i.e. $y_t \sim I(0)$. Conversely, an $I(1)$ variable is a random walk that exhibits a unit root process at level and is integrated of order one. This means that the variable is nonstationary at level and stationary at first difference.

The procedure for verifying the existence of a unit root was developed by Dickey and Fuller (1979), who tested the null hypothesis of a unit root against the alternative hypothesis of a stationary process. The main problem with the Dickey-Fuller test is that it is unable to control for the possibility of autocorrelation in the error terms. This would have a distortionary effect on the tests of significance and overlooking the autocorrelations could lead to a rejection of the null hypothesis of a unit root at the 5% significance level, where in reality, the significance level might be well above 20%. To control for autocorrelation, Dickey and Fuller (1981) suggested the inclusion of lagged variables within the model. Thus, the augmented Dickey-Fuller test (ADF) takes on the following form:

$$\Delta y_t = \alpha + \beta t + \theta y_{t-1} + \delta_1 \Delta y_{t-1} + \delta_2 \Delta y_{t-2} + \cdots + \delta_k \Delta y_{t-k} + \varepsilon_t \qquad (3.4)$$

where Δ is the first difference operator, θ is the unit root testing parameter, δ is the parameter of the lagged first-differenced variable and k is the lag order of the first-differenced variable. The ADF test in equation (3.4) is based on the assumption that y_t is a random walk with drift and time trend ($\theta = 0,\ \beta \neq 0$). In this case, testing a variable for the presence of a unit root is based on the null hypothesis of a random walk with drift and time trend $H_0\!: \theta = 0,\ \beta \neq 0$, against the alternative hypothesis of a stationary process $H_1\!: \theta < 0,\ \beta \neq 0$. Both H_0 and H_1 can also be tested as a random walk or stationary process with drift and no time trend $H_0\!: \theta = 0,\ \alpha \neq 0;\ H_1\!: \theta < 0,\ \alpha \neq 0$ and as a random walk or stationary process with neither a drift nor a deterministic trend $H_0\!: \theta = 0,\ H_1\!: \theta < 0$.

The t-statistic that is derived from the unit root testing parameter θ can be shown as follows:

$$t_\theta = \frac{\hat{\theta}}{SE(\hat{\theta})} \qquad (3.5)$$

where $\hat{\theta}$ is an estimate of the parameter θ and $SE(\hat{\theta})$ is the standard error of the estimated coefficient. Dickey and Fuller (1979) indicated that when a unit root is present, the t-statistic does not follow a t-distribution and they developed critical values from Monte Carlo simulations that would be tested against the t-statistic at various sample sizes. Mackinnon (1991, 1996) provides more recent critical values that are used in this chapter, which are based on a greater number of Monte Carlo simulations than those provided by Dickey and Fuller (1979). Furthermore, the Mackinnon critical values can be calculated for more specific sample sizes than in the original Dickey-Fuller critical values.

The t-statistic from the unit root test is compared with the critical value at the 1%, 5% and 10% levels of significance. If the t-statistic is higher than the critical value (at say the 5% significance level), then we do not reject the null hypothesis of a unit root at level. The unit root test is therefore performed again on the variable at first difference and if the t-statistic is less than the critical value at the relevant significance level (i.e. large negative number), then we reject the null hypothesis of a unit root at first difference i.e. the variable is $I(1)$. As previously mentioned, the unit root test can be calculated based on the selection of any three options: no drift (intercept) and no time trend, drift only and drift with time trend. A number of different lags lengths can be chosen in order to find the minimum lag length that removes serial correlation from the residuals.

Another unit root test that is usually performed alongside the ADF test is the Dickey-Fuller generalised least squares (DF-GLS) test proposed by Elliott, Rothenberg, and Stock (1996, henceforth ERS). The DF-GLS test equation corresponds to the ADF test equation but the DF-GLS is performed on GLS-detrended time series in order to provide efficient estimates for the deterministic parameters of the variables. The DF-GLS test takes on the following form:

$$\Delta y_t^d = \theta y_{t-1}^d + \delta_1 \Delta y_{t-1}^d + \delta_2 \Delta y_{t-2}^d + \cdots + \delta_k \Delta y_{t-k}^d + \varepsilon_t \qquad (3.6)$$

where d is the detrend operator. ERS demonstrated that when the deterministic term in the equation is 1, the asymptotic distributions between the ADF and DF-GLS test are the same but the DF-GLS test has a better overall performance in small sample sizes in relation to its ability to detect near-nonstationarity. ERS also implied that the DF-GLS had more power than the ADF test in cases where there is an unknown deterministic trend and it is more likely to reject a false null hypothesis.

Despite the usefulness of ADF and DF-GLS, the presence of a structural break in data may call into question the validity of the results. Therefore, the breakpoint unit root test could be used to categorically determine the order of integration of a variable around a breakpoint. Vogelsang and Perron (1998) describes two versions of the breakpoint unit root tests that assesses the break motion: an innovation outlier (IO), which assumes the break follows a gradual path and the additive outlier (AO), which assumes the break happens immediately. The following is a representation of the Dickey-Fuller IO breakpoint unit root test, which allows for a break in the intercept (such as from a global financial crisis or an oil shock) as well as a break in the trend, which involves a gradual change in the long run rate of growth:

$$y_t = \alpha + \beta t + \lambda DU_t(T_b) + \gamma DT_t(T_b) + \omega D_t(T_b) + \theta y_{t-1} + \sum_{i=1}^{k} \delta_{\mathrm{i}} \Delta y_{t-i} + \varepsilon_t \qquad (3.7)$$

where T_b is the date when the break took place and λ, γ and ω are the break parameters. DU_t is the intercept break dummy which takes on the value $DU_t = 1$ if $t \geq T_b$ but otherwise takes on the value of 0, DT_t is the trend break dummy which takes on the value $DT_t = 1(t \geq T_b) \cdot (t - T_b + 1)$ but otherwise takes on the value of 0 prior to the break date. D_t is a one-time break dummy which takes on the value $D_t = 1$ if $t = T_b$ but otherwise takes on the value of 0.

As equation (3.7) tests for a break in the intercept and trend, the second option is based on an intercept-only break, which requires the removal of DT_t. The third option is based on a trend-only break, which requires the removal of DU_t and D_t. Each of these three options tests for the null hypothesis of a unit root with break with the alternative hypothesis being a time trend stationary process with break. The fourth option is based on the removal of time trend βt from the second option of the intercept-only break, with H_0 based on a unit root with break and H_1 based on a stationary process with break.

An issue of the IO approach that was implied by Perron (1989) is that in the event of a known or estimated break date, the first, second and fourth options permit breaks under the null hypothesis of a unit root but the third option (trend-only break) does not allow breaks under the null hypothesis of a unit root. Furthermore, Harvey et al (1998) specifically criticised the IO framework by declaring it to be an unsuitable tool for the detection of structural breaks and recommended that they should not be used at all.

The implementation of the more common AO break framework involves a two-stage process. The first stage requires the use of the intercept, trend and break dummy variables to detrend the time series via Ordinary Least Squares (OLS) and the second stage involves a modified Dickey-Fuller test for a unit root on the detrended time series. The following is a representation of the Dickey-Fuller AO breakpoint unit root test:

$$\hat{y}_t^* = \sum_{i=0}^{k} \omega_i D_{t-i}(T_b) + \theta \hat{y}_{t-1}^* + \sum_{i=1}^{k} \delta_{\mathrm{i}} \Delta \hat{y}_{t-i}^* + \varepsilon_t \tag{3.8}$$

where $\hat{y}_t^*$ are the residuals gained from the first stage of the detrending process. Equation (3.8) can be used to test data that was detrended on the following three bases: non-trending data with an intercept-only break, trending data with intercept-only break and trending data with intercept and trend breaks. Detrended data based on trend-only break requires the replacement of the first part of the equation (3.8) $\sum_{i=0}^{k} \omega_i D_{t-i}(T_b) + \theta \hat{y}_{t-1}^*$ with θy_{t-1}. If a break date is known then it can be defined prior to model estimation but if a break date is estimated, it is chosen using a selection method that minimises the Dickey-Fuller t-statistic t_θ. Finally, unlike the ADF and DF-GLS tests, which assess H_0 by using the t-statistic to compare θ with 0, both the IO and AO Dickey-Fuller breakpoint unit root tests use the t-statistic to compare θ with 1.

The unit root tests and subsequent time series regressions in this chapter require the use of a truncation lag (for example, p) which denotes the lag order of a variable. The significance of the lag order selection process must be emphasised as Ng and Perron (1995, 2001) demonstrated that there is a strong relationship between the value of p and the extent of size distortions. The value of p may also have an impact on the power attribute of the unit root test, which is especially important as unit root tests are generally noted for having low power.

The main approach to estimating the maximum desirable value of p is through lag selection criteria such as the Akaike Information Criterion (AIC) and the Schwarz Information Criterion (SIC). Calculations are made on the information criteria functions for models with different lag orders and the selection criteria is based on the model that minimises the value of the function. The following are the representations of AIC and SIC model selection criteria:

$$\text{AIC} = -2\left(\frac{\text{LL}}{T}\right) + \frac{2t_p}{T} \quad (3.9)$$

$$\text{SIC} = -2\left(\frac{\text{LL}}{T}\right) + \frac{\ln(T)}{T}t_p \quad (3.10)$$

where LL is the log likelihood function, T is the number of included observations in the model (after adjustments) and t_p is the total number of parameters to be estimated. For both information criteria, preference is given to parsimonious models that are correctly specified and have the least lagged coefficients to estimate. However, Davidson and Mackinnon (2004) suggested that if there was an option to select two or more nested models, AIC may not choose the most parsimonious one. Furthermore, SIC imposes a penalty for additional lagged coefficients and this helps to provide a safety-first mechanism in its restriction of the lag order. Lütkepohl (2005) also demonstrated the theoretical superiority of SIC in large sample sizes, which provides more reliable estimates of the true lag order than AIC, which tends to overestimate the true lag order. However, Lütkepohl (2005) argues that although AIC overestimates the true lag order in large sample sizes, AIC is more consistent in being able to select the correct lag order in small sample sizes than SIC.

3.4.2 Description of ARDL / bounds testing model of cointegration analysis

The empirical literature has firmly established the link between CO_2 emissions and GDP. However, a very small number of literature sources have attempted to provide a theoretical framework to support this link such as the environmental Kuznets curve (EKC), which suggests that an inverted U-shaped quadratic relationship exists between CO_2 emissions and economic growth. As previously highlighted in Chapter 2, there is a particularly scarce number of studies that assesses the role of nuclear energy in the nuclear-GDP-CO_2 nexus such Jobert et al (2013), who proved a rare analysis of the role of nuclear energy consumption that provided mixed results from a basket of 21 countries.

Most of these studies had followed a bivariate approach in their analysis of this relationship. The main problem from the bivariate estimates stems from omitted variable bias, which implies that a model's results are likely to be biased and inconsistent if there is an omission of other potential variables that have a direct influence on CO_2 emissions. Our analysis thus follows the Iwata et al (2010) selection of additional variables in their study of the nuclear-GDP-CO_2 nexus: energy consumption and trade (imports and exports of products and services). Energy consumption in the Iwata et al (2010) selection consists of total energy consumption whereas energy consumption in this chapter differs as it consists of total industrial electricity consumption. This is based on the focus on electricity consumption related to manufacturing and trade. This inclusion also stems from the key role that industrial energy demand has on CO_2 emissions (Polemis, 2007) as well as the British government's heavy promotion of electricity consumption to industries in order to meet the UK's CO_2 emissions abatement targets.

The study is based on a comparative analysis of nuclear electricity generation and environmental taxes so the general model takes on the following logarithmic form:

$$\ln(co_2)_t = \alpha_0 + \alpha_1 \ln gdp_t + \alpha_2 \ln nuc_t + \alpha_3 \ln entax_t + \varepsilon_t \tag{3.11}$$

where co_2 is CO_2 emissions per capita, *gdp* represents real GDP per capita, *nuc* represents nuclear electricity generation in KWh per capita and *entax* represents real environmental taxes per capita. The general model is incrementally increased by one variable in order to assess the comparative impact between *nuc* and *entax* on CO_2 emissions. The total trade variable (*trade*) is first added to the general model, followed by the industrial electricity consumption variable (*indelec*). As previously mentioned in the introduction section, *trade* and *nuc* are changed from share variables to total trade in British pounds (GBP) and KWh per capita respectively.

The theoretical pre-estimation assumptions based on previous studies of the nuclear-GDP-CO_2 nexus are that the sign for *nuc* is expected to be negative and the sign for *gdp* is expected to be positive. For this chapter, the sign for *entax* is expected to be negative due to the UK Government's affirmative action against climate change while the sign for *indelec* is expected to be positive as there was a slight decline in industrial electricity consumption between 2000 and 2007, with the declining trend becoming steeper between the financial crisis of 2008 and the end of the sample period of 2014. The expected sign for *trade* is unknown at this stage.

Cointegration analysis is subsequently used for the empirical estimation of the long run relationship between these variables. Cointegration theory asserts that nonstationary time series that are $I(1)$ share a cointegrating relationship if a linear combination of two or more variables are stationary i.e. $I(0)$. The relationship between the cointegrating variables is often underpinned by economic theory as they share an equilibrium relationship in the long run. Engle and Granger (1987) describe a set of time series where their cointegrating relationships are drawn together by economic theory such as commodities prices and their substitutes in the same market and household incomes and expenditure. The implication is that cointegrating variables are unable to stray too far from each other in the long run because economic forces tend to draw them back towards their long run equilibrium relationship.

For a clearer picture, let $Y_t = (y_{1t},\ y_{2t}, \dots ,y_{Kt})'$ represent a $K \times 1$ vector of $I(1)$ variables. Y_t consists of a cointegrating relationship if a $K \times 1$ vector of $\beta = (b_1,\ b_2, \dots, b_K)$ linearly combined parameters exist, such that:

$$\beta' Y_t = b_1 y_{1t} + b_2 y_{2t} + \cdots + b_K y_{Kt} \sim I(0) \tag{3.12}$$

If any part of β is equal to zero, then only the non-zero parts of β are cointegrated within $\beta' Y_t$. Thus, the cointegrated elements within $\beta' Y_t$ are said to share a long run equilibrium relationship. Although β is the cointegrating vector, its identity is not unique as any scalar on β would still render $\beta' Y_t \sim I(0)$. Therefore a normalisation process would be carried out by choosing which coefficient to normalise to unity as this would provide a unique identification for β. The normalised cointegration relationship can now be uniquely expressed as follows:

$$\beta' Y_t = y_{1t} - b_2 y_{2t} - \cdots - b_K y_{Kt} \sim I(0) \tag{3.13}$$

There are a number of cointegration modelling techniques that are used for time series analysis, with the most well-known methods consisting of the two-step method originated by Engle and Granger (1987) and the maximum likelihood (ML) estimator proposed by Johansen (1988, 1991). Johansen's approach has several advantages over the Engle-Granger approach such as the greater clarity offered on the statistical significance tests on the speed of adjustment parameters as well as its ability to identity multiple cointegrating relationships on more than two $I(1)$ variables. However, Johansen's approach requires that all variables in a model must have a symmetry of lag lengths and obstacles inevitably arise for modellers who have a specific desire to demonstrate the relationships between variables that have varying lag lengths.

The autoregressive distributed lag (ARDL) model for cointegration analysis, which was popularised by Pesaran and Shin (1999) and expanded into the bounds testing framework by Pesaran, Shin and Smith (2001) can override this inflexibility as valid assumptions could be made from models whose regressors have varying lag lengths. The ARDL-bounds test approach has also demonstrated a strong capability in handling relatively small sample sizes. Furthermore, endogenous variables do not hinder the model's ability to provide unbiased estimates of the long run parameters.

The ARDL model is an OLS regression that consists of lags that are distributed among the dependent and independent variables. The model is usually written in the (p,q) format where p is the maximum number of lags for the dependent variable and $q = q_1, q_2, \ldots, q_k$ is the maximum number of lags for each of the independent variables up to the k-th independent variable. Based on the Patterson (2000, p.349) notation, the general form of a multivariate ARDL model is based on the following representation:

$$Y_t = \alpha_0 + \sum_{i=1}^{p} \beta_i L^i Y_t + \sum_{j=0}^{q} \gamma_{ij} L^{ij} X_t' + \varepsilon_t \qquad (3.14)$$

where L is the lag operator and X' is a vector of independent variables. X' may have dynamic variables which consist of lagged terms or static variables, which do not have any lagged terms i.e. $q = 0$. The actual number of lags for each of the variables in the ARDL model will be truncated using the AIC (equation 3.9) due to its greater accuracy in selecting the true lag order in small sample sizes (Lütkepohl, 2005).

The relationship between the variables in equation (3.11) follows a time path prior to the achievement of a long run relationship. Therefore, equation (3.11) can be written in the following unrestricted error correction form of the ARDL model:

$$\begin{aligned}\Delta\ln(co_2)_t &= \beta_0 + \sum_{\mathrm{i}=1}^{p} \beta_{1\mathrm{i}} \Delta\ln(co_2)_{t-i} + \sum_{\mathrm{i}=0}^{q} \beta_{2\mathrm{i}} \Delta\ln gdp_{t-i} + \sum_{\mathrm{i}=0}^{q} \beta_{3\mathrm{i}} \Delta\ln nuc_{t-i} \\ &+ \sum_{\mathrm{i}=0}^{q} \beta_{4\mathrm{i}} \Delta\ln entax_{t-i} + \lambda_1 \ln(co_2)_{t-1} + \lambda_2 \ln gdp_{t-1} + \lambda_3 \ln nuc_{t-1} \\ &+ \lambda_4 \ln entax_{t-1} + e_{1t} \qquad (3.15)\end{aligned}$$

where e_t is the error term. The steps of the ARDL-bounds testing procedure are as follows: First, we test for the existence of a long run relationship between the variables in equation (3.15) by testing the null hypothesis of no cointegration, $H_0: \lambda_1 = \lambda_2 = \lambda_3 = \lambda_4 = \lambda_5 = 0$, against the alternative hypothesis, H_1 requiring at least one of the λ relationships to be $\neq 0$.

Pesaran, Shin and Smith (2001) provide critical values for ARDL-bounds testing cases where all of the variables are *I*(0) and critical values where all of the variables are *I*(1). These critical values would then act as the lower and upper bounds in cases where the model contains a combination of *I*(0) and *I*(1) variables. The *F*-statistic that is calculated from the ARDL-bounds test is compared to the reported asymptotic critical value bounds. If the *F*-statistic is below the lower bound, then we do not reject the null hypothesis of no cointegration relationship between the variables. Conversely, if the *F*-statistic is above the upper bound, then we reject the null hypothesis of no cointegration relationship between the variables. However, if the *F*-statistic falls between the two bounds, then the results are uncertain.

The next step involves the estimation of the long run coefficients of the cointegrating model in equation (3.15). The final step involves an estimation of the short run coefficients from the restricted error correction representation, which is defined below:

$$\Delta \ln(co_2)_t = \beta_0 + \sum_{\mathrm{i}=1}^{p} \beta_{1\mathrm{i}} \Delta \ln\,(co_2)_{t-i} + \sum_{\mathrm{i}=0}^{q} \beta_{2\mathrm{i}} \Delta \ln gdp_{t-i} + \sum_{\mathrm{i}=0}^{q} \beta_{3\mathrm{i}} \Delta \ln nuc_{t-i} + \sum_{\mathrm{i}=0}^{q} \beta_{4\mathrm{i}} \Delta \ln entax_{t-i} + \varphi ec_{t-1} + \varepsilon_t \tag{3.16}$$

where ec_{t-1} is the lagged error correction term obtained from the residuals of the preceding ARDL model and φ is the speed of adjustment parameter that converges the ECM towards its long run equilibrium state. Diagnostic tests are subsequently carried out in order to determine the statistical robustness of the model. The Lagrange Multiplier (LM) test known as the Breusch-Godfrey LM test is used to assess for the presence of autocorrelation and the Breusch-Pagan-Godfrey LM test is used to assess the residuals for the presence of heteroskedasticity. The Jarque-Bera normality test assesses whether the residuals follow a normal distribution and provides information on the kurtosis and skewness of the residuals while the Ramsey RESET test is a structural test that determines whether there are any specification errors in the functional form of the model.

Stability tests are performed on the recursive residuals of the error correction model in order to determine its structural stability. The recursive residuals are the error terms of the one-step ahead forecasts that are generated from recursive least squares. The recursive residuals are independent and identically distributed (i.i.d.) and can be viewed as demonstrating the cumulative effect of removing successive observations from the data set. The two stability tests that are performed are the cumulative sum (CUSUM) and the cumulative sum of squared recursive residuals (CUSUMSQ) proposed by Brown, Durbin, and Evans (1975). The CUSUM test shows the systematic adjustments in the recursive residuals over time and the CUSUMSQ test identifies any unusual or sudden instabilities in the recursive residuals. A graph shows the recursive residuals fitted between two straight bars in the CUSUM and CUSUMSQ test, with each bar representing the 5% significance level. The null hypothesis of stability is rejected if the recursive residuals breach the 5% significance bars for a consistent length of time.

3.4.3 Environmental Kuznets Curve (EKC)

In order to test the hypothesis of an EKC turning point for CO_2 and GDP per capita, we estimate a number of models that consist of a combination of the previously identified variables: ln co_2, ln *indelec*, ln *gdp*, ln *trade*, ln *nuc* and ln *entax*. The basic relationship in the EKC hypothesis between CO_2 emissions and GDP is given by the following representation:

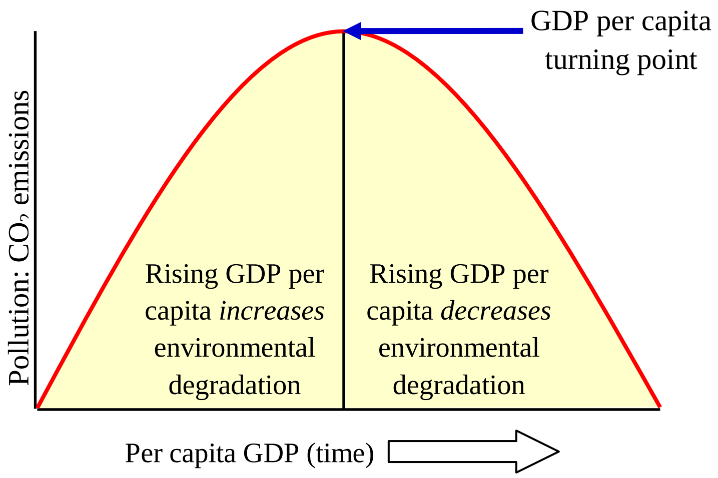
$$\ln(co_2)_t = \alpha_0 + \alpha_1 \ln gdp_t + \alpha_2 (\ln gdp_t)^2 + \varepsilon_t \tag{3.17}$$

where $(\ln gdp_t)^2$ constitutes the quadratic form of ln *gdp*, which allows the EKC to follow an inverted "U" shaped path. EKC equation (3.17) seeks to determine the long run relationship between the variables so an unrestricted error correction form of the ARDL model can be estimated as follows:

$$\Delta \ln(co_2)_t = \beta_0 + \sum_{i=1}^{p} \beta_{1i} \Delta \ln (co_2)_{t-i} + \sum_{i=0}^{q} \beta_{2i} \Delta \ln gdp_{t-i} + \sum_{i=0}^{q} \beta_{3i} \Delta (\ln gdp_{t-1})^2 + \sum_{i=0}^{q} \beta_{4i} \Delta \ln nuc_{t-i} + \sum_{i=0}^{q} \beta_{5i} \Delta \ln entax_{t-i} + \lambda_1 \ln(co_2)_{t-1} + \lambda_2 \ln gdp_{t-1} + \lambda_3 (\ln gdp_{t-1})^2 + \lambda_4 \ln nuc_{t-1} + \lambda_5 \ln entax_{t-1} + e_{1t} \tag{3.18}$$

The multivariate group in equation (3.18) is increased by 1 with the addition of ln *trade*, and then with the addition of ln *indelec*, which brings the number of estimated models to three. The EKC hypothesis is supported if $\lambda_2 > 0$ and $\lambda_3 < 0$ and if confirmed, the GDP per capita turning point can be calculated as the exponent $(-\lambda_2/2(\lambda_3))$ applied to base *e* (2.7182818). At this point, an increase in GDP per capita would proportionately correspond to a decrease in environmental degradation, which is measured by CO_2 emissions. Figure 3.13 provides an illustration of an EKC based on equation (3.17):

Figure 3.13: Quadratic representation of an environmental Kuznets curve



Source: Created by author based on EKC hypothesis

Richmond and Kaufmann (2006) describe three alternative scenarios that could arise from the estimated results that would not support the EKC hypothesis: a linear relationship based on $\lambda_2 \neq 0$ and $\lambda_3 = 0$, a U-shaped relationship based on $\lambda_2 < 0$ and $\lambda_3 > 0$ and an exponential relationship based on $\lambda_2 = 0$ and λ_3 shares the same sign as λ_2. The EKC hypothesis would also lack support if λ_2 or λ_3 were found to be statistically insignificant, regardless of the correctness of the coefficients' signs.

3.4.4 Granger causality: Wald test and the Toda-Yamamoto (T-Y) approach

As previously mentioned in the literature review, the Granger (1969) approach of causality assesses whether variable X has a causal relationship with variable Y based on the predictive quality of past values of X on past values of Y. However, an *X Granger causes Y* result does not imply a strict cause and effect relationship between the two variables but provides a measurement of antecedence that could supplement the results from the cointegration and error correction models. Furthermore, non-Granger causality between variables does not mean that the variables cannot share a long run equilibrium relationship and care should be taken to distinguish the meaning of the results from these differing assessment tools.

Pairwise Granger causality is based on a bivariate vector autoregression (VAR) with a p lag order that follows the following specification:

$$Y_t = \alpha_0 + \sum_{i=1}^{p} \beta_i Y_{t-i} + \sum_{j=1}^{p} \gamma_j X_{t-j} + \varepsilon_t \qquad (3.19)$$

$$X_t = \alpha_0 + \sum_{i=1}^{p} \beta_i X_{t-i} + \sum_{j=1}^{p} \gamma_j Y_{t-j} + u_t \qquad (3.20)$$

The Wald test assesses the linear restrictions on the coefficients of the VAR and is performed on the γ coefficients from equations (3.19) and (3.20). This in order to test the null hypothesis of no Granger causality, $H_0: \gamma_1 = \gamma_2 \cdots \gamma_p = 0$, against the alternative, $H_1: \gamma_j \neq 0$ for all j. The Wald test produces an F-statistic and chi-squared (χ^2) statistic, which are matched against their respective probability values. If the probability value is below a predetermined significance level (say 5%), then the null hypothesis of no Granger causality is rejected.

The typical representation of Granger causality in the literature involves an assessment of the causal aspects of the predictor variable from the bivariate VAR equations (3.19) and (3.20). However, causal interactions between two variables usually involve complex and coordinated interactions with additional variables in a multivariate framework, which may result in spurious inferences from a bivariate causal analysis. Therefore, a multivariate Granger causality analysis is deemed to be more statistically appropriate where causal inferences are sought between two variables in a multivariate group (Barrett et al, 2010).

Another problem with Granger causality arises where some of the variables in a VAR model are non-stationary. The Wald test statistic in this scenario does not follow a typical asymptotic χ^2 distribution under the null hypothesis of no Granger causality and the limiting distribution often contains unobservable nuisance parameters (Sims, Stock and Watson, 1990; Toda and Phillips, 1993). To overcome this problem, Toda and Yamamoto (1995) proposed a method of Granger causality based on the maximum order of integration (*m*) of the variables in a VAR. The augmented VAR model in this scenario is estimated at level (not first difference) and consists of a (*p* + *m*) lag order. The Wald test is then carried out on all of the lagged *p* coefficients of the predictor variables apart from the final lagged (*p* + *m*) coefficients, which are ignored. The resulting Wald test statistic follows an asymptotic χ^2 distribution with the usual degrees of freedom and this is applicable regardless of the order of integration of the variables.

Based on Toda-Yamamoto (T-Y) methodology, the following is the representation of the augmented VAR(*p* + *m*) that is estimated in this chapter prior to the modified Wald (MWald) test for Granger causality:

$$\boldsymbol{y}_t = \mathbf{c} + \sum_{\mathrm{i}=1}^{p+m} \mathbf{A}_{\mathrm{i}} \mathbf{y}_{t-\mathrm{i}} + \boldsymbol{\varepsilon}_t \tag{3.21}$$

where $\boldsymbol{y}_t$ is a $K \times 1$ vector of dependent variables, **c** is a $K \times 1$ vector of intercept parameters, $\mathbf{A}_{\mathrm{i}}$ $(i = 1, \dots, p + m)'$ is a $K \times K$ matrix of parameters and $\boldsymbol{\varepsilon}_t$ is a $K \times 1$ vector of error terms. The break dummy variable dv_t is also included in the estimation. Similarly to the cointegration and ECM cases, the main variable of interest is ln co_2 and this variable is assessed for bidirectional causality against ln *nuc*, ln *entax* and the other variables within the multivariate group. The results from the MWald test are compared to the Wald test results from a standard Granger causality analysis in order to determine their economic significance.

3.5 Empirical analysis

This section contributes to the empirical literature on the nuclear-GDP-CO_2 nexus by providing an assessment of the econometric effect of electricity supply from nuclear fission on CO_2 emissions in the UK. The findings in this section provide an important reference point for the future commercialisation of electricity from fusion power due to the similarities with nuclear fission, based on their nuclear reactions for energy generation, capital-intensive nature and the long periods of power plant construction. A key contribution comes in the form of a comparative analysis on the effect on CO_2 emissions between environmental taxes and nuclear fission, which ultimately compares the UK government's action against GHG emissions with the generation of decarbonised electricity respectively.

The results of the empirical analysis are based on the methodology that was highlighted in section 3.4, which consists of estimates generated from the unrestricted and restricted ECMs, an EKC turning point and competing Granger causality analyses from the Wald and MWald tests. The estimates in Tables 3.3 to 3.15 and Figures 3.14 to 3.20 are based on the variables from section 3.3, which consists of annual data from 1975 to 2014.

3.5.1 Unit root tests for the ARDL variables

Table 3.3 shows the results from the unit root tests on each of variables highlighted in section 3.3. The unit root tests are based on a lag order of 1 and the t-statistic results are shown for each variable alongside their corresponding probability value. The first difference operator is represented by Δ and a star denotes the existence of a stationary process at first difference:

The option of selecting "intercept" or "intercept and trend" is determined by the pattern of the data and graphical representation. The ADF and DF-GLS results show that ln *gdp* is $I(1)$ at the 5% significance level and the remaining five variables are $I(1)$ at the 1% significance level. Therefore based on ADF and DF-GLS results, we can reject the null hypothesis of a unit root at first difference for all variables.

Table 3.3: ADF and DF-GLS unit root tests

Variable	Included in test	ADF t-statistic	DF-GLS t-statistic
ln co_2	Intercept and trend	-0.826 (0.954)	-1.254
Δln co_2	Intercept and trend	-7.286 (0.000) ***	-7.176 ***
ln *gdp*	Intercept only	-2.082 (0.539)	-2.277
Δln *gdp*	Intercept only	-3.583 (0.045) **	-3.686 **
ln *nuc*	Intercept only	-2.365 (0.158)	-1.044
Δln *nuc*	Intercept only	-5.931 (0.000) ***	-4.916 ***
ln *entax*	Intercept and trend	-1.308 (0.871)	-1.498
Δln *entax*	Intercept and trend	-4.759 (0.002) ***	-4.852 ***
ln *trade*	Intercept only	-0.764 (0.818)	0.353
Δln *trade*	Intercept only	-5.752 (0.000) ***	-4.453 ***
ln *indelec*	Intercept only	-1.546 (0.500)	-1.086
Δln *indelec*	Intercept only	-5.023 (0.000) ***	4.111 ***

1. ***, ** and * denotes $I(1)$ at the 1%, 5% and 10% significance levels respectively
2. The numbers in parentheses are the probability values of the t-statistics

Perron (1989) indicated that a rejection of the null of a unit root does not necessarily mean that the data is stationary around a structural break. Furthermore, Stock (1994) demonstrated that structural breaks in detrended variables may deteriorate the power of unit root tests as well as cause severe size distortions. These distortions often point towards an over-rejection of the true null hypothesis i.e. a random walk falsely declared as a stationary process. For some time series, a moderate structural break may not have any real impact on the conclusion of the unit root tests. However, if there is a reason to believe the existence of an important structural break, a more specific test is carried out in order to determine the true order of integration.

The unit root breakpoint test is therefore performed in order to test the null hypothesis of a unit root process with break against a stationary process with break. The break date of 2008 is easily determined from the first difference graphs of ln co_2 and ln *gdp* in section 3.3. The break motion assessment is solely based on the additive outlier as a result of the Harvey et al (1998) rejection of the innovation outlier. Table 3.4 provides a summary of the results from the breakpoint unit root tests based on 1 lag:

Table 3.4: Breakpoint unit root tests

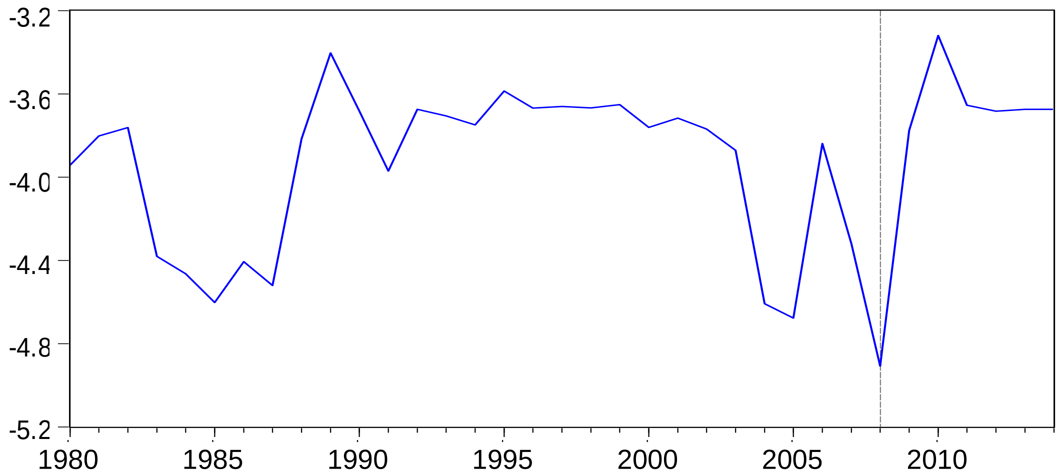
	Break Type:	Break Specification	Est. / Known break date	t-statistic
ln co_2	Additive outlier	Intercept and trend	2008	-4.331 (<0.025)••
Δln co_2	Additive outlier	Intercept and trend	2008	-8.066 (<0.01)***
ln *gdp*	Additive outlier	Intercept	2008	-0.418 (>=0.50)
Δln gdp	Additive outlier	Intercept	2008	-4.904 (0.012)**

1. •••, •• and • denotes *I*(0) at the 1%, 5% and 10% significance levels respectively
2. ***, ** and * denotes *I*(1) at the 1%, 5% and 10% significance levels respectively
3. The numbers in parentheses are the probability values of the t-statistics

The uncertainty surrounding ln co_2 is confirmed as the null hypothesis of a unit root with break is rejected at level for the 5% significance level, thereby providing strong evidence that ln co_2 is an *I*(0) process around a structural break. The null hypothesis of a unit root with break is also rejected at first difference at the 1% significance level.

Despite the breakpoint unit root test confirming the *I*(1) status of ln *gdp*, the break date for Δln *gdp* was endogenously determined rather than predefined so it is useful to view a graph of the Dickey-Fuller t-statistics in order to view the location of the break.

Figure 3.14: Graph of the Dickey-Fuller t-statistics - Δln GDP



The indicator line and sharp dip in 2008 appears to confirm the year that the break took place. 2008 is therefore the selected break year that will be used for estimation purposes in subsequent sections in this chapter.

To summarise, the ADF and DF-GLS unit root tests demonstrates that all variables are $I(1)$ but the unit root breakpoint test shows that ln co_2 is appears to be $I(0)$ around a structural break at the 5% significance level. The appearance of the graphs, their first difference representations and the unit root test results were largely expected, especially considering the major economic events that took place over the last 40 years such as the political and economic turmoil of the late 1970s and early 1980s, the recession of the early 1990s and the financial crisis of 2007-08.

3.5.2 Johansen's maximum likelihood (ML) estimator for cointegration analysis

Section 3.5.1 showed the results of the unit root tests of the orders of integration, with five variables demonstrating their $I(1)$ status. However, the unit root breakpoint test demonstrated that ln co_2 is an $I(0)$ variable around a structural break at the 5% level and near unit root at the 10% level via the ADF unit root test. Elliott (1998) demonstrated that false inferences could be drawn from Johansen's (1988, 1991) maximum likelihood (ML) estimator results if the model contained variables with near unit root processes. Such results are likely to suffer from significant size distortions that produce spurious rejections of the null hypothesis of a cointegrating rank (r). Furthermore, Hjalmarsson and Österholm (2007) carried out Monte Carlo simulations to test the effect of near unit root processes in cointegrating vectors using Johansen's method and concluded that there was a substantial chance of erroneously concluding that unrelated variables were cointegrated.

Nevertheless, Johansen's ML estimator of cointegration analysis is used in this section to provide additional information on the number of cointegrating vectors at a specific lag order. Cointegration test results are therefore obtained for the models that are to be estimated. This is important as Pesaran, Shin and Smith (2001) indicated that the ARDL-bounds test method is only appropriate where $r = 1$ as their ARDL-bounds test critical values are inappropriate where $r > 1$. However, considering the structural break in 2008, the statistical importance from Johansen's test is slightly weakened as the 5% critical values that are reported assume that no exogenous variables are included within the test. Nevertheless, a breakpoint dummy is included in all versions of Johansen cointegration test.

For brevity, the procedure for Johansen's ML estimator for cointegration analysis begins with the following VAR specification with p lag order:

$$\mathbf{y}_t = \mathbf{v} + \mathbf{A}_1 y_{t-1} + \mathbf{A}_2 y_{t-2} \cdots \mathbf{A}_p y_{t-\mathrm{p}} + \boldsymbol{\varepsilon}_t \tag{3.22}$$

where $\boldsymbol{y}_t$ is a $K \times 1$ vector of $I(1)$ variables, $\mathbf{v}$ is a $K \times 1$ vector of parameters, $\mathbf{A}_1 \cdots \mathbf{A}_p$ is a $K \times K$ matrix of parameters and $\boldsymbol{\varepsilon}_t$ is a $K \times 1$ vector of error terms. The VAR(p) can be rewritten in the following vector error correction model (VECM) format:

$$\mathbf{\Delta y}_t = \mathbf{v} + \mathbf{\Pi y}_{t-1} + \sum_{\mathrm{i}=1}^{p-1} \mathbf{\Gamma}_{\mathrm{i}} \mathbf{\Delta} y_{t-i} + \boldsymbol{\varepsilon}_t \tag{3.23}$$

where:

$$\mathbf{\Pi} = \sum_{i=1}^{p} \mathbf{A}_{\mathrm{i}} - \mathbf{I} \text{ and } \mathbf{\Gamma} = -\sum_{j=i+1}^{p} \mathbf{A}_j \tag{3.24}$$

where $\mathbf{I}_{\boldsymbol{K}}$ constitutes an identity matrix of order $K \times K$. If the coefficient matrix $\mathbf{\Pi}$ experiences a reduced rank such that $0 < r < K$, then coefficient matrix $\mathbf{\Pi}$ can be defined as $\mathbf{\Pi} = \boldsymbol{\alpha\beta}'$, where $\boldsymbol{\alpha}$ are the speed of adjustment parameters in the VECM and $\boldsymbol{\beta}$ is the cointegrating vector of long run coefficients such that $\boldsymbol{\beta}'\boldsymbol{y}_t \sim I(0)$. Therefore, the objective of Johansen's procedure involves the use of an unrestricted VAR to estimate the number of cointegrating relationships (r) within $\mathbf{\Pi}$. The implementation of Johansen's test involves the estimation of the trace and the maximum eigenvalue statistics, which are compared to their respective critical values in order to test the null hypothesis of r cointegrating relationships against the alternative of $r \leq K - 1$ cointegrating relationships.

Table 3.5 provides a summary of the results for Johansen's test for both the trace statistic and the maximum eigenvalue (max) statistic at 1 lag. The results are shown for the case 1 general model in equation (3.11) and the additional comparative models for the general model with ln *trade* (case 2) and the general model with ln *trade* and ln *indelec* (case 3):

Table 3.5: Johansen's cointegration rank test - trace and max eigenvalue statistics

Models: (1 lag)	H_0: Coint. equations	Eigen value	Trace Statistic	5% Crit. Value	Prob.	Eigen value	Max Statistic	5% Crit. Value	Prob.
Case 1	None	0.572	55.447	47.856	0.008 (R)	0.572	32.219	27.584	0.012 (R)
	At most 1	0.336	23.229	29.797	0.235 (A)	0.336	15.543	21.132	0.253 (A)
	At most 2	0.151	7.686	15.495	0.500	0.151	6.201	14.265	0.588
Case 2	None	0.697	92.680	69.819	0.000 (R)	0.697	45.374	33.877	0.001 (R)
	At most 1	0.452	47.306	47.856	0.056 (A)	0.452	22.878	27.584	0.179 (A)
	At most 2	0.274	24.428	29.797	0.183	0.274	12.163	21.132	0.532
Case 3	None	0.813	132.713	95.754	0.000 (R)	0.813	63.706	40.078	0.000 (R)
	At most 1	0.458	69.007	69.819	0.058 (A)	0.458	23.273	33.877	0.510 (A)
	At most 2	0.417	45.734	47.856	0.078	0.417	20.478	27.584	0.309

(R) denotes a rejection of the null hypothesis at the 5% level
(A) denotes a non-rejection of the null hypothesis at the 5% level

The 'H_0: coint. equations' part of the first column of Table 3.5 indicates the null hypothesis of r cointegrating relationships among the variables while the main column of interest contains the trace statistic results. The eigenvalue is used to calculate the trace statistic and if the trace statistic is greater than the 5% critical value, then the null hypothesis of no cointegration is rejected among the 5 variables in each section. In Table 3.5, (R) denotes the rejection of the null hypothesis of no cointegration at the 5% level and there is no rejection of the null hypothesis for the 'at most 1' row. Therefore, the three models are shown to have one cointegrating vector.

The max statistic in the second section below tells a similar story to the trace statistic concerning the rejection of the null hypothesis of no cointegrating vectors for all models and the non-rejection of the null hypothesis for one cointegrating vector. The results of a single cointegration vector for all models therefore support the use of the ARDL-bounds test methods of cointegration for further analysis and testing.

3.5.3 Lag selection for the ARDL model

The procedure for selecting the most parsimonious ARDL(p, q) model involves the estimation of the maximum possible combination of models with different lag lengths of the individual variables. The total number of regression models to be estimated is $(p+1)^k$ where p is the maximum number of lags and k is the number of variables in the regression. Given the relatively small sample size of 40 observations and the number of variables used in the model, the lag order is truncated to 1 lag, which allows for a sufficient number of degrees of freedom for econometric estimation. Therefore, a total number of $(1+1)^4 = 16$ ARDL models were generated for the case 1 general model using the Akaike Information Criteria (AIC). The model selection criteria are therefore based on the models that minimises the AIC value.

A structural break in the intercept and/or trend in 2008 was confirmed so a break dummy variable is included. This follows the procedure of Balaguer and Cantavella (2016), whose ARDL model reflected a break in the intercept and trend in their consideration of the relationship between crude oil, GDP and CO_2 emissions abatement in Spain. Table 3.6 provides a comparative analysis of the top 5 ARDL(*p, q*) models for case 1, 2 and 3:

Table 3.6: AIC selection criteria for case 1, 2 and 3

	Case 1 - General model		Case 2 - General model with ln *trade*		Case 3 - General model with ln *trade and ln indelec*	
Rank	AIC	Specification	AIC	Specification	AIC	Specification
1	-4.089	ARDL(1, 1, 1, 0)	-4.049	ARDL(1, 1, 1, 0, 0)	-4.729	ARDL(1, 1, 1, 0, 1, 0)
2	-4.061	ARDL(1, 1, 1, 1)	-4.046	ARDL(1, 1, 1, 0, 1)	-4.716	ARDL(1, 1, 0, 0, 1, 0)
3	-4.017	ARDL(1, 0, 1, 0)	-4.031	ARDL(1, 1, 1, 1, 1)	-4.715	ARDL(1, 1, 1, 1, 1, 0)
4	-4.007	ARDL(1, 0, 1, 1)	-4.023	ARDL(1, 1, 1, 1, 0)	-4.687	ARDL(1, 1, 0, 1, 1, 0)
5	-4.003	ARDL(1, 1, 0, 0)	-3.967	ARDL(1, 0, 1, 0, 0)	-4.680	ARDL(1, 1, 1, 0, 1, 1)

The results from the AIC procedure show that optimum models for cases 1, 2 and 3 are ARDL(1, 1, 1, 0), ARDL(1, 1, 1, 0, 0) and ARDL(1, 1, 1, 0, 1, 0) respectively. These three ARDL models will now be subjected to further testing and analysis.

3.5.4 Bounds test for cointegration analysis

After determining the optimum lag order for the four ARDL models, the next step involves the verification of a long run cointegrated relationship between the variables. This is done by means of the bounds test procedure, which checks the joint significance of the lagged level coefficients that are estimated from equation (3.15). The null hypothesis of no cointegrating relationship among the variables requires that all these coefficients are jointly equal to zero and the alternative hypothesis of a cointegration relationship requires at least one of the λ relationships in equation (3.15) is equal to any figure other than zero. The calculated *F*-statistic is compared with the critical value $I(0)$ lower bound and $I(1)$ upper bound to confirm the existence of cointegration. Table 3.7 provides a list of the critical value bounds and the *F*-statistics from the ARDL models:

Table 3.7: Bounds test of ARDL models

Model	Signif. level	10%	5%	1%	F-Stat	Result
Case 1 - ARDL(1, 1, 1, 0)	$I(0)$ Bound	2.37	2.79	3.65	3.915 **	Cointegration
General model	$I(1)$ Bound	3.20	3.67	4.66		
Case 2 - ARDL(1, 1, 1, 0, 0)	$I(0)$ Bound	2.20	2.56	3.29	3.176 *	Cointegration
General with ln *trade*	$I(1)$ Bound	3.09	3.49	4.37		
Case 3 - ARDL(1, 1, 1, 0, 1, 0)	$I(0)$ Bound	2.08	2.39	3.06	4.428 ***	Cointegration
General with ln *trade* and ln *indelec*	$I(1)$ Bound	3.00	3.38	4.15		

***, ** and * are based on the 1%, 5% and 10% significance levels respectively

For the case 1 general model, the calculated F-statistic is higher than the upper bound at the 10% and 5% significance levels. This means that we reject the null hypothesis of no cointegration at these levels of significance. The bounds test is also applied to case 2, which shows cointegration at the 10% significance level and uncertainty at the 5% significance level. Case 3 shows the strongest confirmation of cointegration at the 1% significance level. Overall, the results show that there is evidence of a long run cointegrating relationship among the variables for all cases.

3.5.5 Cointegration and long run representation of the ARDL model

We initially consider case 1 for demonstration purposes, which consists of the ARDL(1, 1, 1, 0) model that was selected by the AIC. The following is the general specification of the model's ARDL(1, 1, 1, 0) equation:

$$\ln(co_2)_t = \alpha_0 + \gamma_1 \ln(co_2)_{t-1} + \beta_0 \ln gdp_t + \beta_1 \ln gdp_{t-1} + \delta_0 \ln nuc_t + \delta_1 \ln nuc_{t-1} + \lambda_0 \ln entax + \psi_0\, dv + e_t \quad (3.25)$$

The case 1 general model assumes that ln co_2 is dependent on its own lag, one lag each for ln *gdp* and ln *nuc* and the levels of all independent variables. There is also an assumption that the global financial crisis of 2008 had an impact on CO_2 emissions and some of the other independent variables, which is denoted by the break dummy variable dv. Additional variables are added to the general case 1 model in order to provide a comparative analysis between government action against GHG emissions (ln *entax*) and decarbonised electricity generation (ln *nuc*). Table 3.8 provides the ARDL coefficients from the estimated regressions in all three cases:

Table 3.8: ARDL regression output

Dep variable ln co_2	Case 1 ARDL(1, 1, 1, 0)	Case 2 ARDL(1, 1, 1, 0, 0)	Case 3 ARDL(1, 1, 1, 0, 1, 0)
$intercept$	3.717 (0.966)	3.749 (0.978)	7.579 (0.954)
$\ln(co_2)_{t-1}$	0.212 (0.186)	0.169 (0.202)	-0.331 (0.167)
$\ln gdp$	0.550 (0.304)	0.638 (0.344)	0.416 (0.256)
$\ln gdp_{t-1}$	-0.543 (0.269)	-0.572 (0.277)	-0.590 (0.210)
$\ln nuc$	-0.036 (0.053)	-0.038 (0.053)	-0.023 (0.039)
$\ln nuc_{t-1}$	0.128 (0.060)	0.126 (0.060)	0.060 (0.044)
$\ln entax$	-0.323 (0.112)	-0.336 (0.115)	-0.357 (0.084)
$\ln trade$		-0.048 (0.084)	-0.286 (0.087)
$\ln trade_{t-1}$			0.191 (0.082)
$\ln indelec$			0.500 (0.091)
dv	-0.032 (0.007)	-0.032 (0.008)	-0.033 (0.006)
$R\text{-}squared$	0.962	0.963	0.983
$SE\ of\ regression$	0.029	0.029	0.020

The numbers in parentheses are the standard errors.

As previously mentioned, if the variables exhibit a cointegrated long run equilibrium relationship, they would have a tendency not to stray too far from their equilibrium values. Based on the ARDL regression results, we can determine the long run equilibrium relationship for the case 1 ARDL(1, 1, 1, 0) model in lag polynomial terms:

$$\ln(co_2)_t = \frac{\alpha_0}{1-\gamma_1} + \frac{\beta_0+\beta_1}{1-\gamma_1}\ln gdp_t + \frac{\delta_0+\delta_1}{1-\gamma_1}\ln nuc_t + \frac{\lambda_0}{1-\gamma_1}\ln entax_t + \frac{\psi_0}{1-\gamma_1}dv_t + \hat{\varepsilon}_t \qquad (3.26)$$

where $\hat{\varepsilon}_t$ are the residuals from the case 1 ARDL regression model, ϕ is the coefficient of the ARDL model's lagged dependent variable, $\frac{\alpha_0}{1-\gamma_1}$ is the coefficient of the equilibrium model's intercept and $\frac{k_0+k_1}{1-\gamma_1}$ for all $k = \beta, \delta, \lambda, \psi$ are the long run coefficients of the equilibrium model's independent variables. All of the variables are measured in their natural logarithms so the long run equilibrium coefficients can be construed as long run elasticities. The long run coefficients from equation (3.26) are given in Table 3.9:

Table 3.9: Long run coefficients from the unrestricted error correction representation

Dependent variable: ln co_2	Case 1 ARDL(1, 1, 1, 0)	Case 2 ARDL(1, 1, 1, 0, 0)	Case 3 ARDL(1, 1, 1, 0, 1, 0)
intercept	4.716 (0.591) ***	4.513 (0.660) ***	5.694 (0.366) ***
ln *gdp*	0.009 (0.105)	0.080 (0.156)	-0.130 (0.079)
ln *nuc*	0.117 (0.043) ***	0.107 (0.045) **	0.028 (0.023)
ln *entax*	-0.410 (0.108) ***	-0.404 (0.104) ***	-0.269 (0.051) ***
ln *trade*		-0.057 (0.097)	-0.072 (0.047)
ln *indelec*			0.376 (0.063) ***
dv	-0.040 (0.005) ***	-0.039 (0.005) ***	-0.025 (0.003) ***

1. The numbers in parentheses are the standard errors.
2. The asterisks ***, ** and * are based on the 1%, 5% and 10% significance levels

The coefficients from the regression estimates are largely economically significant as they have the right signs and most are statistically significant. The ln *trade* variable in cases 2 and 3 is statistically insignificant due to the higher volatility of international trade activity and the same applies to ln *gdp*. For case 1, the results shows that a 1% increase in nuclear electricity's share of total electricity generation corresponds to a 0.117% increase in CO_2 emissions per capita in the long run. A similar result is given for case 2, with a 1% increase in nuclear electricity's share of total electricity generation corresponding to a 0.107% increase in CO_2 emissions per capita. These elasticities have a much weaker relationship than the 0.27% decrease in CO_2 emissions per capita that was demonstrated by Iwata et al (2010) in their study of the nuclear-GDP-CO_2 nexus in France. The stronger elasticity in France could be explained by the complete dominance of nuclear electricity and a lack of decarbonised electricity generation alternatives. World Bank (2015) highlighted this by indicating that nuclear electricity production in France averaged approximately 77% of total electricity generation in the 24 years from 1989 to 2013, with a standard deviation of only 1.8% during this period.

On the other hand, the results for case 1 shows that a 1% increase in environmental taxes per capita corresponds to a 0.41% decrease in CO_2 emissions per capita in the long run. For case 2 and 3, a 1% increase in environmental taxes per capita corresponds with decreases of 0.40% and 0.27% in CO_2 emissions per capita respectively. This indicates that, ceteris paribus, CO_2 emissions abatement corresponds far more strongly in the long run to environmental tax increases than to nuclear electricity generation. The British Government's long term promotion of industrial electricity consumption has also not yet translated into the desired long run equilibrium relationship with CO_2 emissions abatement. This is because a 1% increase in industrial electricity consumption per capita actually leads to a 0.38% increase in CO_2 emissions per capita. Evidence of the declining trend of the *indelec* variable could be seen in graph in figure 3.11, which shows a very mild decline between 2000 and 2007 followed by a shaper decline during the 2007-08 financial crisis. This ultimately led to a much weaker industrial demand for electricity between 2008 and the end of the sample period.

3.5.6 Restricted error correction representation of the ARDL model

The residuals in equation (3.15) consist of a series of deviations from the long run equilibrium relationship, which are used in the estimation of the restricted error correction model (ECM). The ECM acts to restrict the long run behaviour of the variables by converging them to their cointegrated relationship, which consequently produces estimates of the short run relationships. The residual series from equation (3.15) can be obtained as follows:

$$\hat{\varepsilon}_t = \ln(co_2)_{t-1} - \left(\frac{\alpha_0}{1-\gamma_1} + \frac{\beta_0+\beta_1}{1-\gamma_1}\ln gdp_t + \frac{\delta_0+\delta_1}{1-\gamma_1}\ln nuc_t + \frac{\lambda_0}{1-\gamma_1}\ln entax_t + \frac{\psi_0}{1-\gamma_1}dv_t\right) \quad (3.27)$$

and the restricted error correction model is given by the following:

$$\Delta\ln(co_2)_t = \beta_0\Delta\ln gdp_t + \delta_0\Delta\ln nuc_t + \lambda_0\Delta\ln entax_t + \psi_0\Delta dv_t - (1-\gamma_1)\Big[\ln(co_2)_{t-1} - \left(\frac{\alpha_0}{1-\gamma_1} + \frac{\beta_0+\beta_1}{1-\gamma_1}\ln gdp_t + \frac{\delta_0+\delta_1}{1-\gamma_1}\ln nuc_t + \frac{\lambda_0}{1-\gamma_1}\ln entax_t + \frac{\psi_0}{1-\gamma_1}dv_t\right)\Big] + u_t \quad (3.28)$$

which can now be simplified as:

$$\Delta\ln(co_2)_t = \beta_0\Delta\ln gdp_t + \delta_0\Delta\ln nuc_t + \lambda_0\Delta\ln entax_t + \psi_0\Delta dv_t - (1-\gamma_1)ec + u_t \quad (3.29)$$

where $1-\gamma_1$ is the speed of adjustment parameter towards long run equilibrium, $ec = \hat{\varepsilon}_t$ is the error (or equilibrium) correction term, u_t are the new residuals of the restricted error correction representation and $\beta, \delta, \lambda, \psi$ are the short run coefficients. Table 3.10 provides a comparison of the short run coefficients between the case 1 general model, case 2 general model with ln *trade* and case 3 general model with ln *trade* and ln *indelec*:

Table 3.10: Short run coefficients for the restricted error correction model (ECM)

Dependent variable: ln co_2	Case 1 ARDL(1, 1, 1, 0)	Case 2 ARDL(1, 1, 1, 0, 0)	Case 3 ARDL(1, 1, 1, 0, 1, 0)
intercept	-0.014 (0.009)	-0.014 (0.010)	-0.008 (0.007)
Δln *gdp*	0.620 (0.280) **	0.759 (0.320) **	0.352 (0.274)
Δln *nuc*	-0.024 (0.050)	-0.023 (0.051)	-0.008 (0.039)
Δln *entax*	-0.269 (0.145) *	-0.298 (0.154) *	-0.202 (0.099) **
Δln *trade*		-0.103 (0.120)	-0.130 (0.089)
Δln *indelec*			0.317 (0.138) **
Δ*dv*	-0.026 (0.015) *	-0.024 (0.015)	-0.022 (0.011) *
ec_{t-1}	-0.832 (0.233) ***	-0.902 (0.257) ***	-1.460 (0.242) ***
R-squared	0.486	0.490	0.735
SE of regression	0.031	0.031	0.023

1. The numbers in parentheses are the standard errors.
2. The asterisks ***, ** and * are based on the 1%, 5% and 10% significance levels
3. SE = standard error

The coefficients in all three cases show a greater statistical significance for ln *entax* in the short run as there are no statistically significant coefficients for ln *nuc*. The results for environmental taxes across the three cases are also economically significant with the right signs. The results shows that a 1% increase in environmental taxes corresponds to a 0.2% to 0.3% decrease in CO_2 emissions per capita in the short run. GDP also increases with CO_2 emissions but interestingly, the ec_{t-1} coefficient indicates that there is a 83.2% speed of adjustment to its long run equilibrium for case 1 and 90.2% for case 2. These are very quick rates that indicate a near instantaneous speed of adjustment to the disequilibrium in the previous year. The ec_{t-1} coefficient in case 3 indicates that the inclusion of ln *indelec* in case 3 leads to an improbable overadjustment to long run equilibrium as the coefficient should be between 0% (no adjustment) and -100% (full adjustment).

3.5.7 Diagnostic and stability tests

A series of diagnostic tests are performed on the residuals of the error correction model in order to check the robustness of the model and the reliability of its estimates. This is important as the inclusion of irrelevant variables, the omission of important variables and/or data issues could present estimation problems such as inefficient estimates with high parameter variability and incorrect standards errors of coefficients and hence, erroneous t-statistics. These problems could be evident even in the presence of a high R^2 and strong statistical significance within a model.

The Durbin-Watson statistic from the regression output is an indicator that tests for the presence of autocorrelation, also known as serial correlation. For a model with a small sample size, a strong indicator of the presence of autocorrelation would be a Durbin-Watson statistic that is below 1.5. The Durbin-Watson statistics for cases 1, 2 and 3 are 2.02, 2.07 and 2.56 respectively. However, an important limitation is that while the test is valid for first order autocorrelation, it is not suitable for dynamic models that have already captured an element of autocorrelation in the autoregressive model. This limitation can be overcome by the Breusch-Godfrey Lagrange Multiplier (LM) test, which can produce valid autocorrelation test results from higher order autoregressive errors.

Table 3.11 shows the results from the Breusch-Godfrey LM test for autocorrelation in all four cases as well as the results for three additional tests for heteroskedasticity, normality and functional form:

Table 3.11: Diagnostic tests for cases 1 to 4

Diagnostic test	Autocorrelation χ^2 (*p*-value)	Functional form *F*-stat (*p*-value)	Normality χ^2 (*p*-value)	Heteroskedasticity χ^2 (*p*-value)
Case 1: ARDL(1, 1, 1, 0)	1.267 (0.260)	1.768 (0.193)	0.904 (0.636)	6.960 (0.224)
Case 2: ARDL(1, 1, 1, 0, 0)	2.343 (0.126)	1.932 (0.175)	0.778 (0.678)	8.668 (0.193)
Case 3: ARDL(1, 1, 1, 0, 1, 0)	1.238 (0.266)	0.677 (0.417)	1.710 (0.425)	15.260 (0.033)

The numbers in parentheses are the probability values (*p*-values)

The Breusch-Godfrey LM test statistic is based on a supplementary regression on the residuals and is calculated as the number of observations × the R^2. The test statistic follows an asymptotic χ^2 distribution with the null hypothesis of no autocorrelation at lag order *p* tested against the alternative hypothesis at the 5% significance level. In all cases, we do not reject the null hypothesis of no autocorrelation at the 5% significance level as the probability value of the test statistics are higher than 5%.

The Breusch-Pagan-Godfrey LM test is another test that uses the observations × R^2 calculation to detect the presence or absence of heteroskedasticity. The Breusch-Pagan-Godfrey LM test statistic also follows a χ^2 distribution with the null hypothesis of no heteroskedasticity tested against the alternative hypothesis. The probability values in Table 3.11 indicate that the null of no heteroskedasticity is not rejected at the 5% significance level for case 1 and 2. However, the case 3 model with the additional variable ln *indelec* shows evidence of heteroskedasticity at the 5% significance level. This means that although the model with ln *indelec* has unbiased parameter estimates and appropriate tests of significance, the OLS estimates for the ECM are suboptimal and the standard errors are biased. There might also be some interplay between the heteroskedasticity in case 3 and the over-adjustment in the error correction coefficient.

The Jarque-Bera statistic is a test that assesses whether the residuals follow a normal distribution and is displayed as a bell-shaped histogram. The Jarque-Bera test equation produces the kurtosis and skewness estimates and the Jarque-Bera statistic follows a χ^2 distribution with the null hypothesis of a normal distribution tested against the alternative hypothesis. Again, cases 1, 2 and 3 shows that we cannot reject the null hypothesis of a normal distribution at the 5% significance level. The functional form of a model can be determined by Ramsey's RESET test, which assesses the model for problems that could bias the least squares estimates such as omitted variables and incorrect functional formats such as certain variables not in their natural logarithms. Further evidence of these specification and functional form problems consists of the generation of a non-zero mean for the residuals. Therefore, the null hypothesis is based on the residuals following a normal distribution with a mean of zero and a variance of one against the alternative hypothesis of a non-zero mean for the residuals. The F-statistic is produced in cases 1, 2 and 3, which shows that we cannot reject the null hypothesis of a correct functional form for the model.

Parameter stability is assessed by the cumulative sum (CUSUM) of the recursive residuals from the one-step ahead forecasts. The test statistic assesses whether the recursive residual diverges from its zero mean over time. Two 5% significance bars act as containers of the recursive residuals throughout the sample period. Any extended upward or downward breach of the 5% significance bars would imply that the estimates of the non-zero mean coefficient are unstable. While the CUSUM test highlights the systematic adjustment of recursive residuals, the cumulative sum of squared residuals (CUSUMSQ) is a stronger test that demonstrates the impacts of shocks in the data, which are subsequently reflected as instabilities in the recursive residuals. Similarly to the CUSUM test, the CUSUMSQ test statistic considers the departure from its expected value of zero and is assessed by reference to its confinement within or breach of two parallel 5% significance bars. Figures 3.15 to 3.20 show the graphs of the CUSUM and CUSUMSQ statistics for the ECM cases 1, 2 and 3:

Figure 3.15: CUSUM and CUSUMSQ test for case 1: General ECM (no break)

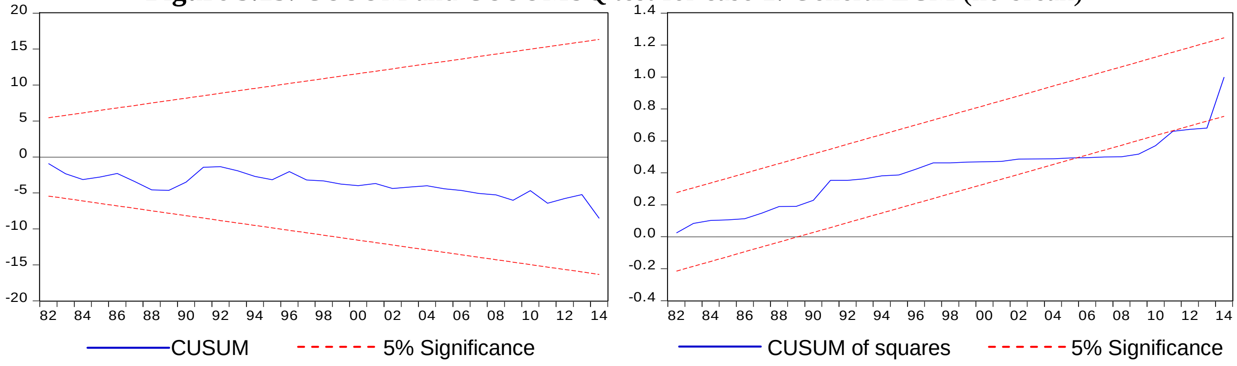


Figure 3.16: CUSUM and CUSUMSQ test for case 1: General ECM (with break)

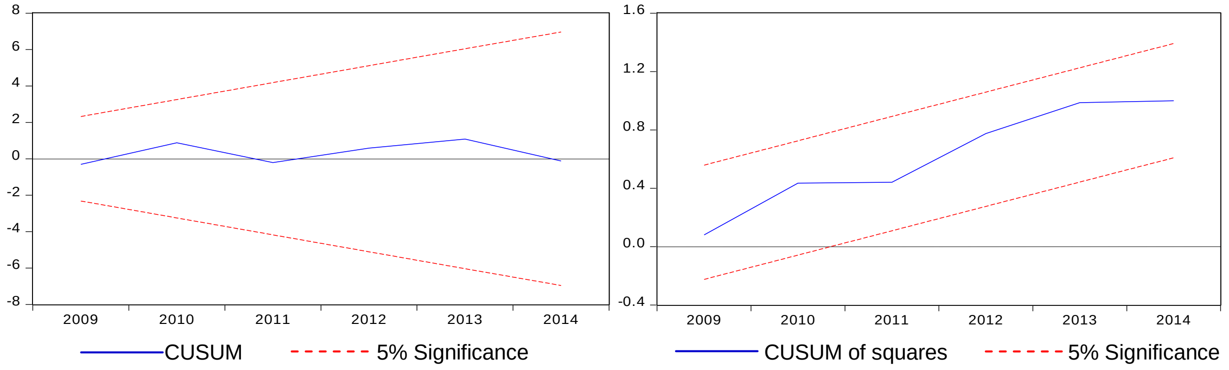


Figure 3.17: CUSUM and CUSUMSQ test for case 2: General ECM with ln trade (no break)

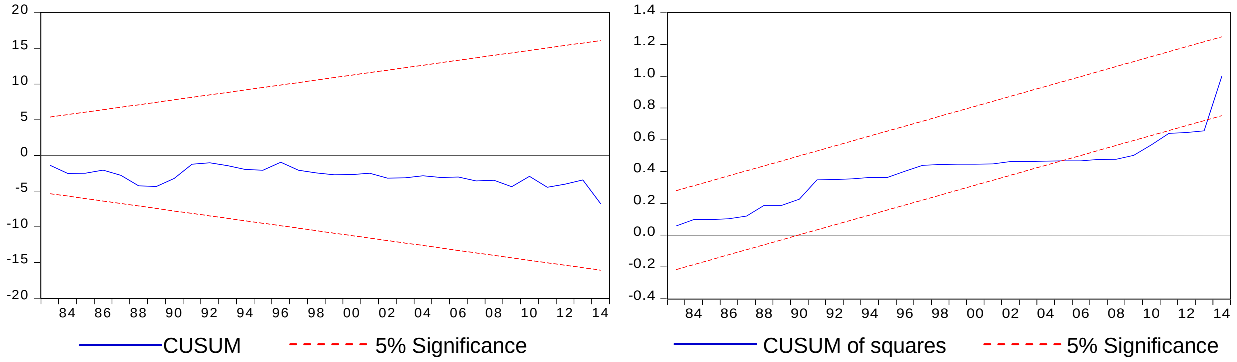


Figure 3.18: CUSUM and CUSUMSQ test for case 2: General ECM with ln trade (with break)

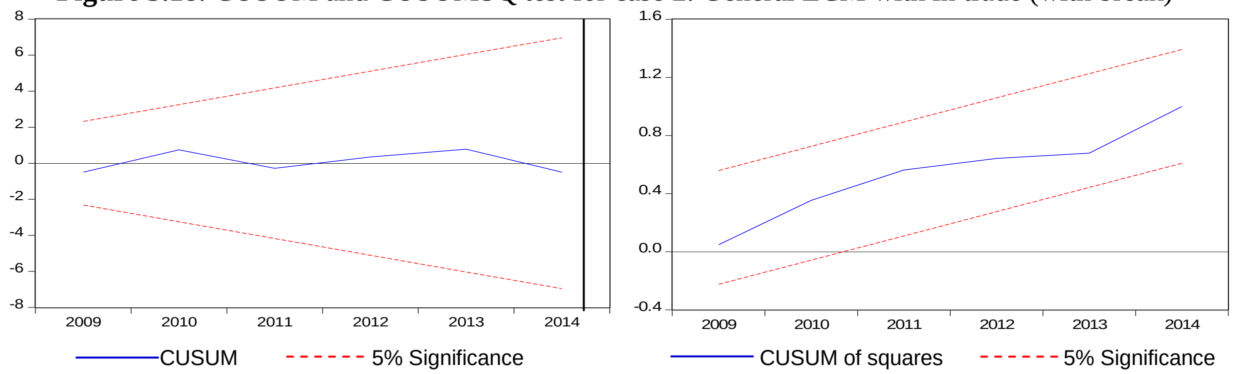


Figure 3.19: CUSUM and CUSUMSQ test for case 3: General ECM with ln trade & ln indelec (no break)

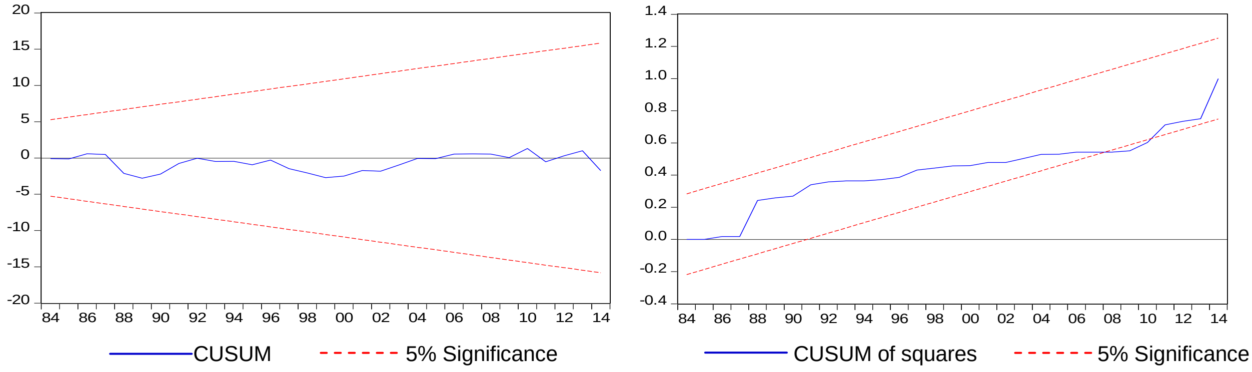
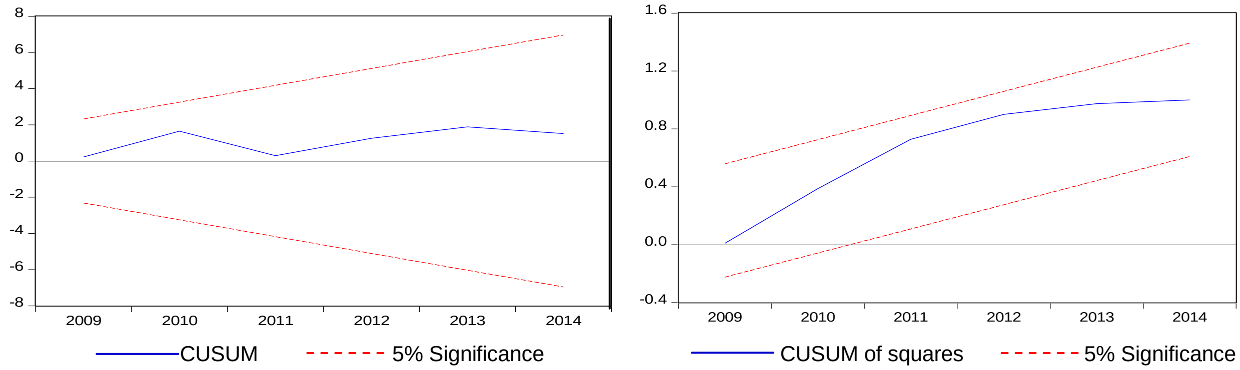


Figure 3.20: CUSUM and CUSUMSQ test for case 3: General ECM with ln trade & ln indelec (with break)



All of the CUSUM tests for ECM cases 1, 2 and 3 demonstrate that the systematic adjustments of the recursive residuals are stable during the course of the sample period. However, the CUSUMSQ tests for the case 1, 2, and 3 ECM models without a break dummy variable show that the null hypothesis of parameter stability is rejected at the 5% significance level due to the breach of the lower bar at approximately 2007 and 2008. Both breaches unsurprisingly coincide with the 2007-08 global financial crisis and this event is now proven to have had the greatest statistical impact on the data during the 40 year sample period. However, we do not reject the null hypothesis of parameter stability for the CUSUMSQ case 1, 2 and 3 graphs with a break dummy variable included as the graphs are all stable after the shock period.

3.5.8 EKC results

Similarly to the nuclear-GDP-CO_2 nexus study in the previous section, the EKC estimation process involves the selection of the most parsimonious ARDL models, using the AIC model selection criteria. The parsimonious ARDL models that were initially selected for the pre-EKC estimation were as follows: ARDL(1, 1, 0, 1, 0) general model, ARDL(1, 1, 0, 1, 0, 1) general model with ln *trade*, ARDL(1, 0, 1, 0) model with ln *nuc* only and ARDL(1, 0, 1, 0, 0) model with ln *nuc* and ln *trade*. The ARDL estimation results for all models can be found in Appendix 3.1. Table 3.12 provides the long run pre-EKC estimation results from the unrestricted error correction models:

Table 3.12: Pre-EKC long run estimates for general models and models with ln *nuc*

Dep. var: ln co_2	General model (1, 1, 0, 1, 0)	General with ln *trade* (1, 1, 0, 1, 0, 1)	ln *nuc* only (1, 0, 1, 0)	ln *nuc* and ln *trade* (1, 0, 1, 0, 0)
intercept	-25.402 (25.188)	-28.737 (28.684)	-48.994 (53.705)	-73.938 (77.635)
ln *gdp*	6.080 (5.078)	6.704 (5.744)	10.600 (10.839)	15.537 (15.542)
(ln *gdp*)^2	-0.306 (0.256)	-0.340 (0.294)	-0.548 (0.547)	-0.806 (0.796)
ln *nuc*	0.064 (0.060)	0.067 (0.056)	-0.111 (0.107)	-0.134 (0.127)
ln *entax*	-0.410 (0.103)***	-0.423 (0.095)***		
ln *trade*		0.067 (0.121)		0.155 (0.302)
dv	-0.041 (0.005)***	-0.042 (0.005)***	-0.055 (0.011)***	-0.059 (0.015)***

1. The numbers in parentheses are the standard errors.
2. The asterisks ***, ** and * are based on the 1%, 5% and 10% significance levels

The ln *entax* shows strong statistical significance at the 1% level for the general model: ARDL(1, 1, 0, 1, 0) and the general mode with ln *trade*: ARDL(1, 1, 0, 1, 0, 1). However, the centre of our focus lies with the estimates of the long run coefficients for ln *gdp* and (ln *gdp*)^2. Both are statistically insignificant for all three models, which shows that the EKC hypothesis is not supported with the inclusion of ln *nuc* in a multivariate group. For a comparison, Table 3.13 provides the estimation results from the unrestricted error correction models with ln *nuc* omitted:

Table 3.13: Pre-EKC long run estimates for models with ln *entax*

Dep. variable: ln co_2	ln *entax* only (1, 0, 1, 0)	ln *entax* and ln *trade* (1, 0, 1, 0, 1)	ln *entax*, ln *trade* and ln *indelec* (1, 0, 1, 0, 1, 0)
ln *gdp*	9.240 (3.974)**	11.033 (4.747)**	0.831 (2.362)
(ln *gdp*)^2	-0.463 (0.199)**	-0.559 (0.243)**	-0.049 (0.120)
ln *entax*	-0.390 (0.107)***	-0.402 (0.101)***	-0.246 (0.048)***
ln *trade*		0.108 (0.138)	-0.070 (0.061)
ln *indelec*			0.408 (0.063)***
dv	-0.045 (0.005)***	-0.047 (0.005)***	-0.025 (0.004)***
intercept	-41.437 (19.468)**	-50.663 (23.605)**	0.815 (11.788)

1. The numbers in parentheses are the standard errors.
2. The asterisks ***, ** and * are based on the 1%, 5% and 10% significance levels

As expected, the long run coefficients of the first two models show much stronger results than the previous four models with ln *nuc* in Table 3.12. The ln *gdp* and (ln *gdp*)^2 variables are statistically significant at the 5% level for ARDL(1, 0, 1, 0) and at the 5% significance level for ARDL(1, 0, 1, 0, 1). Crucially, the coefficients for ln *gdp* and (ln *gdp*)^2 in both models have the rights signs for EKC estimation purposes based on the criteria set out in section 3.4.3 i.e. ln *gdp* coefficient > 0 and (ln *gdp*)^2 coefficient < 0.

The turning points based on the $exp\ (-\lambda_2/2(\lambda_3\ ))$ formula can now be calculated as follows:

(a) ARDL(1, 0, 1, 0): $exp\ (-9.240/2(-0.463\ ))$ = £21,556 per capita (2010 GBP)
(b) ARDL(1, 0, 1, 0, 1): $exp\ (-11.033/2(-0.559\ ))$ = £19,313 per capita (2010 GBP)

Based on the data from the Office of National Statistics (2015c) used for the GDP per capita graph (figure 3.3), the ARDL(1, 0, 1, 0) turning point of £21,556 per capita was approximately reached in 1999. Furthermore, the ARDL(1, 0, 1, 0, 1) turning point of £19,313 per capita was approximately reached in 1995. The EKC hypothesis is easily supported for the models with ln *entax* and the approximate turning point of 1995 to 1999 is conveniently located near the mid-point section of the 1975 to 2014 sample period. The results for the models therefore indicate that as annual UK GDP per capita increases beyond 1999, environmental taxes have a statistically measurable impact on the decline of CO_2 emissions-related environmental degradation. The 1999 turning point also comes relatively soon after the 1992 UN Framework Convention on Climate Change (UNFCCC) and the 1997 Kyoto Protocol. This therefore statistically confirms the UK Government's immediate compliance to international environmental treaties through a controversial and aggressive environmental tax policy.

3.5.9 Multivariate Granger causality: Wald test versus modified Wald test

A standard VAR is estimated prior to the multivariate Granger causality test. The *p* lag order of the VAR must be sufficient to ensure the removal or minimisation of serial correlation in the error terms. However, lag selection criteria are applied as preference is given to the most parsimonious model that consists of the minimum information criterion. The lag order is initially restricted to 2 and consideration is given to the results from different information criteria as well as information criteria from a lower lag order of 1 in order to determine the appropriate lag order for the VAR. Table 3.14 provides a summary of the lag selection criteria results for the VAR model with all variables included:

Table 3.14: lag selection criteria for VAR

Lag	LogL	LR	FPE	AIC	SIC	HQIC
0	241.76	NA	1.6e-13	-12.41	-12.32	-12.15
1	466.73	449.94	8.1e-18*	-22.35*	-21.71*	-20.54*
2	497.47	61.47*	1.2e-17	-22.08	-20.88	-18.72

* Denotes the minimum value from each information criterion

According to the various information criteria, the unanimous lag length that should be chosen is 1 lag. However, diagnostic tests were performed on the residuals of the VAR, which showed evidence of serial correlation at this lag order. The lag order is therefore increased by a 1 lag increment until serial correlation is removed. Therefore, a new lag order of 2 is chosen for the VAR models for estimation purposes. The results from the VAR estimation can be seen in Appendix 3.2 for both VAR(p) and augmented VAR($p + m$). Granger causality tests were performed on both of the VAR models using the standard Granger causality Wald test and the T-Y Granger causality MWald test. The results of the Granger causality tests are shown below in Table 3.15:

Table 3.15: Multivariate Granger Causality tests

H_0: X does not Granger cause Y	Wald test			T-Y MWald test		
	χ^2	Prob.	Result	χ^2	Prob.	Result
ln co_2 does not Granger cause ln *gdp*	1.414	0.493		1.574	0.455	
ln *gdp* does not Granger cause ln co_2	18.263	0.000	Reject H_0***	1.287	0.525	
ln co_2 does not Granger cause ln *nuc*	0.112	0.946		0.695	0.706	
ln *nuc* does not Granger cause ln co_2	2.271	0.321		0.084	0.959	
ln co_2 does not Granger cause ln *entax*	5.203	0.074	Reject H_0*	6.216	0.045	Reject H_0**
ln *entax* does not Granger cause ln co_2	16.523	0.000	Reject H_0***	12.961	0.002	Reject H_0***
ln co_2 does not Granger cause ln *trade*	0.895	0.639		5.769	0.056	Reject H_0*
ln *trade* does not Granger cause ln co_2	15.453	0.000	Reject H_0***	15.920	0.000	Reject H_0***
ln co_2 does not Granger cause ln *indelec*	3.450	0.178		1.086	0.581	
ln *indelec* does not Granger cause ln co_2	18.213	0.000	Reject H_0***	16.760	0.000	Reject H_0***

The asterisks ***, ** and * are based on the rejection of the null H_0 at the 1%, 5% and 10% significance levels

As expected, the null hypothesis of no Granger causality in the standard Wald test is rejected from ln *indelec* → ln co_2 at the 1% significance level, which highlights the causal role that increased electrification of industry has on CO_2 emissions abatement. Strong unidirectional causality is also evident from ln *gdp* → ln co_2 and from ln *trade* → ln co_2 at the 1% significance level. Bidirectional causality also exists from ln *entax* ↔ ln co_2, which demonstrates the strong causal effect that punitive fiscal action from the UK Government has on CO_2 emissions abatement.

Although the MWald test results in Table 3.15 shows strong causality that follows a robust asymptotic χ^2 distribution, the T-Y MWald test omits the strong unidirectional causality from ln *gdp* → ln co_2 in the Wald test. The difference in the results could be explained by Dolado and Lütkepohl (1996) who used multiple Monte Carlo replications to demonstrate the inefficiencies of T-Y's MWald test for Granger causality. They concluded that if the VAR($p + m$) model has many variables (6 in their case) and the lag length is short, then the MWald results could exhibit a severe reduction in power, thereby increasing the likelihood of a false acceptance of the null hypothesis of no Granger causality. A large number of variables are used for this section (6 in this case) with a relatively low lag order, which may support the Dolado-Lütkepohl inference of low power in MWald tests.

3.6 Conclusion

This chapter sets out to provide an assessment of the impact of several energy-economic variables on environmental degradation, commonly measured as CO_2 emissions per capita (ln co_2). The multivariate assessment for the UK was based on previous studies of the nuclear-GDP-CO_2 nexus and economic theory. Testing was carried out using suitable econometric methods to generate estimates for comparison and analysis. The statistical attributes of the variables led to the use of the ARDL-bounds test model for cointegration analysis as it provides statistically robust results for small sample sizes with different orders of integration. The long run estimates were obtained from the unrestricted ECM form of the most parsimonious ARDL models in order to determine the impact of the energy-economic variables on CO_2 emissions abatement. The restricted ECM was used to obtain the short run estimates as well as estimates of the speed of adjustment towards long run equilibrium. Granger causality tests on the variables provided the measures of antecedence and the environmental Kuznets curve (EKC) hypothesis was tested in order to confirm the turning point of CO_2 emissions decline as a ratio of GDP.

A number of contributions to the empirical literature on the nuclear-GDP-CO_2 nexus field were made in this chapter. Firstly, this is the first time series analysis of the nuclear-GDP-CO_2 nexus for the UK that uses the total trade (ln *trade*) and industrial electricity consumption (ln *indelec*) variables in a multivariate group. There were two notable previous studies among the very sparse literature that used the ARDL-bounds test method of cointegration and similar variables in their analysis. Baek and Kim (2013) assessed the nuclear-GDP-CO_2 nexus on South Korea while considering aggregate energy consumption (ln *en*) as an additional variable while Iwata et al (2010) assessed the CO_2-GDP-nuclear nexus in France with consideration given to ln *en* and *trade*. This chapter follows the Iwata et al (2010) choice of *trade* as an additional variable but converts *trade* and *nuc* from share variables in the Iwata et al (2010) study to the natural logarithms of GBP per capita (ln *trade*) and KWh per capita (ln *nuc*) respectively. This chapter also replaces their choice of ln *en* with industrial electricity consumption (ln *indelec*) as it was deemed to be more relevant in the context of this analysis.

Secondly, this chapter goes much further than previous studies by contributing a first of a kind comparison of decarbonised nuclear electricity generation (ln *nuc*) against the UK Government's action against climate change through the inclusion of aggregate environmental taxes (ln *entax*) as a proxy variable. This comparison was carried out throughout the cointegration and ECM sections of this chapter. Thirdly, new insights were gained through a comparison of Granger causality analyses between the Wald test and modified Wald (MWald) test for the 6 variables used in this chapter. The final contribution goes towards the EKC hypothesis literature and is based on the answers gained from the question of whether nuclear electricity generation offers a better statistical impact to a British EKC than the UK government's controversial environmental tax policy, especially when considering ln *trade* and ln *indelec* in a multivariate framework.

The statistical analysis of the variables confirmed the presence of a structural break in 2008, the year of the global finance crisis. Unit root tests confirmed that all but one of the variables were guaranteed to be $I(1)$, with the unit root breakpoint test confirming that ln co_2 was an $I(0)$ variable around a structural break at the 5% significance level. Evidence of this can be seen in the figure 3.1 graph, which has a relatively smooth bow shape after 1983 and a noticeable break around 2008. The dependent variable throughout this chapter is ln co_2 and the diagnostic tests indicate that an omission of a break dummy variable (*dv*) impedes the stability of the parameters during and after the 2008 structural break as evidenced by the CUSUMSQ graphs, which showed a parameter breach of the 5% significance bars for the models without *dv* and parameter stability within the 5% significance bars for the models with *dv*.

The estimated elasticities for cases 1, 2 and 3 demonstrate that in the long run, increases in ln *entax* correspond to strong reductions in ln co_2 but increases in ln *nuc* correspond to a slight increase in ln co_2. This is expected due to the volatility of the UK's nuclear power plant capacity and the exponential growth in the environmental tax curve. The same is true in the short run as the three restricted ECM models show ln *entax* as having a stronger statistical effect on ln co_2 reduction than ln *nuc*. The results imply that in the short run, environmental taxes are able to decrease CO_2 emissions but has a knock on effect on reducing overall industrial electricity capacity, thereby affecting the consumption of electricity from primary energy substitutes of nuclear such as coal. The implied negative consequences for the UK of high environmental taxes would be the gradual erosion of national energy security and increased energy bills to households and businesses.

The short run inferences from the restricted ECMs also receive support in the Granger causality MWald test, which are statistically more appropriate than the standard Wald test results through its adherence to an asymptotic χ^2 distribution. The multivariate MWald test shows ln *entax* as having a statistically stronger causal influence on ln co_2 than ln *nuc*. Two of the variables that show a strong unidirectional causality at the 1% level of significance (ln *indelec* and ln *entax*) are the same two variables that share a strong short and long run elasticity with ln co_2.

The question of whether the EKC hypothesis could be supported for the UK while taking into account the additional variables is answered through the results. The EKC hypothesis is not supported for all combinations of the model with ln *nuc*. However, there is strong evidence to support the existence of an EKC at the 5% significance level when ln *entax* is solely added to the base group of three variables: ln co_2, ln *gdp* and $(\ln gdp)^2$ and at the 5% significance level when ln *entax* and ln *trade* are added to the base group. The seamless assimilation of ln *entax* into this theoretical relationship indicates the key role that environmental taxes plays in the economy-environment relationship. Environmental taxes are able to have a decisive impact on increased business electrification, greater home insulation, cleaner methods of transport and stronger carbon markets, thereby inducing the EKC turning point.

The lessons for fusion power from the nuclear-GDP-CO_2 nexus, Granger causality and EKC hypothesis estimates are that a secure, steady and sustainable source of high volume electricity generation is vital for the UK's objective of increased CO_2 emissions abatement towards the 2050 decarbonisation target. The pre-1998 upward trend in the nuclear electricity generation curve (see Figure 3.5) and the post-1998 downward trend have seriously weakened the long run equilibrium relationship between nuclear fission electricity with CO_2 emissions and removed altogether any potential for a bidirectional causal relationship between the two variables. The long run equilibrium relationship could be weakened further as there is a distinct lack of a like-for-like replacement strategy for ageing nuclear power plants that are coming towards the end of their technical lives. The risks to the long run equilibrium relationship could be further compounded by construction risks and possible changes in government policy that may question the commercial viability of increasingly pricy quotations of nuclear power plant construction[12]

The econometric methods of analysis and the underlying theoretical assumptions were appropriate with the data and provided consistent, interpretable results that were analogous to the underlying assumptions. There are of course limitations to this study. For example, attempts to replicate this study on the same variables in other developed countries would require pre-testing of the variables in order to determine the number of cointegrating equations. Currently, the ARDL-bounds test can only provide statistically robust results for cointegration if there is one cointegrating equation (r). If $r > 1$, the analysis would be improper as the critical values from Pesaran, Shin and Smith (2001) tables would be unsuitable. The model is also unable to statistically determine the additional benefit to CO_2 emissions abatement that would come from further increases in environmental taxes above the current 2014 level and so sensitivity analysis models may be used to expand the research further.

[12] The government provisionally agreed to a deal that supported the construction of a new nuclear power plant at Hinkley Point, Somerset. This was the first site that a nuclear licence was awarded for since Suffolk's Sizewell B nuclear power plant in 1987. The deal was made with NNBG, a subsidiary of French energy company EDF and China General Nuclear Power Corporation. The problem lies with the financial terms of the deal, which have been widely decried as overpriced as the government has agreed to pay an index-linked £92.50 per MWh based on 2012 prices as well as the offer of a guarantee of up to £2bn in bonds if NNBG wishes to issue debt to finance its construction (National Audit Office, 2016)

CHAPTER 4

THE ROLE OF FUSION POWER IN THE UK'S FUTURE ENERGY MIX: LONG-TERM ENERGY SCENARIOS TO 2050

4.1 Introduction

The Climate Change Act (2008) sets out the UK's legal requirement to reduce its emissions of greenhouse gases (GHG) by at least 80% of the 1990 baseline level by 2050. Among the other provisions within the Climate Change Act (2008) are the establishment of the Committee on Climate Change (CCC) and the system of carbon budgets, which ensures the UK's compliance with the law and its determination to stay on its decarbonisation course. The UK Government highlighted its policies for meeting the carbon budgets based on a minimum reduction of 23% of the 1990 level during the 1st carbon budget of 2008-2012, 29% during the 2nd carbon budget of 2013-2017, 35% during 3rd carbon budget of 2018-22 and 50% during the 4th carbon budget of 2023-2027 (HM Government, 2011). Further highlights were provided on the progress of the decarbonisation agenda between 1990 and 2010, with emissions from power stations falling by a third, emissions from buildings falling by 18%, emissions from agriculture falling by nearly a third, emissions from transport staying roughly the same and emissions from industrial output falling by 46% (HM Government, 2011).

However, there remains a considerable number of techno-economic uncertainties beyond the 4th carbon budget of 2023-2027. For example, the long period beyond 2027 would suggest that it is impossible to know the changing contributions from various energy sources, the future energy production costs, the projected energy demand levels and the shape of the emissions abatement trajectory. The UK's vote to leave the European Union during the 2016 referendum also adds uncertainty to its commitment to costly EU-derived energy regulations that are aimed at reducing GHG emissions such as the UK Renewable Energy Strategy, whose cost is £4.7bn per annum (Open Europe, 2015). Furthermore, the projected role of a fast-track fusion power option in 2050 adds to these uncertainties as its potential market share and ability to compete with existing energy sources are uncertain in the long run. Nevertheless, what is certain is that the UK is legally required to meet the GHG emissions reductions targets while ensuring its energy security in order for supply to meet demand. Indeed, choices can be made now by policymakers and the energy industry regarding the different pathways that could be followed towards 2050 as well as the tough trade-offs on the costs that would be incurred.

The last decade has seen a growing number of studies from governments, NGOs and industries that focused on the decarbonisation scenarios towards 2050 (IPCC, 2007a; WWF, 2007; Business Europe, 2010; Eurelectric, 2010; ECF, 2010; Greenpeace, 2010; HM Government, 2010; IEA, 2010; Shell, 2011; UKERC, 2013). Despite the presentation of well-researched, detailed trajectories in these existing studies, there is no presence of fusion power as a powerful decarbonised energy option in 2050. Also, many of these studies strictly follow the cost optimisation route towards 2050. This means that the "minimisation of total system costs" approach of their partial equilibrium models can represent a barrier to adoption of energy-efficient technologies that assist with climate change mitigation (Fleiter et al, 2011). On the other hand, careful consideration should be given to the overall benefits of high expenditure budgets for energy decarbonisation. The House of Commons (2011) demonstrated the need for such considerations in their National Policy Statement (NPS) based on their preference of an "all electric" decarbonisation solution from 2010 - 2050, despite this costing an estimated £700 billion more than a "green gas" solution over the same period.

Much of the empirical literature on long-term energy scenarios consists of the use of techno-economic energy models, which Timmerman et al (2013) describes as providing a holistic approach to the configuration of energy systems for the identification of optimal trade-offs between energy, economic and environmental performances. The empirical literature for scenarios of the UK's 2050 energy mix generally consists of projections of several energy variables such as primary energy supply, electricity generation and capital expenditure data. The UK's former Department for Energy and Climate Change (DECC) created its own energy model, the 2050 Energy Calculator in order to stimulate public engagement in energy modelling scenarios and widen the debate on climate change mitigation. However, despite the abundance of energy scenarios studies that provide energy-economic projections towards 2050, the vast majority have energy supply trajectories that are capital-intensive. There is also no current evidence in the literature of a cost-effective, future commercialised fusion power scenario, despite the UK's technical expertise in fusion power engineering and strong UK Government backing (Energy White Paper, 2003).

The next section highlights the decarbonisation policies from different pathways that were developed by HM Government (2010) as well as the contrasting modelling assumptions from two expert pathways that used the 2050 Energy Calculator for their future energy mix. Based on this background, this chapter provides a unique contribution to the field by recalibrating the 2050 Energy Calculator in order to consider the impact of fusion power within the future energy mix, with a commercialisation year of 2045. More importantly, this chapter will aim to achieve the 80% decarbonisation target for 2050 with fusion power while demonstrating the cost-effectiveness of the new “Fusion Pathway” when compared to two competing expert pathways.

4.2 UK Government's use of the 2050 Energy Calculator for the "2050 Pathway Analysis"

4.2.1 Pathway scenarios

HM Government (2010) carried out the "2050 Pathway Analysis", which is based on projections of future scenarios of the UK’s energy system. The 2050 Energy Calculator was used to develop a range of trajectories in five year intervals from 2010 to 2050. A so-called "Reference Case" was developed, which is based on scenario projections in the absence of new technologies for emissions abatement. There is little or no attempt to decarbonise the energy system in this scenario and there is a relatively weak effort to enhance sustainable sources of energy that will help meet the 80% decarbonisation target in 2050. This pathway leaves the UK in a weakened position to defend its energy security and supply shocks may leave the UK exposed to significant economic instabilities.

Another pathway that was developed by HM Government (2010) is called "Pathway Alpha", which takes into account the coordinated effort that government, industry and society would put into the decarbonisation agenda. This scenario employed a balanced effort to decarbonise across the three main routes: nuclear fission (henceforth, nuclear), renewables (e.g. wind) and carbon capture and storage (CCS) from fossil fuel power stations. Despite the need for food production sustainability, Pathway Alpha consists of a determined effort to increase the UK's production of bioenergy within the energy mix. Imports of bioenergy from foreign suppliers is also an important consideration and forms half of the projected market share for the UK's consumption of bioenergy.

Five additional pathways were developed in the HM Government (2010) report, with varying volumes of energy output from different primary energy sources: Pathway Beta (no carbon capture & storage), Pathway Gamma (no development of new nuclear plants), Pathway Delta (minimum renewables), Pathway Epsilon (limited bioenergy) and Pathway Zeta (limited behavioural change in consumers and businesses). However, the Reference Case and Pathway Alpha could be assumed to represent the two baseline cases: the Reference Case representing a minimal decarbonisation effort and Pathway Alpha representing a proportional and balanced cross-sectional decarbonisation effort.

4.2.2 Assumptions used in the "Reference Case" and the "Pathway Alpha"

Among the input assumptions provided by HM Government (2010) for the "Reference Case" and the "Pathway Alpha" are *GDP growth* of 2.5% per annum based on projections used by HM Treasury and *population growth* of 0.5% per annum based on the Office of National Statistics (ONS) "central scenario". The projections of *energy production costs* (oil, hydro, wave, tidal stream and tidal range) are based on DECC estimates, with the projection of the remaining energy sources carried out by Mott MacDonald (2010). Economic decisions surrounding energy production are driven by technological innovation and market forces within the backdrop of the Climate Change Act (2008). The *fuel price* assumptions take an initial upward trend towards 2020 but stabilise due to uncertainty in an overly volatile energy price climate.

The *drivers* of the trajectories include lifestyle changes, improvements in energy technology, structural change in the economy, differing energy technologies, industrial energy intensity and fuel choices. The trajectories are also created within the framework of the freedoms permitted by UK Government *policies* such as the Emissions Performance Standard (EPS) to boost CCS deployment and the National Policy Statement (NPS) for the removal of barriers to private sector participation in nuclear power development. Table 4.1 highlights the scenarios for the assumptions of capital costs of energy production:

Table 4.1: Capital cost assumptions for energy production based on 2009 prices

Capital cost: £/kW	Low	Central	High	Low	Central	High	Low	Central	High
		2020			2030			2040	
CCS (coal, ASC, FGD)	1,530	2,035	2,500	1,440	1,943	2,500	1,387	1,914	2,500
Nuclear (PWR)	2,114	2,686	3,125	1,983	2,584	3,125	1,924	2,549	3,125
Gas (CCGT)	470	588	688	454	580	688	440	572	688
Tidal range	2,000	2,600	3,100	2,000	2,600	3,100	2,000	2,600	3,100
Tidal stream	1,698	2,043	2,462	1,024	1,239	1,466	637	768	921
Wave	1,979	2,380	2,771	904	1,097	1,284	532	644	754
Onshore wind	997	1,258	1,500	966	1,241	1,500	934	1,223	1,500
Offshore wind	1,900	3,000	3,250	1,627	2,369	3,250	1,559	2,328	3,250
Oil	853	1,075	1,266	741	1,002	1,266	715	987	1,266
Hydro	1,438	1,594	1,688	1,438	1,594	1,688	1,438	1,594	1,688

Key: ASC = Advanced supercritical, FGD = Flue gas desulphurisation, PWR = Pressurised water reactor, CCGT = Combined Cycle Gas Turbine.

Source: HM Government (2010)

Apart from onshore wind, the capital costs for most low carbon energy technologies in Table 4.1 are much higher than the capital costs for oil and gas. In most cases, this is offset by the lower primary fuel costs that are incurred for the decarbonised energy generation sources. Pathway Alpha therefore, involves a shift in expenditure on primary fuel costs towards capital costs of power plant construction.

4.2.3 Summary of the "Reference Case" and the "Pathway Alpha" results

The results focused on the main decarbonised energy sources, including fossil fuels that use carbon capture and storage (CCS). However, there are no trajectories of fossil fuels without CCS due to the assumption that these energy sources are available from national and international sources in the required quantities. The model subsequently uses fossil fuels without CCS once all of the decarbonised energy sources are exhausted. The energy consumption and power generation trajectories of the Reference Case and Pathway Alpha were generated by HM Government (2010) and can be summarised as follows:

4.2.3.1 Energy consumption

Domestic energy demand for lighting and kitchen appliances is stable towards 2050 in the Reference Case as opposed to Pathway Alpha where energy demand is reduced by 30% due to efficiency measures such as the increased use of compact fluorescent lamp (CFL) bulbs.

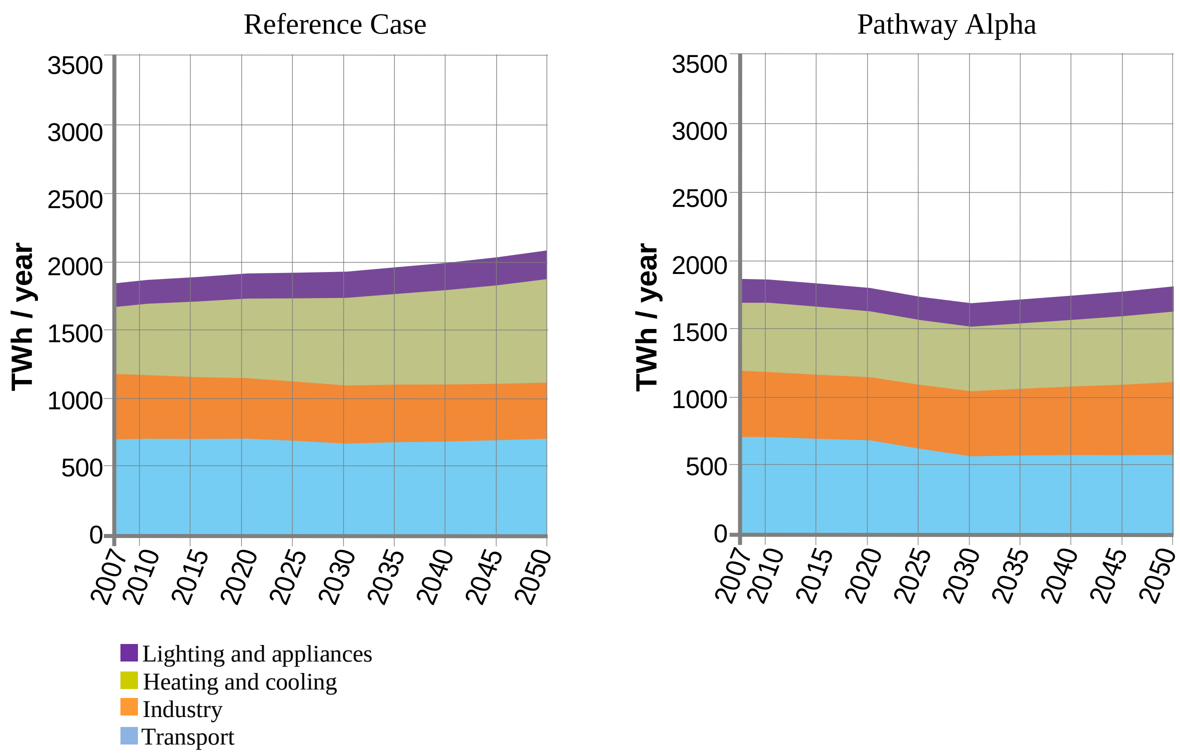
Energy demand for cooking in Pathway Alpha is 10% lower than the Reference Case by 2050 due to improvements in the efficiency of cooking appliances. Energy demand for consumer electronics is up 50% in the Reference Case by 2050 compared to a 40% increase in Pathway Alpha. Therefore, the total domestic energy demand increases by 20% in 2050 for the Reference Case compared to a 15% increase in Pathway Alpha.

Non-domestic energy demand for lighting would increase by 25% in 2050 in the Reference Case as opposed to a decrease of 30% in Pathway Alpha due to the extensive use of CFL bulbs and other efficiency measures. Energy for catering in the Reference Case is stable but decreases in Pathway Alpha due to a greater use of energy efficient appliances. Energy use in computing for Pathway Alpha is limited to a 10% increase, which is in line with the total increase in non-domestic energy demand in Pathway Alpha at 10% as opposed to the total increase in the Reference Case at 25%. Industrial output in the Reference Case is expected to rise by 33% by 2050 with a corresponding increase in emissions of 4%. This contrasts with Pathway Alpha where industrial output increases by 130% with a reduction in emissions of 56% due to better efficiency of industrial plants and the role that the emissions trading system (ETS) cap plays in the reduction of energy intensity.

Transport activity in terms of the mode of transport is stable in the reference scenario when compared to historic trends with a slowing of growth towards 2050 based on the weakening relationship between car ownership and income. The average number of people per mode of transport with the Reference Case and Pathway Alpha is the same for both cars (1.6 people) and vans (1 person). The average number of passengers per bus for the Reference Case is 9 but is a third higher for Pathway Alpha at 12, which comes as a result of policies that encourage shifts away from car use. Growth in domestic aviation is the same with the Reference Case and Pathway Alpha and reflects the advice given to the UK Government by the Committee on Climate Change within its "likely scenario". Similarly, domestic aviation emissions are the same in both scenarios. Efforts in Pathway Alpha to decrease emissions caused by road freight activity would lead to rail and water taking an 11% and 19% share of total freight transport by 2050 as opposed to the reference scenario, where rail and water freight experiences a 9% and 13% share of total freight transport respectively.

The Reference Case shows a continuous domination of internal combustion engines (ICE) in 2050 at nearly 80% of car and van travel. Plug-in hybrid vehicles represents 20% of car and van travel in the Reference Case and 54% in Pathway Alpha while fully electric vehicles only cover 2.5% of car and van travel in the Reference Case as opposed to 10% for Pathway Alpha. ICE-hybrid buses experience a 40% share in 2050 for the Reference Case but enjoys a very strong level of growth in Pathway Alpha from 20% of distance travelled to a 100% replacement of ICE buses by 2050 due to the expected economies of scale that could be achieved in the production of ICE-hybrid buses. For rail, there is a slight increase in the share of electric trains for Pathway Alpha from the 64% projected share in the Reference Case and energy efficiency is greater for Pathway Alpha by 6%. Energy efficiency in freight transport is also greater in Pathway Alpha than the Reference Case for ICE rigid heavy goods vehicles (HGVs) and rail freight by 33% and 22% respectively.

Figure 4.1: Energy demand projection of the "Reference Case" and "Pathway Alpha"



Source: HM Government (2010)

4.2.3.2 Power generation

Table 4.2 provides the key highlights of the 2050 projections, which shows Pathway Alpha's greater effort in meeting the objectives of the UK's decarbonisation agenda:

Table 4.2: Power generation projections for the Reference Case and Pathway Alpha

Energy source	**Reference case**	**Pathway Alpha**
Fossil fuels using CCS	The first of four demo plants operates by 2015. No commercial deployment beyond 2015	Build-rate at 1 GW p/a from 2030, resulting in 40 GW of total capacity from fossil fuels. This generates 239 TWh of electricity p/a by 2050.
Nuclear	Output decline due to lower finance available for decommissioning of nuclear energy facilities.	Development of 1 to 1.5 GW p/a results in 39 GW of total capacity that generates 275 TWh of electricity p/a by 2050
Hydroelectric power	The existing installed capacity of 1.6 GW is preserved through major refurbishment works	Efficiency upgrades and refurbishment works to existing plants. Development of smaller micro-power plants, which increases the capacity by 0.5 GW to 2.1 GW in 2050.
Onshore wind	Build rate steady at around 0.55 GW p/a. Total capacity rises to a maximum of 11 GW in 2025, with a steady decline thereafter to 2050.	Total capacity reaches 20 GW in 2030 at a build rate of 1 GW p/a. The maximum capacity is steady towards 2050 and generates around 53 TWh of electricity per annum.
Offshore wind	Build rate at 0.5 GW p/a. Total installed capacity of 8 GW in 2025 declines towards 2050.	Capacity at 60 GW by 2050, due to new sites leased from the Crown Estate and the extension of projects in the North Sea. 184 TWh of electricity p/a by 2050.
Micro solar	Lack of major solar photovoltaic (PV) installations and 0% average growth towards 2050	20% p/a growth during 2020 - 2030 and 13% p/a from 2030 onwards. Total installed capacity to 70 GWp by 2050.
Bioenergy	Just under 100 TWh by 2050	Just over 100 TWh due to the focus on energy recovery and less waste to landfill
Biomass imports	Decline towards zero by due to sustainability concerns.	50% of the UK market in 2050 due to an increase in the international biomass trade.
Geothermal	No interest beyond the two demo power plants in Cornwall. 0% average growth in electricity generation towards 2050.	32% p/a growth based on the successful deployment of geothermal plants in Cornwall. Electricity generation capacity reaching a peak of 1 GW by 2050.
Total capital costs p/a in 2050 (new plants)	No new capital costs. Electricity cost of £40 per MWh (low fossil fuel price). Medium and high electricity costs per MWh are more costly than Pathway Alpha	£16bn per annum in 2050. Electricity cost of £40 per MWh (low fossil fuel price) to £85 per MWh (very high fossil fuel price).
Total fuel costs p/a in 2050 (undiscounted)	In excess of £25bn per annum	Less than half of the 2009 cost at £5bn per annum

Key: p/a = per annum, GW = gigawatt, GWp = gigawatt peak, TWh = Terwatt hours

Source: Based on data compiled from HM Government (2010)

4.2.4 Summary

HM government (2010) used the 2050 Energy Calculator to model a number of long-term scenarios, with the Reference Case assuming the business as usual scenario of a minimal decarbonisation effort. The Reference Case was only able to reduce GHG emissions in 2050 by 3% on 1990 levels while Pathway Alpha successfully reduces emissions by 82% in 2050. In both cases, there was sufficient energy supply to meet the demand requirements of domestic, commercial and industrial consumers. However, version 3.4.6 of the 2050 Energy Calculator was used in the "Response to the Call for Evidence" report by HM government (2011a) and Pathway Alpha was subsequently found to have total costs (capital, operating and fuels costs) of the UK energy system that reached a very high level at £386.8bn p/a by 2050, £41.6bn higher than the total costs of the Reference Case at £345.2bn p/a by 2050.

This raises the question of whether there would be sufficient public acceptance for prohibitively high expenditure on energy supply, which subsequently feeds back to energy consumers in the form of higher energy bills. The rest of this chapter aims to address this issue by comparing the results of two expert pathways to a third fusion power-related pathway in order to assess the significance of the supply, demand, GHG emissions, energy security and cost implications of alternative pathways towards the 2050 energy mix.

4.3 Methodology

4.3.1 The 2050 Energy Calculator

This chapter aims to assess the variations that are possible within the energy system that would enable the UK's 80% decarbonisation target to be reached by 2050, with the projections using a base year of 2007 (using existing data) and a start year of 2010. The 2050 Energy Calculator is a bottom-up, scenario model for the generation of energy production and consumption projections and has a robust techno-economic framework around the choice of energy production infrastructure and the cost of substitute fuels. There is a detailed representation of electricity generation by the relevant sector as well as technical performance definitions such as energy efficiency and emissions levels by consumer type. The model acknowledges the competition for primary energy resources and simultaneously produces solutions based on the relative cost of emissions abatement.

The 2050 Energy Calculator (version 3.6.1) is a comprehensive model that offers 42 energy-related topics for consideration. Slightly more than half of the energy-related topics relate to energy supply from various sectors and the remaining ones relate to GHG abatement methods in final energy demand such as moves towards high electrification in industries. Each of the 42 energy-related topics contains a mini-model that incorporates data in order to perform calculations for the model's projections. Figure 4.2 shows the overall structure of how the model estimates GHG emissions, energy supply and consumption while Figure 4.3 shows the structure of how costs are estimated:

Figure 4.2: How the model produces GHG emissions, energy supply and consumption trajectories

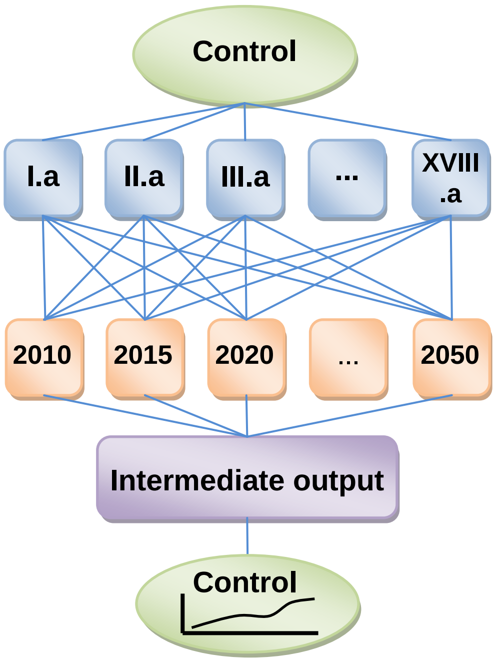
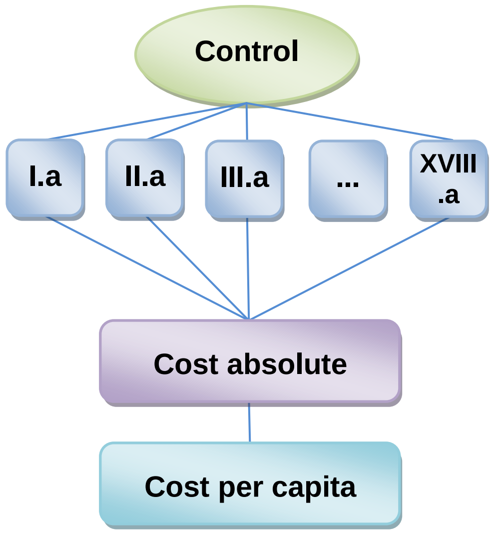


Figure 4.3: How the model produces costs



Source: DECC (2012)

Figure 4.2 and 4.3 maps each of the 42 energy-related topics in the "control" worksheet (e.g. nuclear energy) to their respective sector worksheet (e.g. II.a). Each of the 42 energy-related topics consists of 4 pathway choices per topic. A large number of pathway choices relate to the scale of ambition and these choices range from level 1 (low effort to decarbonise at relatively low cost) to level 4 (maximal effort to decarbonise at a high cost). The level also depends on the lead time towards the development of new energy production facilities as well as improvements in technology. On the other hand, a smaller number of pathway choices relate to specific energy routes rather than a scale (e.g. choice of fuel) and these are highlighted as trajectories A, B, C and D.

After the user-defined pathway choices are made, the 2050 Energy Calculator determines their implications, for example, whether or not the GHG emissions abatement target of 80% on the 1990 baseline has been reached. The most important outputs that will be generated from the 2050 Energy Calculator are the full range of demand and supply possibilities (by sector), cost implications and GHG emissions levels in a sequence of five year intervals until 2050. Among the other important outputs include the impact of choices on the electricity sector, land use, air quality and energy security (DECC, 2015a).

4.3.2 Description of scenarios

The 2050 Energy Calculator is used to assess the previously projected energy scenarios from two expert pathways. The first expert pathway consists of the projections that were developed by the British multinational energy company and FTSE 100 constituent, National Grid plc. The second expert pathway is based on the projections that were developed by Friends of the Earth, a global multi-tiered network of environmental organisations in 75 countries that campaigns extensively on energy sustainability and environmental preservation issues. Both pathways are compared to the new “Fusion Pathway”, which involves a complete recalibration of the 2050 Energy Calculator with fusion power included in the energy mix.

The National Grid Pathway acknowledges the threat from climate change and the widespread behavioural changes that are required in energy generation and demand. However, there is a strong emphasis on the need for a wide range of primary energy sources and versatile interconnected energy networks in order to sustain the security of supply. This pathway therefore seeks a balanced economic approach to the range of existing primary energy sources with a limited focus given to future primary energy sources that are yet to be commercially exploited. Cost effectiveness of energy supply is balanced with the importance of meeting the customer's needs in their energy requirements. This pathway also anticipates the move of heating and transport away from fossil fuels but recognises the techno-economic challenges of a push towards the maximal electrification of heating.

The Friends of the Earth Pathway seeks to demonstrate the environmental benefits of a dramatic increase in the percentage reduction of emissions against 1990 levels through an aggressive reduction in the UK energy system's emissions, measured in 'million tonnes of carbon dioxide equivalent' ($MtCO_2e$). There is a high use of renewables and other decarbonised energy generation that is currently not at a commercialised state. Due to the configuration of the highly-decarbonised energy infrastructure, there is a weaker emphasis on cost containment. High importance is given to energy efficiency in homes and commercial premises and there is also a significant amount of consideration given to the behavioural changes that are needed in the varying modes of transport during the course of the modelling time period. This pathway notably omits and reduces primary energy generation from sources that are contrary to the organisation's core values.

The new Fusion Pathway affirms its commitment to the 2050 decarbonisation target and every effort is put into arranging the energy system to meet this objective. It adopts a similar energy demand pathway to the one generated by National Grid plc due to the optimistic view of efficiencies and behavioural changes in transport and commercial premises as well as uncertainties in home energy use. However, the most significant difference in this pathway is the inclusion of fusion power within the energy mix. The commercialisation year of fusion power commences in 2045 and is based on the Cook et al (2005) report from scientists at EURATOM/UKAEA. The strong commercial viability of a future supply of fusion power fits into a wider emphasis on cost control, thereby favourably impacting the energy bills of households and businesses. The 2050 Energy Calculator therefore requires a recalibration in order to incorporate the demand side, supply side, economic and emissions assumptions from this future source of electricity from commercialised fusion power.

There are a number of additional differences in the primary energy generation assumptions of the Fusion Pathway and some of the recent UK Government policy announcements have helped to shape its scenarios. For example, the UK Government recently accepted a £6bn investment from China General Nuclear Power Corporation (CGN) for the Hinkley Point nuclear plant in Somerset and this signal of China's new role in the UK's nuclear future has been reflected in the model (BBC, 2015a). The model also considers the cancellation of the £1bn CCS fund by the British Chancellor of the Exchequer in 2015. This effectively ended the interest of the UK Government and its partner in the Peterhead CCS scheme, Royal Dutch Shell, in this decarbonisation route for the short term at least (Royal Dutch Shell, 2015). Furthermore, the UK Government's cuts to rooftop solar subsidies have eroded confidence in solar PV's future within the model as a medium to high volume producer of electricity (Reuters, 2015). The UK's Secretary of State for Energy and Climate Change also announced the closure of all UK coal power plants by 2025 (BBC, 2015b). However, no consideration is given to this declaration in the model due the viability of the Shell (2008) “flight into coal" expectation that was envisaged for the global economy beyond 2025.

4.4 Socio-economic assumptions of the recalibrated model

4.4.1 Demand-side assumptions

The National Grid and Fusion Pathways share similar demand-side assumptions, which are designed to show a general gravitation of consumers towards electrification and increased energy efficiencies while maintaining cost effectiveness in their energy choices. The demand-side assumptions from the Friends of the Earth Pathway shows a greater level of public awareness of the UK’s decarbonisation targets. The Friends of the Earth Pathway also anticipates that all energy stakeholders would be involved in a concerted effort towards maximal electrification and energy efficiency with significant reductions in non-zero emissions road and air travel. All demand assumptions are projected from a base year of 2007 and shows the pattern of demand over the course of the projection period.

UK energy demand from domestic transport is expected to decrease by 52% in 2050 from the base year to 203 TWh/yr in the National Grid and Fusion Pathway assumptions through greater efficiencies in public transport and a decline in the use of personal vehicles. There is also a greater shift towards zero emission personal vehicles by 2050 with a 65% decline in energy consumption to 151 TWh/yr. Domestic freight is expected to see a 36% decrease to 70 TWh/yr by 2050 due to the shift towards electrified rail freight Increases in shipping and air travel are expected, especially when considering the expected increase in aviation capacity in the southeast of England but energy consumption would be tempered by a new generation of fuel efficient ships and aircraft. On the other hand, the Friends of the Earth assumption sees a greater decline in energy use for domestic transport through a larger shift towards public transport and bicycles. Emissions from personal vehicles are expected to fall by 73% in 2050 and there is a greater emphasis on the move away from road freight.

Average UK home temperatures in the National Grid and Fusion Pathway assumptions are expected to have a moderate increase of 0.5% from the base year as there is a significant increase in home insulation. For lighting and appliances, energy demand per household decreases by 34% in 2050 due to greater efficiencies and energy displays on appliances while commercial premises sees a modest decrease of 5% by 2050. Domestic and commercial energy for heating, cooling and cooking is predominantly electric with the remaining (if any) portion of primary energy coming from gas. The Friends of the Earth route sees a nationwide drive towards greater insulation in homes, full electrification of cooking and bigger efficiencies in home lighting and appliances. This pathway shares a similar objective with the National Grid / Fusion route through a near full electrification of commercial premises.

The assumptions in the National Grid and Fusion Pathways sees a 30% increase in the UK's industrial output by 2050. Industrial energy intensity is the ratio of industrial energy consumption to GDP and is expected to decrease by 20% for the National Grid and Fusion Pathways. The Friends of the Earth assumption expects industrial energy intensity to decline by 40%, which means that half of all industrial emissions are captured by 2050 and the total contained emissions amount to 8.2MtCO_2e. Table 4.3 and 4.4 contains a list of the share of energy consumption per demand sector for the Friends of the Earth and the National Grid / Fusion Pathways.

Table 4.3: Percentage of energy consumption per demand sector: National Grid and Fusion Pathways

Category	Energy demand	Setting	Percentage share of the total in 2050
Transport	Domestic transport	3	Vehicles (74%), rail (8%), bus (13%), foot (2%), air (2%) & bicycle (1%).
	Zero emissions	3	Conventional car (20%), hybrid (32%), zero emissions car (48%).
	Battery technology	1	Share of zero emissions cars - electric (100%).
	Domestic freight	3	Road (58%), rail (19%), waterway (19%), pipeline (4%).
Residential	Insulation	3	No. of homes: loft insulation (18m), triple glazing (14m), floor (7m).
	Electric heating	4	Share of new home heating systems - electric (80% - 100%).
	Non-electric heating	1	Share of remaining new home heating systems - non-electric (0% - 20%).
	Electric cooking	1	Share of energy in cooking - electric (63%) and gas (37%).
Industrial	Energy intensity	2	Industrial electricity demand (40%), coal, oil, gas & district heating (60%)
Commercial	Electric heating	4	Share of new commercial heating systems - electric (80% - 100%).
	Non-electric heating	4	Fossil fuels, bioenergy and power stations heat (0% - 20%).
	Electric cooking	2	Share of commercial cooking - electric (100%).

Table 4.4: Percentage of energy consumption per demand sector: Friends of the Earth Pathway

Category	Energy demand	Setting	Percentage share of the total in 2050
Transport	Domestic transport	4 >	Vehicles (62%), rail (10%), bus (19%), foot (2%), air (2%) & bicycle (5%).
	Zero emissions	4 >	Share of car travel - zero emissions car (100%).
	Battery technology	2 >	Share of zero emissions cars - electric (80%), hydrogen fuel cell (20%).
	Domestic freight	4 >	Share of freight - road (50%), rail (23%), waterway (23%), pipeline (4%).
Residential	Insulation	4 >	No. of homes - loft insulation (21m), triple glazing (22m), floor (11m).
	Electric heating	3 <	Share of new home heating systems - electric (30% - 60%).
	Non-electric heating	3 >	Share of remaining new home heating systems - non-electric (40% - 70%).
	Electric cooking	2 >	Share of energy in cooking - electric (100%)
Industrial	Energy intensity	2 >	Industrial electricity demand (66%), coal, oil, gas & district heating (34%).
Commercial	Electric heating	4 =	Share of new commercial heating systems - electric (80% - 100%).
	Non-electric heating	4 =	Fossil fuels, bioenergy and power stations heat (0% - 20%).
	Electric cooking	2 =	Share of commercial cooking - electric (100%).

Key: > Table 4.4 setting greater than table 4.3
< Table 4.4 setting less than table 4.3

Source: Estimated assumptions from the 2050 Energy Calculator (MacKay, 2012)

4.4.2 Supply-side assumptions

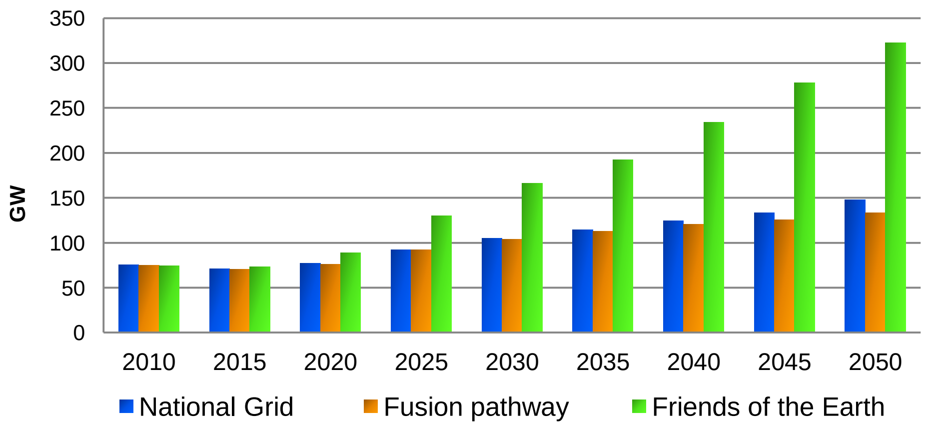
The National Grid Pathway is a scenario where fossil fuels form the largest share of primary energy supply. Total installed capacity is 62.6 GW in 2010 but steadily declines during the course of the projection period due to a lack of renewal of oil and coal plants for electricity. Some fuel fossil generation is mitigated by CCS deployment, which is commercialised by 2020 but experiences a slow build rate until 2035. Between 2035 and 2050, CCS enjoys a build rate of approximately 4 GW every five years until 2050. Nuclear fission plays a prominent role in the energy mix behind fossil fuels with a steady build-up of capacity until 2030, then experiencing a peak build rate of 0.8 GW per annum until 2050. There are a limited number of new-build biomass power plants during a 10 year period until 2040, where 600 MW p/a of new capacity is installed due to the retirement of ageing biomass plants. There is no consideration for wave, tidal stream, geothermal and small scale wind in the energy mix. However, offshore wind experiences a build rate of just over 300 wind turbines p/a at 5.8 MW per turbine from 2025. On the other hand, onshore wind experiences a new-build decline from 328 turbines p/a in 2015 to 240 new turbines p/a at 2050 at a capacity of 2.5 MW per turbine. There is a large investment in bioenergy as 10% of British land is used for bioenergy crops and imported bioenergy amounts to approximately 70 TWh/year.

In contrast, the impact of China's £6bn investment in the Hinkley Point nuclear plant sees nuclear fission enjoying the largest share of primary energy in the Fusion Pathway at 39.2 GW of installed capacity by 2050. There is a marginally weaker emphasis on CCS but the Fusion Pathway acknowledges the national importance of CCS as mentioned by the former British Prime Minister, David Cameron who stressed the need for investment in CCS technology in the 2011 Carbon Plan (HM Government, 2011). Primary energy from fossil fuels is at a lower level than the National Grid Pathway but remains high.

Fusion power is added to the energy mix and is commercialised in 2045 with a total output of 7.2 GW of installed capacity from 2 power plants in 2050. The anticipation of fusion has a direct impact on unpopular onshore wind farms, which see a decline in installed capacity from 11 GW in 2025 to a mere 33 MW in 2045, with no new turbines built after 2025. Fusion also impacts wave, tidal stream and tidal range, which receive no significant investment for commercialisation due to technological uncertainties but geothermal achieves a maximum capacity of 1 GW p/a from 2035 due to the relatively high confidence in the Cornwall resource. Less confidence is given to solar energy in this pathway than in the National Grid Pathway as the high costs and low efficiency act as a barrier to mass deployment. However, more commitment is given to increasing hydroelectric capacity in Scotland as well as moderate increases in the small-scale wind.

The Friends of the Earth pathway is notable for its commitment to a very high investment in renewable energy generation. Figure 4.4 shows how the GW capacity of this pathway is similar to the National Grid and Fusion Pathways in 2010 and 2015 but far exceeds these pathways from 2020 onwards. Onshore wind increases rapidly to a maximum capacity of 23.6 GW by 2035 and remains stable towards 2050 while offshore wind has an installed capacity in excess of 70 GW by 2040. Hydroelectric power would use most of the UK's available sites and reaches a maximum capacity of 3.1 GW by 2035. There is a large amount of investment in Solar PV, which is widely deployed at an average capacity of 6m^2 per person and 108.7 GW of power by 2050. Wave, tidal stream, tidal range and geothermal all receive significant investment with capacities in 2050 of 36 GW, 22 GW, 13 GW and 3 GW respectively. There is also a significant amount of carbon dioxide sequestration with 110 million tonnes p/a of carbon dioxide pumped underground by 2050. There is a much greater move towards gas supply than the other two pathways but there is an immediate halt to the development of new nuclear plants and existing plants are expected to come to the end of their useful life by 2035.

Figure 4.4: UK total energy production capacity (GW)



Source: Fusion Pathway capacity by author, other capacities are from DECC (2015a)

4.4.3 Economic assumptions

There are a wide variety of technologies within the model that are associated with energy production, consumption and GHG emissions such as petroleum refineries, power plants, electricity grid distribution, land use, storage, insulation, heating, transport and industrial processes. These technologies incur costs with the principal cost estimates consisting of capital expenditure, operations and fuel (both own use fuel and converted primary fuel). The 2050 Energy Calculator categorises costs between a low, point and high cost. The low and high costs are based on published expert opinions of the future path of the UK's energy system such as Mott MacDonald (2010) and Parsons Brinckerhoff (2011) whereas the 'point' estimates are based on an intermediate cost that corresponds to the energy model, MARKAL 3.26.

For fusion, the power plant low cost was derived from the £2,150/kW, 3.6 GW PPCS Model B design that was highlighted by the European Fusion Development Agreement (EFDA, 2005) whereas the high cost of \$3940/KW (£2550.95 at \$1.5445$_{2015}$ to £1) was based on the estimates from scientists at EURATOM/UKAEA (Han and Ward, 2009). The operating costs are based on the Tokimatsua et al (2003) estimate of 4% of fusion capital costs. Where no MARKAL estimates exist for the intermediate point cost (e.g. wave, tidal stream and fusion), a 35th percentile is used by the 2050 Energy Calculator between the low and high cost estimates in order to produce the "point" cost estimates. As the total cost estimates are produced, the low and high costs per kW remains the same as they are considered to be exogenous. However, provisions are made in the model for incremental progress in efficiency and technical improvements in energy infrastructure over time. In addition, the per capita cost uses ONS projections of the UK's population over the model's projection period (ONS, 2008).

Table 4.5 shows a list of the techno-economic parameters used for the model. The table highlights the typical sizes for primary energy plants as well as capital expenditure (£/kW), operating costs (£/kW), fuel costs (£/kW) and plant availability in terms of the load factor. Capital expenditure is a function of new build plants while operating and fuels costs are a function of total installed capacity at any given time. Costs are generally dependent on the extent of the work that goes into the set-up and operation of energy generation as well as the lifetime of the plant. For example, nuclear fission plants are assumed to have a 60 year lifetime, with a price per kW that is more expensive than coal due to the more complex engineering works and greater isolation of the plants from residential, commercial and industrial areas. Some costs for power plants such as oil are retired during the course of the projection period while other costs for power plants such as CCS are uncertain due to the residual cost of the long-term storage of carbon. Costs for renewables such as offshore wind may experience significant low / high differences in the £/kW cost due to technical challenges of deep water wind turbines that are a significant distance away from the UK's coastline.

Table 4.5: Techno-economic parameters used for the model

Primary energy	Generation type	Plant size (MW)	Capital costs £/kW (Point)	Operating costs £/kW (Point)	Plant availability
Oil	Power plant	2,000	725	52	6%
Coal	Power plant	2,000	1,749	53	90%
Gas	Power plant	2,000	462	27	70%
Biomass	Power plant	500	1,774	87	90%
CCS - coal	Power plant	1,200	2,115	81	85%
CCS - gas	Power plant	1,200	995	61	85%
Nuclear fission	Power plant	3,000	2,744	76	80%
Onshore wind	Wind turbine	2.5	1,365	14	30%
Offshore wind	Wind turbine	5.8	1,968	73	45%
Hydroelectric	Hydro plant	100	1,036	104	38%
Wave	Wave turbine	1.5	3,573	272	25%
Tidal range	Tidal range project	240	3,423	32	24%
Tidal stream	Tidal stream turbine	2	2,997	63	40%
Geothermal	Geothermal plant	10	4,138	146	80%
Fusion	Power plant	3,600	2,290	92	83%
Solar PV	Solar source	0.0025	2,027	26	10%
Small scale wind	Wind turbine	0.0050	1,230	27	24%

1. Additional parameters for solar thermal and bioenergy are excluded from the model
2. Point costs for fusion are based on a 35% percentile between the low cost (EFDA, 2005) and high cost (Han and Ward, 2009)

The 2050 Energy Calculator contains oil price assumptions that were based on DECC fossil fuel projections in 2010. The oil prices that were projected in the model for 2015 were based on a low price of $80/bbl, a point price of $94/bbl and a high price of $104/bbl. However, in light of the 2015 collapse in oil prices, these assumptions are now obsolete so the DECC (2015b) assumptions would now be used instead for all fossil fuels prices. The new oil price assumptions are based on a low price of $44/bbl, a point price of $64/bbl and a high price of $83/bbl. New gas price assumptions are based on a low price of 38p/therm, a point price of 47p/therm and a high price of 55p/therm. The new coal price assumptions are based on a low price of $53/tonne, a point price of $60/tonne and a high price of $67/tonne. Fossil fuel price assumptions beyond 2015 are set in accordance with the projected schedule presented by DECC (2015b).

The economic performance of fusion power is assessed through the levelised cost of electricity generation (LCOE), which is essentially the discounted lifetime costs of ownership and generation of electricity, converted to £/MWh or £/kWh. The levelised cost of fusion power would be compared to the costs of competing energy sources, using the following formula highlighted by Ward et al (2010):

$$\text{LCOE} = \frac{\sum_{\text{t}}(C_t + OM_t + F_t + R_t + D_t)(1+r)^{-t}}{\sum_{\text{t}} E_t(1+r)^{-t}} \quad (4.1)$$

Where:

C = Capital costs in year t
OM = Operation and maintenance costs in year t
F = Fuel costs in year t
R = Replaceable components costs in year t
D = Decommissioning costs in year t
E = Electricity generation in operating year t
r = Discount rate

There is no consideration for the residual cost of decommissioning energy infrastructure unless it was originally implied in the capital costs. The discount rate used in the formula, which is based on the recommended Green Book discount rate (HM Treasury, 2011) is 3.5% from 2010 to 2040 and 3% from 2041 to 2050.

4.5 Empirical results

This section presents the results of the energy scenarios that were generated from the recalibrated 2050 Energy Calculator. A unique recalibration of the 2050 Energy Calculator provides a significant contribution to the empirical use of the model as it permits the inclusion of fusion power into the UK's future energy mix. The recalibrated model integrates the underlying assumptions for the new Fusion Pathway from a demand-side, supply-side and economic perspective. Various possible configurations of the UK's energy system were considered prior to the generation of the Fusion Pathway scenarios, which are compared to the two expert pathways from National Grid plc and Friends of the Earth. The author's comprehensive estimates of the results are shown in the "chapter 4 appendices" section.

Figures 4.5 to 4.15 provides a visual comparison of the three energy mix pathways, which are subject to further interpretation and analysis.

4.5.1 Electricity demand and supply: National Grid Pathway versus Fusion Pathway

As the Fusion and National Grid Pathways share similar demand assumptions, the electricity supply outcomes are of particular interest. Figure 4.5 and 4.6 shows the percentage share of fusion power within the primary energy mix in 2050. Fusion power's share of UK primary energy is 6% and this has had a direct effect on gas, which has a 3% lower market share in the Fusion Pathway than in the National Grid Pathway due to the substitution effect. Oil imports and reserves also have a 3% lower market share in the Fusion Pathway than in the National Grid Pathway due to the energy system's recognition of the UK's move towards domestic and commercial electrification.

Figure 4.5: Share of UK total primary energy supply for the Fusion Pathway (%)

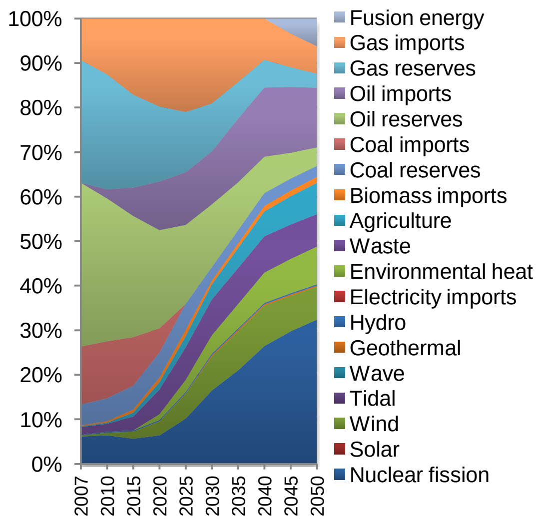


Figure 4.6: Share of UK total primary energy supply for the National Grid Pathway (%)

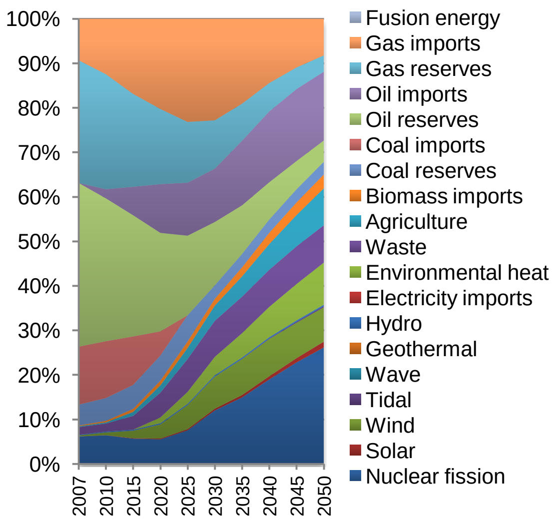


Figure 4.7 and 4.8 shows the UK's total electricity supply (line graph) and demand (bar graph) by sector from the National Grid Pathway and the Fusion Pathway in TWh/yr. The total electricity supplied for both pathways is projected to increase at a similar rate between 2010 and 2040. However, there is a noticeable acceleration in the amount of the electricity that is supplied by 2050 during the commercialisation phase of fusion. The total electricity supplied for the Fusion Pathway in 2050 is 668 TWh/yr with a growth rate of 70% between 2010 and 2050 while the total electricity supplied for the National Grid Pathway in 2050 is 578 TWh/yr with a growth rate of 55% during the same period.

Figure 4.7: Total UK electricity supply and demand by sector - National Grid Pathway

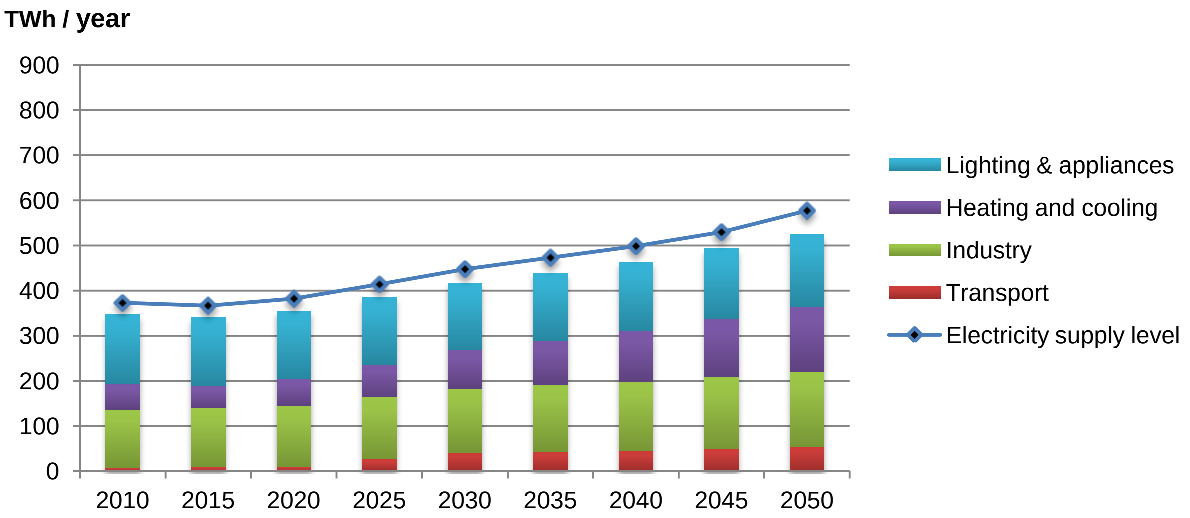
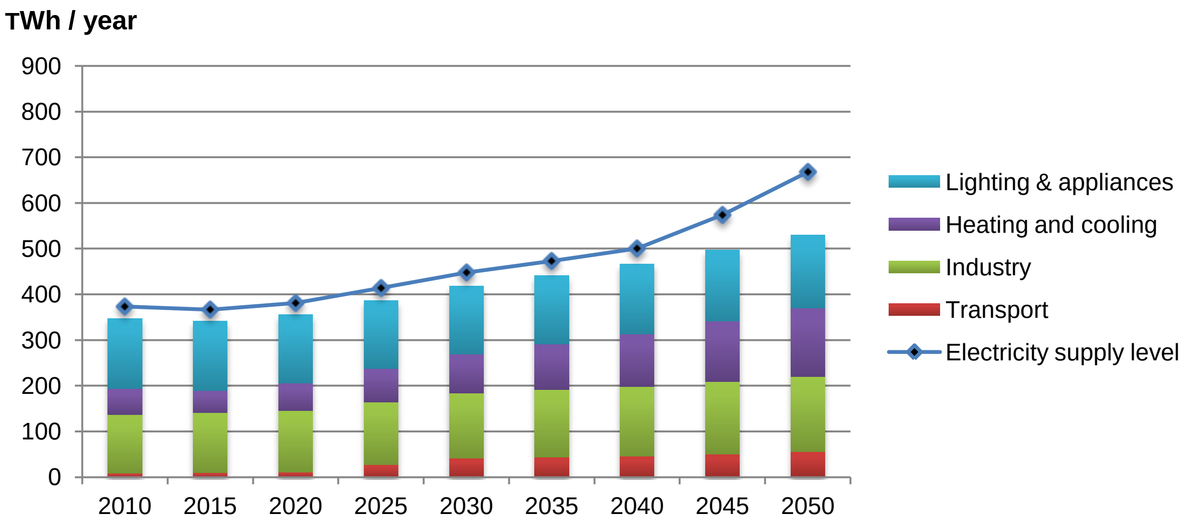


Figure 4.8: Total UK electricity supply and demand by sector - Fusion Pathway



There are additional major causes for the diversion in both electricity generation pathways. The Fusion Pathway proposes a stronger drive towards higher nuclear and offshore wind than in the National Grid Pathway in order to act as a buffer against weaker CCS deployment, onshore wind retirement and limited confidence in solar PV distribution due to major UK Government cuts in rooftop solar subsidies. Nuclear energy is therefore 43% higher in the Fusion Pathway than the National Grid Pathway at 275 TWh/yr and offshore wind enjoys the second largest share of electricity output at 189 TWh/yr, which is 33% higher than the output experienced in the National Grid Pathway. Total renewable electricity generation in the

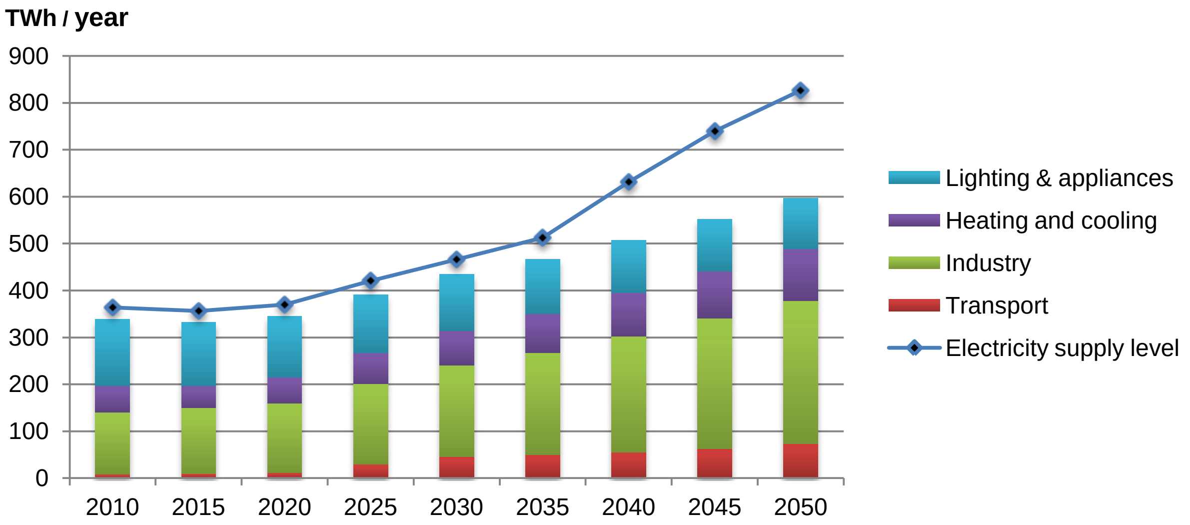
Fusion Pathway has an output of 31% of all electricity supply in 2050 while renewables in the National Grid Pathway has a greater share at 34% of all electricity supply.

Conventional thermal generation is retired in the Fusion Pathway in 2040 in preparation for fusion commercialisation but still has an output of 24 TWh/yr for the National Grid Pathway. CCS experiences the highest rate of growth in the National Grid Pathway throughout the length of the modelled time period from 0 TWh/yr in 2010 to 189 TWh/yr in 2050. This is approximately 50 TWh/yr more than the total electricity generated from CCS in the Fusion Pathway. However, the 52.6 TWh/yr of fusion electricity in 2050 offsets this deficit in decarbonised output.

4.5.2 Electricity demand and supply: Friends of the Earth Pathway versus the Fusion Pathway

Figure 4.9 shows the UK's total electricity supply and demand by sector from the Friends of the Earth Pathway, with electricity demand in this pathway projected to be 13% higher than the Fusion Pathway. Industrial processes are the highest electricity-consuming sector in the Friends of the Earth Pathway at 197 TWh/year, approximately 42 TWh/yr higher than the Fusion Pathway. The high level of demand is driven by high electrification and approximately 48% of carbon emissions captured by CCS. This has had a knock-on effect on the exceptionally high geosequestration intensity of 110 million tonnes of CO_2 a year at a consumption rate of 99 TWh/yr. This is a very high level of electricity demand, especially when considering the findings in the HM Government (2010) "2050 Pathway Analysis" report, which consisted of 5 out of 7 distinct pathways with a maximum CO_2 sequestration level of 1 million tonnes p/a in 2050 and the remaining 2 pathways at 30 million tonnes p/a. Nevertheless, the increased CCS capacity in the Friends of the Earth Pathway means that the UK's total energy supply from fossil fuels represents 45% of total primary energy compared to the Fusion Pathway where fossil fuels represents just 28% of the primary energy.

Figure 4.9: Total UK electricity supply and demand by sector - Friends of the Earth Pathway



Electricity demand in the domestic sector (heating, lighting, appliances and cooking) for the Fusion Pathway shows demand at approximately 36% of the UK's total electricity demand. However, the national drive towards greater home insulation and electrification would pay off in the Friends of the Earth Pathway, which exhibits a strong level of efficiency in its electricity demand level at 20% of total energy demand. A similar scenario is envisaged in the commercial sector, with commercial electricity consumption in the Fusion Pathway approximately 32% higher than the Friends of the Earth Pathway.

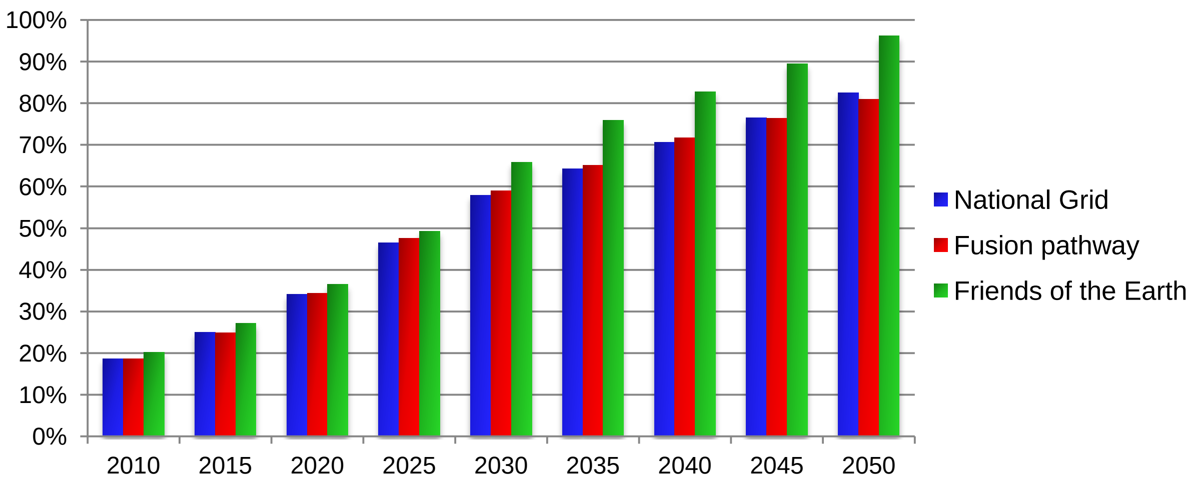
The UK's total electricity supply level in 2050 for the Friends of the Earth Pathway is 24% higher than in the Fusion Pathway. The main drivers of this very high output is offshore wind, which is a third of total supply at 284 TWh/yr and CCS, which at 191 TWh/yr represents nearly a quarter of total supply. There is perhaps an element of overconfidence in the Friends of the Earth Pathway concerning the technical ability of wave, tidal and solar to produce mass electricity at a combined output of 257 TWh/yr by 2050, while the Fusion Pathway demonstrates a lack of confidence in the mass appeal in these electricity sources with supply at 0 TWh/yr. Geothermal electricity is three times greater in the Friends of the Earth Pathway than in the Fusion Pathway at 21 TWh/yr.

Energy use in transport shows the advances in the separate decarbonisation agendas in both pathways by 2050. The Friends of the Earth Pathway demonstrates the stronger advance towards hydrogen use in transport but electricity demand for transport represents just 8.7% of total electricity demand. Overall, total final energy for transport is 315 TWh/yr. On the other hand, the Fusion Pathway does not consider widespread moves towards hydrogen vehicles but moves faster towards transport electrification at 10.4% of total electricity demand. The total final energy use for transport in this pathway has a higher level of GHG emissions than in the Friends of the Earth Pathway at 439 TWh/yr.

4.5.3 GHG Emissions

The GHG results for each of the three pathways underlines the difficulties in meeting the 2nd carbon budget (29% below 1990), 3rd carbon budget (35% below 1990) and 4th carbon budget (50% below 1990) that was highlighted in HM Government (2011) for 2015, 2020 and 2025 respectively. The National Grid Pathway is 25% below the 1990 GHG emissions level in 2015 and nearly matches the 2020 target at 34%, then slips below the 2025 target at 47%. The Fusion Pathway has a similar trajectory at 25% in 2015, 34% in 2020 and 48% in 2025. On the other hand, the Friends of the Earth Pathway has a stronger performance at 27% in 2015, 37% in 2020 and 49% 2025. All three pathways experienced an improvement in GHG emissions abatement in 2020 due to a sharp slowdown and subsequent cessation of coal imports. Figure 4.10 illustrates the GHG emissions reduction levels from 1990 to 2050.

Figure 4.10: Reduction in carbon emissions from 1990 levels (%)



There is a noticeable acceleration in the percentage reduction in GHG emissions in the Friends of the Earth Pathway and this trajectory becomes stronger towards 2050. This could be explained by the huge investment in renewables and steady increases in CCS installed capacity. The introduction of decarbonised fusion power in 2045 also allows for a greater reduction in gas consumption in the Fusion Pathway than in the other two pathways.

Nevertheless, each pathway reaches the 2050 target an 80% reduction in GHG emissions from 1990 levels with the National Grid Pathway at 83%, the Fusion Pathway at 81% and the Friends of the Earth Pathway at a substantially higher level at 96%.

4.5.4 Energy security

Energy security is another key consideration in the move towards electrification and the Fusion Pathway performs strongly in this area as the electricity supply-demand ratio in 1.26:1. This contrasts with the lower National Grid Pathway ratio of 1.10:1, which may increase the long-term reliance on imports and destabilise confidence in an era of political instability in resource-rich regions. Energy security is seemingly higher in the Friends of the Earth Pathway, with an electricity supply-demand ratio of 1.39:1 in 2050. The high ratio for the Friends of the Earth Pathway may call into question the wisdom of high capital expenditure in energy infrastructure, which may lead to financial constraints in power production. However, a closer look at this ratio provides an indicator of the trajectory of import dependence as the percentage share of electricity imports from total energy supply has steadily increased during the course of the projection time period. By 2050, electricity imports in this pathway would reach 186 TWh/yr, a full 11.2% of the UK's total primary energy supply. On the other hand, electricity imports in 2050 are much lower in the Fusion Pathway and National Grid Pathway at 100 TWh/yr and 14 TWh/yr respectively.

4.5.5 Economic outcomes

Perhaps the most important consideration in the energy scenarios over the long-term is the delivery of cost effective solutions that would meet the needs of all sections of society as well as meeting the GHG emissions targets as set out by the Climate Change Act 2008. The government describes the scale of this challenge in 2013 by declaring the UK's pipeline of energy investment is in excess of £200bn - significantly more than the UK's combined pipeline investment in communications, transport and water infrastructure (DECC, 2013b).

Figure 4.11, 4.12 and 4.13 shows the model's point projections of the annual undiscounted capital costs, operating costs and fuels costs for the three pathways in billions of British pounds. Annual capital costs between the three pathways in 2010 and 2015 are relatively close but the Friends of the Earth Pathway accelerates faster from 2020 to the point where annual capital costs are at a very high £211bn p/a, £51bn p/a greater than in the National Grid Pathway and £58bn p/a greater than the Fusion Pathway. The main driver of the high cost in the Friends of the Earth Pathway is the high renewables investment for electricity production, which is more than triple the cost of the other two pathways at £48bn p/a in 2050. Investments in GHG emission abatement in transport are also costly in this pathway and amount to over £10bn p/a more than the other two pathways by 2050. The introduction of fusion power in 2045 allows the Fusion Pathway to switch its capital investment strategy away from wave, tidal and solar PV, providing annual savings over the National Grid Pathway of £6.4bn by 2050.

Figure 4.11: Total energy cost p/a - National Grid Pathway

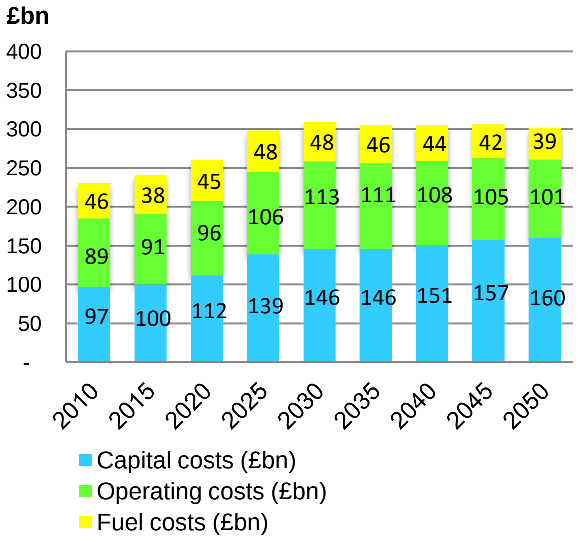


Figure 4.12: Total energy cost p/a - Fusion Pathway

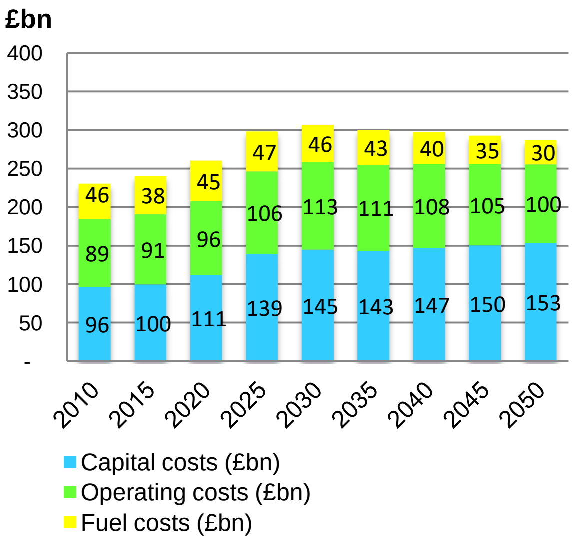


Figure 4.13: Total energy cost p/a - Friends of the Earth Pathway

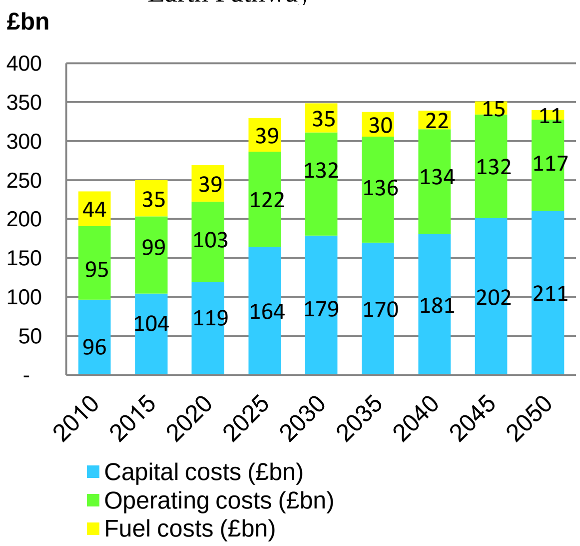
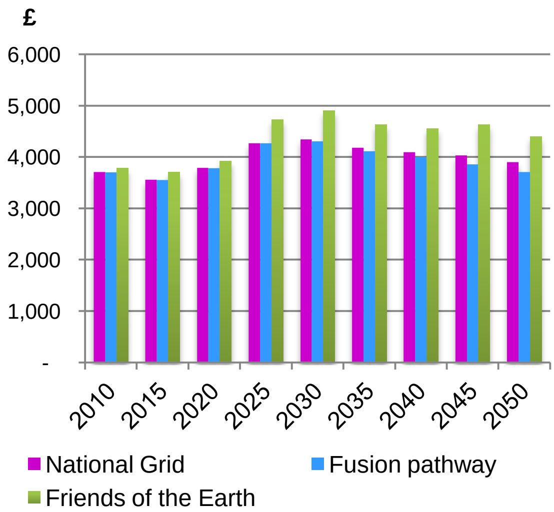


Figure 4.14: Total per capita energy cost p/a

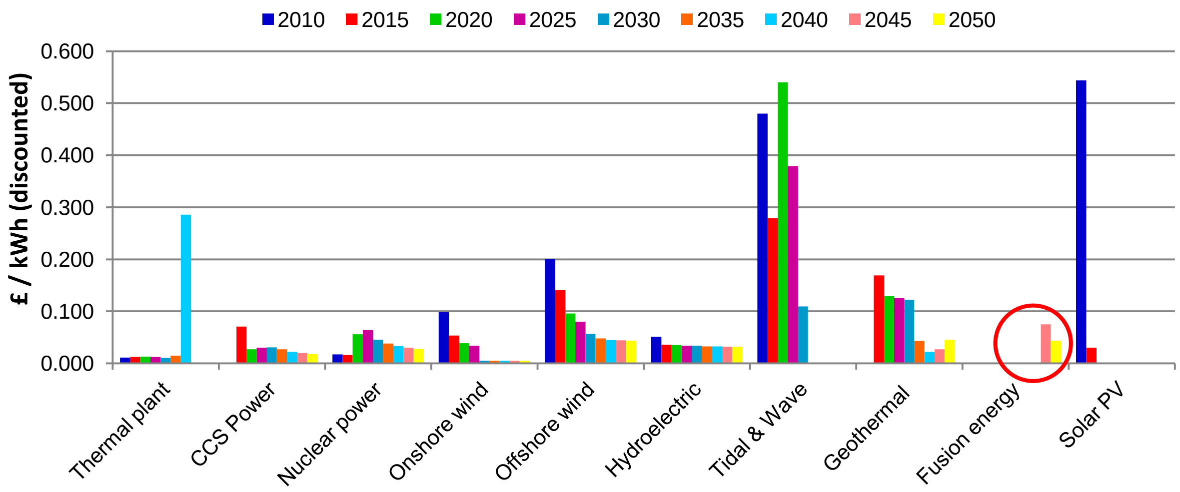


The accumulated operating costs of installed energy capacity are roughly similar between the Fusion Pathway and National Grid Pathways throughout the projected time period but are more than £16bn p/a higher by 2050 in the Friends of the Earth Pathway at £117bn p/a. Operations connected with electricity generation are more than £16bn p/a higher in the Friends of the Earth Pathway than in the other two pathways by 2050 and industrial operations driven by the storage of captured CO_2 emissions are nearly £10bn higher than in the other two pathways at £11.2bn. High renewables in the Friends of the Earth Pathway have rendered the fuel costs negligible at £11bn p/a by 2050 but are more than three times as high in the National Grid Pathway at £39bn p/a due to the high use of bioenergy. Fuel costs in the Fusion Pathway in 2050 are £30bn p/a but are mitigated by exports of surplus electricity. In summary, the total costs of the UK's energy system (capital, operations and fuel) in 2050 are £299.6bn p/a for the National Grid Pathway, £337.8bn p/a for the Friends of the Earth Pathway and £284.8bn p/a for the Fusion Pathway.

Figure 4.14 shows the UK's per capita cost of total energy throughout the projection time period. There is a peak per capita cost of energy in 2030 for the National Grid and Fusion Pathways before the trajectory gently declines towards 2050 to £3,902 p/a and £3,709 respectively. At the same time, the total per capita energy cost peaks in 2030 for the Friends of the Earth pathway but stays relatively stable with a per capita cost in 2050 of £4,399.

The levelised cost of electricity (LCOE) in Figure 4.15 is calculated for fusion power and compared with the LCOE calculations of competing electricity generation sources in the Fusion Pathway. The LCOE for fusion power is dependent on its stage of maturity and the technological learning factor for fusion power plants. Nevertheless, fusion power is expected to compete successfully with other decarbonised electricity sources as the LCOE starts of at £0.08/kWh in 2045 and declines to £0.04/kWh in 2050. This is consistent with the Ward et al (2005) estimates for fusion, with the LCOE ranging from €0.05/kWh to €0.10/kWh (£0.04/kWh to £0.07/kWh at $€1_{2015}$ to £0.73).

Figure 4.15: Levelised unit cost of electricity for the Fusion Pathway p/a (£/kWh)



For comparison purposes, the unabated conventional thermal generation from fossil fuels has an average LCOE that is the lowest among the competing energy sources. Despite the early decommissioning of electricity from oil, conventional thermal generation from fossil fuels remains cheap at an average LCOE of £0.01/kWh between 2010 and 2035 but this does not consider carbon prices and environmental factors. There is also a spike in the LCOE in 2040 at £0.29/kWh as unabated coal and gas are decommissioned in favour of CCS. The LCOE for CCS is competitive and reaches £0.02/kWh in 2050 but there are uncertainties in relation to the implementation period as CCS is not yet proven to be commercially viable. Onshore wind has an LCOE of £0.10/kWh in 2010 and declines to £0.03/kWh in 2025 but new build turbines are discontinued after 2025. Offshore wind is at a higher LCOE of £0.20/kWh in 2010 and gradually declines to £0.04 in 2050, making it a key high-volume source of electricity in the UK's energy mix. Lower volume electricity generation such as hydroelectric power and geothermal remain competitive in 2050 at £0.03/kWh and £0.05/kWh respectively.

4.6 Conclusions and policy recommendations

This chapter considered the expert pathways for the UK's future energy system that were developed by multinational organisations that used the 2050 Energy Calculator, a techno-economic energy model used for the generation of long term energy-related projections. A significant contribution to the empirical literature of scenario energy modelling was derived through the recalibration of the 2050 Energy Calculator in order to permit the inclusion of fusion power into the UK's future energy mix. This chapter's new "Fusion Pathway" consisted of energy, economic and GHG emissions estimates that were compared to two existing expert pathways in order to determine the most competitive future energy pathway. There were similarities in the demand assumptions between the Fusion Pathway and the expert pathway from National Grid plc but strong differences in the supply assumptions. The expert pathway from Friends of the Earth was based on completely different assumptions to the other two, which impacted the results and lessons learnt. Nevertheless, each of the three pathways requires a complete restructuring of the energy system in order to successfully meet the challenges that emerge with energy efficiency improvements, increased electrification, environmental protection, energy security and cost control.

The National Grid Pathway ensures a steady path towards electrification of homes, businesses and transport while maintaining sufficient supply capabilities to meet the needs of energy consumers. The results of the analysis show a good sense of cost control in their expenditure on capital, operating and fuel costs while reducing the 1990 GHG emission levels to 83% by 2050. The Friends of the Earth Pathway has exceeded all the expectations of the Climate Change Act (2008) with a 96% reduction on 1990 GHG emissions by 2050. This pathway greatly increases installed energy capacity of a wide range of renewable energy sources and CCS throughout the course of the projection time period but sacrifices cost containment as an objective, which may subsequently lead to public discontent through significance increases in household energy bills and environmental taxes. There is also a question mark in relation to the financial viability of the Friends of the Earth Pathway as such a large energy investment programme would seemingly be undeliverable without excessive amounts of investment and debt with potentially high gearing ratios.

On the other hand, the new Fusion Pathway delivers a strong performance in energy supply due to the impact of the potential introduction of fusion power towards the end of the projection period. This potential new input of high-volume, decarbonised fusion electricity enables the percentage share of the energy mix to be reconfigured in favour of high offshore wind, nuclear and CCS at the expense of electricity sources with uncertain high-volume capacities such as wave, tidal and solar PV. The energy needs of domestic, commercial and industrial consumers are met and the decarbonisation target is reached in 2050 with an 81% reduction on 1990 levels. Crucially, the Fusion Pathway is shown to have the strongest economic performance by far amongst the three pathways with a £16bn a year saving over the National Grid and a £54bn a year saving over the Friends of the Earth Pathway by 2050. Fusion power's LCOE of £0.04/kWh in 2050 is not only competitive within the UK's energy mix but also against the LCOE values of high-volume electricity sources across the EU, as highlighted in the IEA (2010a) projections.

Despite the many strengths of the 2050 Energy Calculator, there are important limitations to its modelling approach. The model has a strong UK focus, which implies that the model neither considers the emissions from the overseas generation of UK energy imports nor does it take into account the emissions generated from the manufacture of imported products. HM Government (2010) highlighted the model's omission of important feedback effects between different energy trajectories and the wider economy as there are cost implications and knock-on effects that result from changes within the energy mix. The 2050 Energy Calculator (as in all models) might also produce output that diverges to varying degrees from the actual data. For example, the Digest of the United Kingdom Energy Statistics from the Department of Business, Energy and Industrial Strategy (BEIS, 2015) shows that the total electricity supplied from "all generating companies" reached 322.4 TWh in 2015 and total electricity consumption from all sectors of the economy was 310.6 TWh in the same year. This is roughly comparable to the 2015 projections from the Fusion Pathway at 366.3 TWh (+43.9) and 341.3 TWh (+30.7) respectively. On the other hand, the total actual primary energy consumption from all users in 2015 was 137.43 Mtoe (1,598.3 TWh) whereas the 2015 projection in the Fusion Pathway shows a greater degree of divergence at 1,774 TWh (+175.7).

Other cost considerations omitted from the model include the mathematical impacts on energy bills, the climate change costs avoided through CO_2 emissions abatement, the cost interplay between energy demand and supply, the effects of environmental tax policy and the level of sustainable government funding for R&D in nascent energy technologies, especially for fusion power. There is also an ignorance of the volatile nature of some economic assumptions such as oil prices, so newer projections based on fresher data may provide results that are skewed from the previous projections that were carried out. Furthermore, the long-term commercial viability of the Fusion Pathway principally depends on the medium-term technological developments in plasma physics and power plant engineering. For example, the plasma energy breakeven point occurs where the output energy from the plasma at least matches the input energy that is used to produce the plasma in the first place. This breakeven point is yet to be achieved as the JET fusion reactor at the UKAEA site in Oxfordshire only produced 16MW of energy from 24MW of input power. The ITER fusion reactor in France is designed to produce 500MW of energy from 50MW of input power so the technical viability of ITER's energy conversion efficiency would needed to be demonstrated in future.

The UK's vote to leave the European Union during the 2016 Referendum is currently in the process of being enshrined in law through the European Union (Notification of Withdrawal) Bill 2017. This bill also provides for the UK's withdrawal from EURATOM as it is governed by EU institutions, including the European Court of Justice (Lang et al, 2017). Apart from third-party nuclear cooperation and fissile materials agreements that the EU possesses, the potential impact of the UK's withdrawal from EURATOM on the 2050 Energy Calculator are unquantifiable at this stage.

The European Parliament (2016) describes how the realisation of a fully integrated EU "Energy Union" (especially in the gas and electricity markets) is expected to lead to "*more competitive energy prices for both households and industries*", with the aim of boosting economic competitiveness within the EU. Non-British participation in the Energy Union may cause a divergence in the cross-border energy regulatory regimes and a skewing of the long-run total energy supply curve in the 2050 Energy Calculator. EU state aid rules on energy infrastructural investment may also cease to apply to the UK if it refrains from membership of the European Economic Area (Cyndecka, 2017), although the UK would still be subject to WTO state subsidy rules on energy infrastructural investment. The UK's withdrawal from the EU/EEA may therefore lessen the future emphasis on a highly decarbonised future energy mix within the 2050 Energy Calculator as the UK may decide to abolish the renewable energy targets that were highlighted in the EU's Renewable Energy Directive (Eur-Lex, 2009).

Nevertheless, the recalibrated 2050 Energy Calculator clearly demonstrates the strong role that fusion power could potentially play towards the end of the projection period and it is expected that the potential deployment of fusion power plants beyond 2050 would gain much stronger public support than the future installation of new-build nuclear fission power plants. This is especially considering the extra cost savings that may result from the technological refinements in plasma physics and engineering from mature fusion power plants. Future areas of research with the 2050 Energy Calculator could focus on further integration of the UK government's fusion R&D investment strategy with other nations in order to manifest the fast-track route to fusion power commercialisation. Future research should further involve the development and testing of new criteria that would enhance the understanding and impact of each of the energy mix pathways on energy prices and other criteria that are not currently part of the 2050 Energy Calculator's procedures. From an EU withdrawal perspective, UKAEA could consider the Switzerland model as a EURATOM-affiliated fusion R&D laboratory. However, further investigations on the general impact of the UK's withdrawal from EURATOM are required in order to provide the 2050 Energy Calculator with continuous updates on the fusion R&D trajectory towards 2050.

CHAPTER 5

MULTIEQUATION MODELLING: THE IMPACT OF FUSION POWER ON THE UK'S ECONOMIC PROJECTIONS FOR 2050

5.1 Introduction

The previous chapter focused on the long-term projections of the UK's energy mix towards 2050, based on three competing scenarios: the National Grid Pathway, the Friends of the Earth Pathway and the Fusion Pathway. Each of the three scenarios produced estimates of the energy system's supply and demand projections that would enable the UK to meet its decarbonisation target of an 80% reduction in GHG emissions by 2050 relative to 1990 levels. Estimates were also generated of the future projected costs of capital expenditure, operations and primary fuel inputs in accordance with the optimal energy mix strategy that was deemed appropriate. The implication was that appropriate levels of investment were required for the energy system in order to not compromise the competitiveness of the industrial sectors as they are crucial to the long-term sustenance of economic growth and employment. The Fusion Pathway provided a configuration of the energy system with the lowest cost outlay between the three pathways so it would be necessary to understand whether this minimum cost route had beneficial synergies with the performance of other critical elements of the economy.

The UK Government's role was also fundamental to the successful implementation of the long-term decarbonisation agendas of the three pathways. The role of industry and government towards the realisation of each pathway would inevitably require economic adjustments to areas such as government expenditure, environmental taxes and trade competitiveness. These adjustments would need to be considered within the wider context of the economic environment in 2050, which not only represents the UK's decarbonisation target year but also the period of commercialised fusion power. This leads us to two principal questions: (1) What estimates could be generated towards 2050 that would enable reasonable inferences of the British economy to be made? (2) How can we estimate the wider impact of the energy mix pathways on these long-term estimates of the future economic environment?

This chapter addresses the first question through the estimation of time series econometric models, with its structure describing the relationship between the current value of an endogenous variable and the lagged value(s) of itself. However, estimating the long run direction and dynamics of economic phenomena is an intricate process as there are many interrelated and unobservable forces that could underpin the stochastic elements between variables. Shocks to economic variables through policy changes and external market forces could also induce effects that have indeterminate time lags, thereby obscuring the long run expectation of forecasted variables. Therefore, multivariate econometric methods that are grounded in economic theory could not only quantify viable relationships between variables but could also produce forecasts that enable more realistic inferences to be made than forecasts estimated by univariate models.

Multivariate econometric analysis in the context of this chapter should determine the predictive quality of the models under consideration prior to the estimation of long run projections of the future economic environment. Based on this feature, this chapter provides an empirical contribution to the literature by extending the use of Johansen's (1988, 1991) maximum likelihood (ML) estimator of cointegration analysis and the vector error correction model (VECM) towards the estimation of five theoretical relationships that encapsulates the UK's economic activity, with projections made towards 2050. The literature in this field is noticeably scarce and this analysis goes further than previous studies of univariate econometric projections toward 2050 such as Moore (2011) and Fouré et al (2010) as the VECM projections are intended to provide more plausible results based on the perceived interdependencies between the variables.

The second question is addressed through the use of a computable general equilibrium (CGE) model as it could reveal the feedback effects from specific shocks and energy policy changes across sectors. One sub-section of the CGE analysis considers the effect of indirect taxes and its constituent, environmental taxes. There is a significant body of literature in the CGE space that assesses the economic impact of environmental taxes on CO_2 emissions abatement. These studies used CGE models that were underpinned by theoretical frameworks at varying degrees of disaggregation such as the Input/Output cost-push framework in Hamilton and Cameron (1994) and Beauséjour et al (1992), the static ORANI framework in McDougall (1993) and the MSG-EE framework in Alfsen et al (1996). The general theme from these studies was that environmental tax shocks had a distortionary effect on economic variables such as real GDP, output prices and industrial production. However, the CGE models in these studies applied environmental taxes as the primary economic shock, which is inappropriate as Bowen and Stern (2010) suggest that in principle, environmental taxes would generally act as adjustments in response to an economic and/or environmental shock.

This chapter focuses on the use of a CGE model that follows the Salter-Swan framework in order to assess the economic implications of the cost projections from the Friends of the Earth and Fusion pathways in 2050, with the National Grid Pathway acting as the reference pathway. The Salter-Swan framework consists of a basic structure that not only captures the relationship between shocks and policy responses but also highlights an abundant array of issues. The cost projections from each energy mix pathway act as shocks to certain economic variables. The policy responses are the adjustments to equilibrium that are triggered and are specifically focused on international trade via the current account variable on the balance of payments and environmental taxes via the indirect tax variable. This section follows the use of the CGE model with the Salter-Swan framework in Thierfelder and Robinson (2002) for their assessment of the economic effects of international trade.

The CGE model would also permit the assessment of the "double dividend" hypothesis, which suggests that increases in environmental taxes that are designed to reduce industrial pollution provide two kinds of benefits: The first dividend being the actual reduction in greenhouse gas emissions and improved environmental preservation, the second dividend being a reduction in other disproportionate taxes that could distort the labour supply such as income tax. The assessment of the double dividend in this context follows Bovenberg and de Mooij (1994), who used a simple general equilibrium model in a representative two-good economy to assess the existence of the double dividend from environmental taxes.

The contribution from the CGE model section is therefore an empirical analysis that extends the CGE modelling framework towards a scenario where differing energy mixes can compete for influence over the economic policies that are set and implemented by the UK Government and its agencies. The focus on shocks and the policy response adjustments from the current account and indirect taxes (including its environmental tax constituent) are important as they would provide insights into the potential future direction of industrial productivity, trade policy and international competitiveness. The literature in this field tends to focus on environmental taxes as a primary shock so this chapter aims to address the gap in the literature that does not account for environmental taxes acting as an adjustment to the primary economic shock.

The combination of univariate econometric projections of environmental-economic variables towards 2050 and the Salter-Swan framework for CGE modelling can be found in Moore (2011). This chapter extends this process with the econometric projection of five multivariate relationships towards 2050 and a broader economic shock and adjustment assessment in the CGE model. The next section aims to determine the theoretical relationship between the variables in each of the five economic relationships prior to the estimation and analysis of the multivariate econometric models. Real gross domestic product at market price is the ubiquitous endogenous variable and is modelled with its constituents as well as with direct and indirect tax variables, general fiscal variables and current account variables from the balance of payments.

5.2 Theoretical relationships between the variables

5.2.1 GDP: Export-led growth and import-led growth hypotheses

There are a plethora of studies that seek to determine the relationship between economic growth and exports. The export-led growth hypothesis (ELG) suggests that a country's economic growth is not solely boosted by increases in the level of investment, capita flows and labour productivity but also by increases in exports. This engine of economic growth could be accredited to factors such as the greater cooperation in world markets through free trade, investment in technology and expansions of a company's production through economies of scale. However, Rodriguez and Rordik (2000) conducted an analysis of existing empirical studies between trade openness and economic growth. They found that although an open trade policy can be beneficial to growth, caution should be exercised in this assumption as there are apparent differences between large and small countries and between countries with a competitive advantage in primary production and secondary production of manufactured goods.

There are also different directions of causality that are apparent in this relationship. The main outcomes that are estimated from this relationship are the export-led growth hypothesis (ELG), which is derived from the original findings from the works of Balassa (1978) and Thirwall

(1979)[13], and the growth-led export (GLE) hypothesis. Krugman (1989) argued that the GLE hypothesis was more appropriate than the ELG hypothesis based on the assumption that as countries specialise by enhancing their economies of scale, they achieve economic growth and expand their exports, thereby increasing their world market share in specific products and services. Studies such as Wong (2008) and Jarra (2013) also model the GLE relationship by including household consumption and government consumption as proxies for domestic demand.

Another associated relationship that features less prominently in the literature is the import-led growth (ILG) hypothesis. This stems from the assumption that limited factors of production in developing countries are the main driver of increased imports in intermediate goods and foreign technology, which subsequently spurs economic growth. However, Ogbonna (2015) implied that the ILG hypothesis does not hold for certain developing countries due to their inability to take full advantage of advanced imported technologies, corrupt procurement practices and poor maintenance culture. Conversely, the growth-led import (GLI) hypothesis could emerge if internal growth in resource-rich countries stimulates demand for luxury imports. Developed countries that are resource-poor such as Japan and South Korea also display the "extreme importer" behaviour that is necessary to maintain adequate levels of economic growth (Davis, 2009).

5.2.2 Tax Revenue: The effect of tax shocks on GDP and investment

There is a broad consensus in the empirical literature concerning the effect of tax shocks to GDP. The general assumption is that shocks to direct taxes such as income and corporation tax and indirect taxes such as environmental tax have a negative effect on macroeconomic variables. Studies such as Mountford and Uhlig (2005) found that spending increases financed by tax increases from a balanced-budget government would correspond to a decrease in GDP. On the other hand, they found that a tax cut in an unchanged spending scenario financed by a budget deficit only corresponds to a moderate short-term increase in GDP, albeit with a higher debt burden and long-term negative risks that could outweigh the short-term stimulus effect.

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[13] Thirwall's law (Thirwall, 1979) stipulated that if equilibrium of a country's balance of payments is to be achieved, then "*a country's long run growth rate can be approximated by the ratio of the growth of exports to the income elasticity of demand for imports*".

Concerning the individual components of GDP, Mountford and Uhlig (2005) concluded that spending increases financed by higher taxes would negatively affect investment. This was similar to the conclusion reached in Blanchard and Perotti (2002), who found that increases in taxes and government spending corresponded to a decrease in investment spending. However, higher taxes that finance higher government spending would correspond to an increase in household consumption, which leads to a fall in exports. Blanchard and Perotti (2002) highlighted the slow reaction of some macroeconomic variables to fiscal policy shocks. This assumption was also determined in Kaliontzakis (2015), who noted that while fiscal shocks had a long-term effect on most macroeconomic variables, the opposite could be said concerning increases in government spending, which have a short-term effect.

5.2.3 Fiscal account: The effect of fiscal consolidation on economic growth

Fiscal consolidation involves a government's management of their current and capital expenditure in order to reduce a deficit or grow a surplus balance on their fiscal account. Current expenditure consists of government spending on wages, goods and services, interest payments on government debt, transfers and subsidies while capital expenditure consists of investment, development and upgrading of long-term assets and infrastructure.

A large body of the empirical literature supports the idea that spending-based fiscal consolidation has a beneficial effect of on economic growth (Princen and Mourre, 2013; Alesina et al, 2015; Yang et al, 2015). For example, Von Hagen and Strauch (2001) finds that successful fiscal adjustments that benefit economic growth can only occur where a government is committed to spending reductions on politically sensitive sections of current expenditure such as government wages, transfers and subsidies[14]. Mody and Rebucci (2006) also show that reductions in current expenditure have a stronger effect on economic growth than adjustments that increase government revenues.

There are also costs and impacts to investment that are incurred by countries with poor fiscal consolidation programmes. Cournède et al (2014) demonstrated that among a basket of OECD countries, fiscal consolidation was required in order to curb the large costs associated with debt expansion. They implied that failure to balance an increase in taxes with appropriate

[14] Von Hagen and Strauch (2001) emphasise the importance of timing in any fiscal consolidation programme with the suggestion that a greater probability of success occurs during bleak domestic and international economic conditions.

spending cuts in a budget deficit environment would hinder short-term demand and undermine long-term economic growth. Easterly et al (1994) also indicate that the taxation of financial assets to finance budget deficits through the issuance of domestic debt can negatively affect investment. They imply that the expansion of large fiscal deficits and their associated costs only serves as a policy instrument rather than as a response to the domestic economic situation. Furthermore, the IMF (2016) indicated that the post-financial crisis output gaps in many advanced economies were created by "debt overhangs" and low productivity growth, which hindered investment.

5.2.4 Balance of payments: The effect of GDP on the current account balance

The UK's large current account deficit on the balance of payments has been the topic of intense public debate for a number of years. The persistent nature of the UK's current account deficit has confounded the intertemporal models of a nation's current account, which assume that large current account imbalances should not persist over the long run once the short run shocks that triggered the large imbalances have evaporated (Obstfeld and Rogoff, 1996; Kraay and Ventura, 2000). Adjustments to the current account are implemented by domestic agents who focus on smoothing consumption to a stable path, which enables the current account to thereafter return to its long run sustainable level.

The UK's current account balance stood at -5.7% of GDP as off 2015 and has consistently stuck below the 0% level in every year since 1987. There are a number of factors that could explain the trend in this deficit such as the large trade deficit in goods, which stems from the steady decline in manufacturing activity. The decline in manufacturing coincided with the decline in manufacturing jobs from a peak of 9 million in the 1960s to less than 3 million jobs as of 2013 (Fothergill and Gore, 2013). The growth in EU and non-EU migration into the UK has also had an impact on the negative current account balance through the gradual increase in the net private transfer deficit. Furthermore, the current account is impacted by the decline in private savings as post-financial crisis governments in the developed world had tried to revive growth through low interest rates (Belke, 2013).

There are a limited number of studies that assess the theoretical relationship and direction of causality between economic growth, the current account balance and the net trade position of a country. There are also a range of EU countries whose current account positions are in long term surplus such as Germany, Sweden and Denmark and long term deficit countries such as the UK, France and Italy (Europa, 2016), which makes it difficult to determine a general consensus of the relationships between the variables. Thomas (2015) sought to explore the effect on India, which has a similar long-term current account deficit to the UK and found that economic growth corresponded to a decrease in the current account balance in the long run. However, he also found that an increase in net trade in services and economic growth corresponded to an increase in the current account balance in the short run. Similarly to Thomas (2015) but in reverse, Edwards (2007) found that a decline in economic growth corresponded to an increase in the long run current account balance in the US, Europe and Japan. Those results indicated that reductions were needed in the current account surpluses of countries such as China and Germany in order to contribute towards the current account imbalances in the US, UK and other countries within the EU.

5.3 Methodology 1: Cointegration and vector error correction model (VECM)

In Chapter 3, the properties of economic time series were explored based on the concept of stationarity. Standard regression techniques require that variables exhibit a level stationary process i.e. integrated of order zero or $I(0)$. However, a vast number of economic time series show the presence of a unit root, which causes a violation of stationarity, thereby potentially rendering the variable as integrated of order one i.e. the variable is stationary at its first difference. As highlighted in Chapter 3, ignoring the presence of $I(1)$ variables in a standard regression model such as ordinary least squares (OLS) could lead to the generation of spurious regressions.

Granger and Newbold (1974) demonstrated through Monte Carlo analysis that the outputs produced by these regressions were deemed to be statistically invalid, with spurious correlations that were unviable for economic analysis. This has a knock-on effect on any forecasts that are produced from these models as they would be deemed to be suboptimal. They argued that although one could alleviate model misspecification by using the first difference of a non-stationary variable, it may not completely remove the problem. The asymptotic theory that supported the Granger-Newbold experiments was proposed by Phillips (1986), who showed that $I(1)$ variables in a regression do not have the typical asymptotic properties. Furthermore, first differencing of variables in a multivariate regression model may remove important information that could add value to the understanding of relationships between non-stationary variables.

The concept of cointegration, which was proposed in Granger (1981) and formalised in Engle and Granger (1987), was designed to overcome this problem as it promotes the estimation of viable relationships between non-stationary variables. Essentially, two or more non-stationary, $I(1)$ variables in a multivariate group are said to be cointegrated if a linear combination of these variables are stationary in the long run. This means that the cointegrating variables do not drift too far apart as underlying economic forces would draw these variables into a long run equilibrium relationship. An error correction model (ECM) acts as an adjustment mechanism in the short run to converge the cointegrating variables towards their long run equilibrium relationship. Therefore, cointegration modelling is a particularly powerful tool to analyse the dynamic behaviour of $I(1)$ cointegrating variables in the short run and the correction towards an equilibrium relationship in the long run.

In Chapter 3, the variables were tested for the presence of a unit root using the augmented Dickey-Fuller (ADF) and Dickey-Fuller Generalised Least Squares (DF-GLS) tests. Cointegration analysis was performed using the autoregressive distributed lag model (ARDL) with evidence shown of the existence of cointegration within this single equation method. The long run equilibrium relationship was established and short run dynamics were estimated through a restricted ECM. The estimates provided by the single cointegrating equation were subsequently derived and the economic relationships between the variables in the short and long run were evaluated.

The single equation approach of the ARDL model used in Chapter 3 is generally suitable where there is only one cointegrating relationship in a model. However, a multivariate model may contain different interplays between variables and this could result in the discovery of more than one cointegrating relationship. This results in a dual problem as the critical values in Pesaran, Shin and Smith (2001) would be incompatible with the cointegration testing procedure and valuable information from additional cointegrating vectors would be unavailable for analysis. Another limitation of the single equation approach is that the results are more reliable if the independent variables are weakly exogenous as endogenous variables may render the model inefficient due to the loss off information from the conditioning of the model. Therefore, a system of equations that would allow $I(1)$ endogenous variables to act as a dependent variable would be appropriate as it would mitigate the loss of information that could manifest in the single equation approach.

One such system of equations is found in the form of a vector autoregression (VAR), which offers a strong alternative to the single equation approach. Sims (1980) is viewed as one of the early leading advocates of the VAR model as an alternative representation to the traditional multivariate simultaneous equation models that were used at the time. A development of the VAR model is the vector error correction model (VECM), which is a restricted VAR that is used for $I(1)$ variables that are identified as cointegrated. A desirable aspect of the VECM is that it restricts the long run path of the endogenous $I(1)$ variables towards their cointegrated relationship through the implementation of dynamic adjustments in the short run.

This section discusses the features of the maximum likelihood estimator method of cointegration analysis developed by Johansen (1988, 1991) and the VECM methodology as they are both used to analyse the economic variables in each of theoretical relationships highlighted in section 5.2. Alongside the cointegration and VECM analyses, a brief summary of Granger causality results are given for each of the models in order to assess the direction of causality between the variables. Granger causality was covered extensively in Chapter 3 and the results from the Wald test are based on the specification in section 3.4.4. Finally, long-term econometric projections are produced from the VECMs and the projected estimates for 2050 are inputted into a CGE model for further analysis.

5.3.1 Johansen's maximum likelihood (ML) estimator for cointegration analysis

The Johansen (1988, 1991) test for cointegration is based on the maximum likelihood (ML) estimator, which enables a model to be tested for all cointegrating vectors where more than two variables are present. For example, if a model had three $I(1)$ variables, the maximum cointegrating vectors that could be present are two and if there are K $I(1)$ variables, then there could be a maximum of $K-1$ cointegrating vectors. The starting point for cointegration analysis involves the consideration of a VAR(p) model:

$$\mathbf{y}_t = \mathbf{v} + \mathbf{A}_1\mathbf{y}_1 + \mathbf{A}_2\mathbf{y}_2 + \cdots + \mathbf{A}_p\mathbf{y}_p + \boldsymbol{\varepsilon}_\mathrm{t} \qquad (5.1)$$

where $\mathbf{y}_t$ is a $K \times 1$ vector of $I(1)$ variables, $\mathbf{v}$ is a $K \times 1$ vector of intercepts, $\mathbf{A}_1 - \mathbf{A}_p$ are $K \times K$ matrices of parameters and $\boldsymbol{\varepsilon}_\mathrm{t}$ is a $K \times 1$ vector of i.i.d error terms with a mean of 0 and a covariance matrix $\boldsymbol{\Omega}$. The VAR can be rewritten into a VECM:

$$\boldsymbol{\Delta}\mathbf{y}_t = \mathbf{v} + \boldsymbol{\Pi}\mathbf{y}_{t-1} + \sum_{\mathrm{i}=1}^{p-1} \boldsymbol{\Gamma}_\mathrm{i}\boldsymbol{\Delta}\mathbf{y}_{t-i} + \boldsymbol{\varepsilon}_t \tag{5.2}$$

where:

$$\boldsymbol{\Pi} = \sum_{i=1}^{p} \mathbf{A}_\mathrm{i} - \mathbf{I} \text{ and } \boldsymbol{\Gamma} = -\sum_{j=i+1}^{p} \mathbf{A}_j \tag{5.3}$$

where $\mathbf{I}_{\boldsymbol{K}}$ constitutes an identity matrix of order $K \times K$. If the K vector of variables $\mathbf{y}_t$ are $I(1)$, then the long run cointegrating vector in coefficient matrix $\boldsymbol{\Pi}$ must be $I(0)$ in order for $\boldsymbol{\varepsilon}_t$ to be a white noise. Engle and Granger (1987) demonstrated that if the $\mathbf{y}_t$ vector in equation (5.2) are $I(1)$ variables, the coefficient matrix $\boldsymbol{\Pi}$ experiences a rank of $0 \leq r < K$, where r is the number of cointegrating vectors within the model. If cointegration exists within the $\mathbf{y}_t$ vector, then model misspecification occurs if a VAR(p) is fitted in first differences as the $\boldsymbol{\Pi}\mathbf{y}_{t-1}$ term is omitted from equation (5.2). $\boldsymbol{\Pi}$ can be defined as $\boldsymbol{\Pi} = \boldsymbol{\alpha}\boldsymbol{\beta}'$, where $\boldsymbol{\alpha}$ is the speed of adjustment matrix and $\boldsymbol{\beta}$ are the parameters of the cointegrating vectors. For example, if $\mathbf{y}_t$ consists of three variables and $r = 1$, then vector $\boldsymbol{\alpha}$ and vector $\boldsymbol{\beta}$ are 3×1. This means that there are 3 adjustment parameters for each of the three equations, which are multiplied by the single cointegrating vector $\boldsymbol{\beta}'\mathbf{y}_{t-1}$ in order to respond to deviations from the long run equilibrium relationship.

It can be demonstrated that for any given r, the ML estimator of $\boldsymbol{\beta}$ is based on the combination of $\mathbf{y}_{t-1}$ that yields the largest cointegrating canonical correlations of $\Delta\mathbf{y}_\mathrm{t}$ with $\mathbf{y}_{t-1}$ after correcting for the presence of any deterministic variables and lagged differences. On the other hand, if the vector $\mathbf{y}_t$ is $I(1)$ but not cointegrated, then $\boldsymbol{\Pi}$ is a matrix of zeros with a rank of 0 and the result of the relationship is a VAR in first differences i.e. the $\boldsymbol{\Pi}\mathbf{y}_{t-1}$ term is omitted from equation (5.2). One way of viewing this test is to assess the null hypothesis H_0 of $\text{rank}(\boldsymbol{\Pi}) = 0$ against the alternative being $\text{rank}(\boldsymbol{\Pi}) \neq 0 = r,$ with $K - 1$ being the maximum rank if $I(1)$ variables are present and K being the maximum rank if all variables are $I(0)$.

Johansen's ML estimator is widely considered to be the preferred method of cointegration analysis with many econometricians as it is capable of estimating multiple cointegrating equations. This contrasts with other cointegration methods such as the Engle-Granger two-step and Pesaran-Shin-Smith ARDL-bounds testing approaches, which can only estimate one cointegrating equation per model. Estimates of the cointegrating vectors and speed of adjustment coefficients are asymptotically efficient in Johansen's test and there are no real concerns over whether the independent variables are exogenous or endogenous. Johansen and Juselius (1994) also demonstrate the possibility of imposing linear restrictions on the cointegration vector and speed of adjustment coefficients in Johansen's test in order to assess different economic hypotheses[15].

However, there are a number of limitations that are related to this procedure. For example, Johansen's test is static in nature and is unable to predict future cointegrating relationships among variables. Cheung and Lai (1993) showed that finite-sample bias could manifest where estimates are biased towards a cointegration result in more situations than the asymptotic theory suggests and the problem is especially amplified when the lag length increases. The spurious cointegration problem could also arise where test estimates could result in size distortions i.e. the false rejections of a true null hypothesis of no cointegration. Huang and Yang (1996) carried out Monte Carlo analysis to test the long-run purchasing power parity (PPP) hypothesis between developed countries and found that the results might be biased towards a spurious cointegrated vector if the residuals veer away from the independent and identically distributed assumption (i.i.d). The spurious cointegration problem was also found by Gonzalo and Lee (1998), who argued that the problem could be more serious as the sample size tends towards infinity.

5.3.2 Trace test and maximum eigenvalue test for cointegration analysis

Johansen's tests for cointegration are based on eigenvalues that are non-negative and non-zero. Eigenvalues are special scalars that are based on transformations of the data and they represent linear combinations of data that consist of the maximum canonical correlations. Let us first

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[15] Estimates of the adjustment parameter and cointegrating relation involve a series of iterations. When linear restrictions are indicated, the switching algorithm specified in Boswijk (1995) is used to increase the log likelihood function towards its maximum level in order to produce an analytical solution for the estimates of the parameters.

consider the companion matrix **A** from equation (5.3), which can be written using matrix algebra:

$$\mathbf{A} = \begin{pmatrix} A_1 & A_2 & \cdots & A_{p-1} & A_p \\ I_K & 0 & \cdots & 0 & 0 \\ 0 & I_K & \cdots & 0 & 0 \\ \vdots & & \ddots & \vdots & \vdots \\ 0 & 0 & \cdots & I_K & 0 \end{pmatrix} \tag{5.4}$$

Each element in **A** is of the order $K \times K$ so the matrix consists of K_p rows and K_p columns i.e. $K_p \times K_p$. Lütkepohl (2005) shows that under appropriate assumptions, the underlying VAR process satisfies the stability condition if all the eigenvalues in **A** have moduli (absolute values) that are strictly less than one. The set of eigenvalues for matrix **A** are given by the number of roots in the characteristic polynomial equation: $\det(\mathbf{A} - \lambda\mathbf{I}_\mathrm{K}) = 0$, where λ is an eigenvalue of **A** and det(.) represents the determinant of matrix $\mathbf{A} - \lambda\mathbf{I}_\mathrm{K}$.

The rank of $\mathbf{\Pi}$ matrix is based on the number of important eigenvalues found in $\hat{\mathbf{\Pi}}$ with each important eigenvalue representing a cointegrating vector. For example, let the K eigenvalues be ordered according to size with the largest first so that $\lambda_1 \geq \lambda_2 \geq \cdots \lambda_k$. If $H_0\colon \lambda_1 = 0$, then there are no cointegrating vectors i.e. $\mathrm{rank}(\mathbf{\Pi}) = 0$ but if $H_1\colon \lambda_1 \neq 0$, then there is at least one cointegrating vector in the model i.e. $\mathrm{rank}(\mathbf{\Pi}) > 0$. The assessment then goes to $H_0\colon\ \lambda_1 \leq \lambda_2$, with $H_0\colon \lambda_2 = 0$ denoting the settled $\mathrm{rank}(\mathbf{\Pi}) = 1$ and $H_1\colon \lambda_2 \neq 0$ denoting that $\mathrm{rank}(\mathbf{\Pi}) > 1$. The ML estimators for the parameters in equation (5.2) were derived by Johansen (1995), who proposed two likelihood ratio tests: the trace test and the maximum eigenvalue test

The trace test assesses whether the rank of the coefficient matrix is $\mathbf{\Pi}$. The beginning of the test assesses the null hypothesis $H_0\colon \mathrm{rank}(\mathbf{\Pi}) = 0$ against the alternative $H_1\colon 0 < \mathrm{rank}(\mathbf{\Pi}) \leq K$. Rejection of the null hypothesis would require one or more subsequent tests to determine the total number of cointegrating vectors, starting with $H_0\colon\ \mathrm{rank}(\mathbf{\Pi}) = 1$ against $H_1\colon 1 < \mathrm{rank}(\mathbf{\Pi}) \leq K$. The statistic from the likelihood ratio test is derived from the following equation:

$$LR_{trace}(r|k) = -T \sum_{i=r+1}^{k} \ln(1 - \hat{\lambda}_i) \tag{5.5}$$

where LR_{trace} is the likelihood ratio test statistic for testing $H_0: \text{rank}(\mathbf{\Pi}) = r$ against $H_1: \text{rank}(\mathbf{\Pi}) \leq K$, T is the number of observations and $\hat{\lambda}_i$ is the i-th largest eigenvalue from the $\mathbf{\Pi}$ matrix in equation (5.2). For example, testing the null hypothesis for $\text{rank}(\mathbf{\Pi}) = 2$ against the alternative $\text{rank}(\mathbf{\Pi}) \leq K$ is given by the equation $LR_{trace}(2|k) = -T\sum_{i=2}^{k} \ln(1 - \hat{\lambda}_i)$. The trace statistic does not follow an asymptotic chi-squared (χ^2) distribution but is based on the function of the Brownian motion[16]. Furthermore, the critical values are based on a Dickey-Fuller pure unit root inference. The issue with this is that the critical values used in the test would no longer be appropriate for near unit root processes, so there could be a question mark concerning the sensitivity of the trace test results with variables with near unit root processes[17].

The maximum eigenvalue test assesses the null hypothesis of whether the largest eigenvalue is equal to zero against the alternative hypothesis, which is that the next largest eigenvalue in sequence is equal to zero. This means that the first test assesses $H_0: \text{rank}(\mathbf{\Pi}) = 0$ against $H_1: \text{rank}(\mathbf{\Pi}) = 1$. Rejection of the null means that the largest eigenvalue λ_1 is not zero and there could be one or more cointegrating vectors and so the new null is proposed for λ_2 i.e. $H_0: \text{rank}(\mathbf{\Pi}) = 1$ against $H_1: \text{rank}(\mathbf{\Pi}) = 2$. This continues until the null hypothesis that $\lambda_{k\text{th}}$ eigenvalue is zero can no longer be rejected. The statistic from the maximum eigenvalue test can be derived from the following equation:

$$LR_{max}(r, r+1) = -T\ln(1 - \hat{\lambda}_{r+1}) \tag{5.6}$$

where LR_{max} is the likelihood ratio test statistic for testing $H_0: \text{rank}(\mathbf{\Pi}) = r$ against $H_1: \text{rank}(\mathbf{\Pi}) = r + 1$. Similarly to the trace test, the test statistic does not follow an asymptotic χ^2 distribution as it is technically a multivariate version of the unit root distribution from the Dickey-Fuller test. However, differences between the trace and maximum eigenvalue tests were demonstrated by Cheung and Lai (1993), who found the trace statistic results to be more robust than the maximum eigenvalue statistic where the residuals are non-normal with an excessive kurtosis (fat tail). Lütkepohl et al (2000) also used Monte Carlo analysis to assess the performance of the trace and maximum eigenvalue statistics with small sample sizes. The authors found that in some cases, the trace test performed better than

[16] A Brownian motion is a continuous stochastic process. See Johansen (1991) for more information on the asymptotic distribution of the trace statistic, which can be expressed in terms of a Brownian motion.
[17] Elliot (1998) provides more information on the inferences that could be drawn from long run relationships between variables with near unit root processes.

the maximum eigenvalue test in terms of power, especially where the true rank of $\mathbf{\Pi}$ exceeds the null hypothesis rank r by more than one. The implication is that if the results between the trace and maximum eigenvalue tests are ambiguous, then the trace test result should be preferred.

5.3.3 Trend specification for Johansen's cointegration test and VECM

An important consideration in Johansen's cointegration test and subsequent VECM concerns the nature of any deterministic terms to include in the estimation process. Deterministic trends could be present in both the cointegrating vector and in the mean of the first differenced variables. Where the variables are at level, the intercept term $\mathbf{v}$ from equation (5.2) indicates the presence of a linear trend and the inclusion of a time trend term $\boldsymbol{\delta t}$ indicates the presence of a quadratic trend. The inclusion of a trend follows the inherent data pattern, for example, two variables may share a linear trend but a combination of both variables do not trend as they offset against each other. The cointegrated vector would therefore have no trend even though they are both trending individually. Similarly, if a combination of two variables offsets a quadratic trend, then there is the flexibility to adjust the model in order to include an intercept and trend.

Based on the speed of adjustment matrix $\boldsymbol{\alpha}$ in the VECM, the linear trend can be rewritten as $\mathbf{v} = \boldsymbol{\alpha\mu} + \boldsymbol{\gamma}$ and the time trend can be rewritten as $\boldsymbol{\delta t} = \boldsymbol{\alpha\rho t} + \boldsymbol{\tau t}$. The properties of $\boldsymbol{\alpha\mu}$ are orthogonal to $\boldsymbol{\gamma}$ and the properties of $\boldsymbol{\alpha\rho}$ are orthogonal to $\boldsymbol{\tau}$ such that the inner product of these two elements of the linear and time trends are equal to zero i.e. $\boldsymbol{\gamma}'\boldsymbol{\alpha\mu} = 0$ and $\boldsymbol{\tau}'\boldsymbol{\alpha\rho} = 0$. The VECM specification in equation (5.2) can now be rewritten with the inclusion of a time trend in the following equation:

$$\boldsymbol{\Delta}\mathbf{y}_t = \boldsymbol{\alpha}(\boldsymbol{\beta}'\mathbf{y}_{t-1} + \boldsymbol{\mu} + \boldsymbol{\rho t}) + \sum_{\mathrm{i}=1}^{p-1} \boldsymbol{\Gamma}_{\mathrm{i}}\boldsymbol{\Delta}\mathbf{y}_{t-i} + \boldsymbol{\gamma} + \boldsymbol{\tau t} + \boldsymbol{\varepsilon}_t \tag{5.7}$$

where $\boldsymbol{\mu}$ and $\boldsymbol{\gamma}$ are $r \times 1$ and $K \times 1$ vectors of intercept parameters respectively, and $\boldsymbol{\rho}$ and $\boldsymbol{\tau}$ are $r \times 1$ and $K \times 1$ vectors of time trend parameters respectively. Restrictions can be imposed on the deterministic elements of the cointegrating equation and underlying VAR model based on the following five cases from Johansen (1995):

Case 1 (no trend): $\boldsymbol{\mu} = 0, \boldsymbol{\gamma} = 0, \boldsymbol{\rho} = 0, \boldsymbol{\tau} = 0$. This option means that there is no intercept or trend in the cointegrating vector or VAR i.e. there is no growth and there is a zero mean in the cointegrating vector. Selection of this option would be very difficult to justify as it would imply that all measurements would start from a zero base.

Case 2 (restricted intercept): $\boldsymbol{\mu} \neq 0, \boldsymbol{\gamma} = 0, \boldsymbol{\rho} = 0, \boldsymbol{\tau} = 0$. This option has an intercept in the cointegrating vector but is restricted in the VAR. This implies that the only deterministic element in the model is a cointegrating vector that is stationary around a non-zero mean.

Case 3 (unrestricted intercept): $\boldsymbol{\mu} \neq 0, \boldsymbol{\gamma} \neq 0, \boldsymbol{\rho} = 0, \boldsymbol{\tau} = 0$. This option has an unrestricted intercept in the cointegrating vector and VAR but no time trend. This implies that the cointegrating variables are stationary around a non-zero mean and the levels of data consist of a linear time trend.

Case 4 (restricted trend):: $\boldsymbol{\mu} \neq 0, \boldsymbol{\gamma} \neq 0, \boldsymbol{\rho} \neq 0, \boldsymbol{\tau} = 0$. This option has an unrestricted intercept but a restricted trend in that the levels of the data are not quadratic. However, the cointegrating vector exhibits a trend stationary process.

Case 5 (unrestricted trend):: $\boldsymbol{\mu} \neq 0, \boldsymbol{\gamma} \neq 0, \boldsymbol{\rho} \neq 0, \boldsymbol{\tau} \neq 0$. This option means that the levels of data consist of an unrestricted, quadratic trend and the cointegrating vector is trend stationary. The main issue with this option is that out-of-sample forecasts produced with an unrestricted trend can be quite poor and the inferences drawn from the results based on the inclusion of an unrestricted trend could be problematic[18]

The inclusion of specific trends in the cointegrated and data spaces could be determined by economic theory. For example, if household incomes and expenditure are considered to be related, then a deterministic trend could be included in the cointegrating region of Johansen's test. In general, cases 1 and 5 would not typically be appropriate for estimation purposes as the underlying assumptions behind these options could be disproportionate to the data patterns found in most economic variables. A summary of the remaining three cases would be as follows: case 2 would be chosen for non-trending variables with an intercept restricted to the

[18] This is based on the Monte Carlo experiments performed by Doornik et al (1998).

cointegrating region, case 3 would be chosen for variables with stochastic trends and case 4 would be chosen if some of the variables exhibit a trend stationary process[19].

5.3.4 Johansen's identification and parameter restrictions in the VECM

Eigenvectors are a set of vectors that are connected to a linear system of equations such as a VAR and each coefficient matrix can be defined in terms of its eigenvalues $(\lambda_1 \geq \lambda_2 \geq \cdots \lambda_k)$ and associated eigenvectors $(\mathrm{V} = \mathrm{v}_1, \mathrm{v}_2 \cdots \mathrm{v}_k.)$ As previously mentioned, a cointegrating vector $\boldsymbol{\beta}$ would produce a non-negative, non-zero eigenvalue and the estimates of $\boldsymbol{\beta}$ are based on the corresponding eigenvector. The presence of a cointegrating vector would also render at least some of the adjustment parameters $\boldsymbol{\alpha}$ to be non-zero. Conversely, an eigenvector and by extension, a cointegrating vector is insignificant if the corresponding eigenvalue is insignificantly different to zero. Therefore, Johansen's ML estimator for $\boldsymbol{\beta}$ is calculated as the matrix of significant eigenvectors that correspond to the largest eignevalues within the scope of the cointegrating space.

The presence of a cointegrating vector within a vector of variables poses an identification problem because not all of the parameters in $\boldsymbol{\alpha}$ and $\boldsymbol{\beta}$ can be determined[20]. One could choose a non-singular $r \times r$ matrix $\boldsymbol{Q}$ such that $\boldsymbol{\Pi} = \boldsymbol{\alpha}\boldsymbol{\beta}' = (\boldsymbol{\alpha}\boldsymbol{Q})(\boldsymbol{\beta}\boldsymbol{Q}'^{-1})'$. However, the new estimates $\boldsymbol{\alpha} = \boldsymbol{\alpha}\boldsymbol{Q}$ and $\boldsymbol{\beta} = \boldsymbol{\beta}\boldsymbol{Q}'^{-1}$ are observationally equivalent and would not alter the value of the log likelihood function but the economic interpretations could be different. Another way of looking at this is that if a cointegrating vector exists, its identity is not unique as any scalar on $\boldsymbol{\beta}$ would still render the cointegrating vector to be integrated of order zero. In a bivariate model, the identification problem is solved by choosing which coefficient to normalise to unity. This subsequently provides the necessary restrictions on $\boldsymbol{\beta}$ for identification purposes. However, in a multivariate model with $r > 1$, each r would need a restriction in order for the identification process to occur.

The Johansen identification procedure (Johansen, 1995) is a widely used identification method which places r^2 number of independent restrictions on the parameters in $\boldsymbol{\beta}$, with one of the r

[19] It is important to use economic theory and graphical analysis to identify and select the trend specification from the onset. This is because the likelihood ratio test statistic for hypotheses about the cointegrating vector changes in accordance with the trend specification that is selected.

[20] A significant amount of interest has gone into the identification of cointegrated vectors from $I(1)$ variables; see Phillips (1991), Pesaran and Shin (1994), Johansen (1995) and Boswijk (1995).

restrictions provided by normalisation in each cointegrating vector. The r^2 number of restrictions is the same as providing $r + r(r-1)$ number of restrictions where r are the number of parameters used for normalisation[21] and $r(r-1)$ are the number of parameters used for identification in $\boldsymbol{\beta}$. The normalised parameters are set to unity and the identification parameters in an $r > 1$ scenario are restricted to zero, which effectively excludes them from $\boldsymbol{\beta}$. The number of free parameters to estimate in $\boldsymbol{\beta}$ is thus given by $n_{param} - r - r(r-1)$ where n_{param} is the total number of parameters in $\boldsymbol{\beta}$. Johansen's procedure produces the restrictions by assuming the cointegrating vectors and eigenvectors are proportional to each other in the $\mathbf{\Pi}$ matrix. This is mathematically ideal as this procedure causes the cointegrating vectors to be orthogonal to one another. However, the orthogonality restrictions in Johansen's procedure generates standard output that is theoretically arbitrary as the economic interpretations are unclear.

The r^2 restrictions are generally assumed to satisfy the conditions that produce the just-identified cointegrating vectors with $[n_{param} - r - r(r-1)]$ free parameters, which have vague economic interpretations. One could also seek more meaningful economic relationships between variables by either testing different just-identifying restrictions or over-identifying restrictions on the parameters of the cointegrating vector. An example could be an over-identifying restriction in a multivariate model that provides the freedom to focus on the proportionality between income and the demand for interest-bearing liquid assets. However, the number of free parameters in the over-identified cointegrating vectors falls below $n_{param} - r - r(r-1)$ and Johansen and Juselius (1994) observed that an increased restriction in the variation of the parameters' in $\boldsymbol{\beta}$ may result in a non-identification of the model. The validity of the over-identified restrictions can be tested using the Johansen and Juselius (1994) likelihood ratio statistic, which follows an asymptotic χ^2 distribution. This contrasts with a just-identified $\boldsymbol{\beta}$ as the orthogonality restrictions are not subject to any validation tests.

Variables within a cointegrated system are generally assumed to react to deviations from the long run equilibrium relationship. However, we may have certain doubts about the specific effect of an endogenous variable on a cointegrated system. We may want to test whether changes in the i-th endogenous variable respond to deviations from long run equilibrium by

[21] The r number of parameters used for normalisation in Johansen's identification procedure is equal to the r number of cointegrating vectors in $\boldsymbol{\beta}$.

restricting the speed of adjustment parameter in the *i*-th row of the $\boldsymbol{\alpha}$ matrix to zero. For example, if we are unable to reject the null hypothesis of $\boldsymbol{\alpha}_{i-\text{th}} = 0$ at the 5% significance level, then the *i*-th endogenous variable does not respond to deviations from long run equilibrium. The *i*-th endogenous variable is therefore confirmed as being '*weakly exogenous'* as the adjustments to long run equilibrium are performed by the other variables[22]. Similarly to an over-identified model, the null hypothesis of weak exogeneity could be tested through the likelihood ratio statistic. It is thereafter possible to produce estimates of the constrained VECM without reference to the $\boldsymbol{\alpha}$ parameter of an endogenous variable that is confirmed as weakly exogenous.

5.3.5 Forecasting macroeconomic data with a VECM

Time series forecasts provide useful quantitative estimates of future predictions based on theoretical and empirical knowledge of economic phenomena. The principal limitation of an econometric forecast is due to the immeasurable degree of uncertainty on what could happen in the future. However, Clements and Hendry (1998) describes the "measurable certainty" that is known due to the level of randomness that can be expected around a point forecast. This level of randomness is known as a forecast interval, which is similar to a confidence interval that contains a range of values that could possibly contain a population parameter at a certain probability. The forecast interval therefore provides a range of values that defines the extent of the margin of error, which are the highest and lowest possible values around a point forecast.

Previous studies had sought to demonstrate the merits of long-term forecasts from bivariate and multivariate VECMs such as Engle and Yoo (1987), Hoffman and Rasche (1996) and Anderson et al (1998) while studies such as Stock (1996) demonstrated the limitations of forecasts over the longer horizon[23], even if these forecasts were only 10% to 20% of the sample size. Although the forecasts in this chapter are initially evaluated over a short horizon (say 1 – 4 years), the objective lies in the consideration of the appropriate VECM that could

[22] Enders (2010) gives an example of a likely weakly exogenous situation from Johansen and Juselius (1990). He argued that real income could be weakly exogenous because in a full employment scenario, deviations between money demand and supply in the long run would not change real income.
[23] Stock (1996) describes long horizon forecasts as 4 years based on 20 to 40 years of data, longer horizon forecasts as 10 to 20 years based on 20 to 40 years of data and very long horizons (e.g. for global warming scenarios) based on forecasts of up to 100 years.

generate long-term econometric projections that go beyond the sample period. These projections would feed into the CGE model that is discussed in the next section of this chapter.

Estimates from the VECM and constrained VECM (section 5.3.4) have different impacts on the forecasts that could be generated. The forecast performance of the VECM and constrained VECM are initially based on estimates from the full sample period. Thereafter, the models are re-estimated with a few observations set aside towards the end of the sample period. The free observations are then forecasted in order to provide a visual comparison of the forecast performance against the actual data in the graphs. There are also a number of evaluation methods that can be calculated, which are used to compare the forecast performance of the VECM and constrained VECM. Different evaluation methods often produce conflicting results when applied to the same data so the empirical process would involve the simultaneous use of forecast evaluation methods in order to provide an overall picture of the forecasts' accuracy.

This chapter uses the following forecast evaluation methods that are common in the literature: root mean squared error (RMSE equation 5.8), mean absolute error (MAE equation 5.9) and mean absolute percentage error (MAPE equation 5.10):

$$RMSE = \sqrt{\sum_{t=T+1}^{T+n} \frac{(\hat{y}_t - y_t)^2}{N}} \tag{5.8}$$

$$MAE = \sum_{t=T+1}^{T+n} \frac{(\hat{y}_t - y_t)}{N} \tag{5.9}$$

$$MAPE = 100 \sum_{t=T+1}^{T+n} \left(\frac{\hat{y}_t - y_t}{y_t}\right) / N \tag{5.10}$$

where $t = T+1, T+2 \cdots T+n$ is the forecast sample[24] (i.e. number of forecasts), $\hat{y}$ is the forecast value in time t, y is the actual value in time t and $\hat{y}_t - y_t$ is the forecast error in time t. The forecast error is due to the uncertainty in the residuals for the forecasted period and the uncertainty in the coefficients in the VECM as these coefficients are essentially estimates

[24] The forecast sample can be produced using (i) a *dynamic forecast*: this is a multi-step forecast from models that contain lagged dependent variables as regressors and (ii) a *static forecast*: this forecast uses actual values for the one-step ahead forecasts and contain no lagged dependent variables as regressors.

rather than true values of the coefficients, which of course are unknown. The RMSE and MAE methods measure the scale of the forecast error for n, with an absolute value given for the MAE. The VECM and constrained VECM are both assessed on the size of the RMSE and MAE. The quality of each forecast error depends on the size of its value, which means that a low forecast error demonstrates a strong forecasting ability. The MAPE is scale invariant as the forecast error is given as a percentage, with 0% indicating a perfect forecast.

5.4 Methodology 2: Computable general equilibrium model

The methodology in this section involves the assessment of a computable general equilibrium (CGE) model which uses the projected values from the VECM estimations described in the previous section. The CGE model follows the Salter-Swan theoretical framework and is suitable for single country analyses such as for the UK. Salter (1959) and Swan (1960) defined a single country economic model as one that consists of two representative categories of aggregate goods: tradable products and services (both exports and imports) and non-tradable products and services. Goods that are classified as non-tradable due to their nature for example, public services and construction, have prices that are governed by demand and supply forces within the domestic market. Tradable goods that are not exported also come under the category of non-tradable goods. On the other hand, prices for tradable goods such as the production of electricity are governed by world prices in the international market[25]. Equilibrium is achieved by a configuration of the relative prices such that the demand for goods equals supply for each market.

The Salter-Swan distinction between tradable and non-tradable goods represented a significant development from the neoclassical trade model, which was based on the two core assumptions that all tradable goods were perfect substitutes with goods based in the domestic market and that all goods were tradable. The ‘law of one price’ theory that underpins these assumptions implies that the price of domestic goods in the neoclassical trade model are governed by world market prices. The implication of these assumptions in the empirical application of the neoclassical trade model is the exaggerated and improbable change in the domestic price relative to a change in the world market price. However, the tradable and non-tradable goods distinction recognises that world market prices are only partially reflected in the prices of

[25] From an energy supply and demand perspective, one could distinguish tradable and non-tradable goods into categories such as imported gas and exported petrol (tradable) and locally consumed electricity (non-tradable).

domestic goods. Therefore, the Salter-Swan model provides a more realistic illustration of the macroeconomic relationship between the formation of prices and the reactionary levels of production.

The Salter-Swan framework in this chapter is empirically implemented through the one country, two activities and three goods (1-2-3) CGE model from the World Bank (De Melo and Robinson, 1989; Devarajan, Lewis and Robinson, 1990, 1993). The CGE model reflects a competitive economy in that it has four representative economic agents: a producer that maximises revenue subject to any limiting factors that may restrict output, a household that receives all income and maximises its utility subject to its budget limits, a government and the rest of the world. Factor markets are ignored as the equilibrium condition assumes that there is full employment of all primary factors of production.

5.4.1 The representative industry

The representative industry in the CGE model produces goods (products and services) which can either be sold regionally within the domestic market or exported to the international market. On the assumption that the aggregate production variable X_t is fixed, all primary factors of production experience full employment. The omission of intermediate inputs also means that X_t amounts to real GDP Since the domestically sold goods and export goods are distinguished by market, their relationship can be expressed by a constant elasticity of transformation (CET) production function. The CET production function, which was proposed by Powell and Gruen (1968) is a concave form of production-possibility curve that represents the production trade-offs between the domestic and export goods based on the availability of resources, technical feasibility and other economic factors. The transformation possibilities between domestic and export goods are represented by the following CET equation:

$$X_t = \alpha\left[\lambda E_t^{\gamma} + (1- \lambda)DS_t^{\gamma}\right]^{1/\gamma} \qquad (5.11)$$

where E is the export good, DS is supply of the domestic good, α is the CET scale parameter which represents the productive efficiency of output[26], λ is the CET cost share parameter

[26] This could be viewed on the production possibility frontier (PPF) curve where all points along the curve represent the points at which a good is produced at the lowest achievable cost.

between the two types of goods and γ is the CET exponent parameter based on $\gamma = (1/\Omega) + 1$. The transformation elasticity Ω is given by $\Omega = 1/(\gamma - 1)$; $1 < \gamma < +\infty$, and the value of Ω is dependent on the extent of transformability between the export good and the domestically sold good. This means that if $\Omega = 0$, there is no transformability between the two markets and if $\Omega = \infty$, the two markets have perfect transformability. The α and λ parameters in equation (5.11) are further represented by the following equations:

$$\alpha = \frac{X_0}{\left[\lambda E_0^{\gamma} + (1 - \lambda) DS_0^{\gamma}\right]^{1/\gamma}} \tag{5.12}$$

$$\lambda = \left[1 + \left(\frac{PD_0}{PE_0}\right)\left(\frac{E_0}{DS_0}\right)^{\gamma-1}\right]^{-1} \tag{5.13}$$

where PD is the producer price of the domestic good. The producer price of the export good, PE is based on the world price of export good $\pi_E \times$ exchange rate *ER* less any duties that are paid on the export good. Based on the prices and demand for *E* and *DS*, the representative industry would allocate its total output between the export and domestic markets in order to maximise it profits. Therefore, subject to the transformability between the two markets, the optimal ratio of export to domestic goods is given by the following equation:

$$\frac{E_t}{DS_t} = \left[\frac{(1 - \lambda) PE_t}{\lambda PD_t}\right]^{\Omega} \tag{5.14}$$

5.4.2 The representative household

The CGE model defines a domestic composite good as one that is made up of imported goods and demand for domestically produced goods. The domestic composite good is wholly demanded and consumed by the single representative household. Theories of demand usually imply that demand for domestic goods and import goods have some degree of substitutability. However, the CGE model employs the Armington assumption (Armington, 1969), which suggests that regardless of any similarities, domestic goods and import goods are imperfect substitutes that enter the representative household's utility function as different commodities.

The Armington assumption differs from the previously more common assumption in the Heckscher–Ohlin general equilibrium model[27], which suggests that similar products that are produced in different countries are substitutable. However, Shoven and Whalley (1984) provided an early empirical demonstration of the Armington assumption's superior ability to avoid "specialisation effects" in a CGE model. This means that the Armington assumption prevents small changes in trade policy from becoming unrealistically large swings towards consumption specialisation in either imports or domestically produced goods. Therefore, the CGE model expresses the aggregate demand for the composite good and the Armington assumption by a constant elasticity of substitution (CES) utility function of the import good and demand for the domestic good. The substitution possibilities between the import good and demand for the domestic good are represented by the following CES equation:

$$QD_t = \beta\left[\delta M_t^{-\rho} + (1-\delta)DD_t^{-\rho}\right]^{-1/\rho} \tag{5.15}$$

where QD is the demand for the composite good, M is the import good, DD is the demand for the domestically produced good, β is the CES scale parameter which represents the efficiency of the two types of intermediate good into the domestic composite good, δ is the CES cost share parameter and ρ is the CES exponent parameter based on $\rho = (1/\sigma) - 1$. The substitution elasticity σ is given by $\sigma = 1/(1+\rho)$; $-\infty < \rho < +1$. The β and δ parameters from CES equation (5.15) are further represented by the following equations:

$$\beta = \frac{QS_0}{\left[\delta M_0^{-\rho} + (1-\delta)DD_0^{-\rho}\right]^{-1/\rho}} \tag{5.16}$$

$$\delta = \frac{\left(\frac{PM_0}{PD_0}\right)\left(\frac{M_0}{DD_0}\right)^{1+\rho}}{1 + \left(\frac{PM_0}{PD_0}\right)\left(\frac{M_0}{DD_0}\right)^{1+\rho}} \tag{5.17}$$

where QS is the supply of the composite good and PM is the domestic price of the import good, which is based on the world price of the import good $\pi_M \times ER$ plus any import tariffs. The household wishes to maximise its utility, which is the same as maximising QD but it also wishes to minimise its purchase costs subject to CES equation (5.15). Based on these

[27] Flam and Flanders (1991) delve more into the methodical history of the Heckscher–Ohlin model

conditions, the optimal ratio of import to domestically demanded goods is given by the following equation:

$$\frac{M_t}{DD_t} = \left[\frac{\delta PD_t}{(1 - \delta)PM_t}\right]^{\sigma} \tag{5.18}$$

The representative household receives all income, which is the equivalent of GDP plus government transfers and any remittances received from abroad:

$$Y_t = (PX_t)(X_t) + (Tr_t)(PQ_t) + (Re_t)(ER_t) \tag{5.19}$$

where PX is the price of aggregate output, Tr are government transfers, PQ is the price of the composite good and Re are the foreign remittances to the private sector. The CGE model requires demand to equal expenditure so the quantity demanded is therefore $QD_t = Y_t/PQ_t$. The price of aggregate output PX, which resembles the GDP deflator and the price of the composite good PQ are further represented by the following equations:

$$PX_t = \frac{(PE_t)(E_t) + (PD_t)(DS_t)}{X_t} \tag{5.20}$$

$$PQ_t = \frac{(PM_t)(M_t) + (PD_t)(DD_t)}{QS_t} \tag{5.21}$$

General equilibrium theory requires a numeraire price to which all other prices are benchmarked against. A fixed nominal exchange rate is typically used in this case so the numeraire is set to 1.

5.4.3 The Government

The variable *Tax* denotes the sum of UK Government revenues that are generated from domestic economic activity and international trade. The CGE model splits the main sources of tax revenue into two categories: direct taxation such as income tax, corporation tax and NI contributions (*dirTax*) and indirect taxation from the production of goods and services such as VAT and environmental tax (*indTax*). A third category of tax revenue is considered separately in the form of taxes on the international trade of goods. However, these taxes are currently nil as the UK Government has seemingly not levied taxes on international trade for a number of years (World Bank, 2016). Therefore, the savings equation for the government after deductions from its tax revenue is given by the following:

$$SG_t = Tax_t - (G_t)(PT_t) - (Tr_t)(PQ_t) + (FT_t)(ER_t) \tag{5.22}$$

where G is government consumption, PT is the sales price of the composite good represented by $PT_t = PQ_t \times$ (1 + indirect tax rate) and FT are net official transfers (foreign grants).

5.4.4 Equilibrium conditions and adjustments to energy-based shocks

The model must show that the equilibrium conditions conform to Walras' Law, which means that any excess market demand must equal excess market supply. Therefore, the value of excess demand over supply in the domestic good is $DD_t - DS_t = 0$ and the value of excess demand over supply in the composite good is $QD_t - QS_t = 0$. Another equilibrium consideration lies with the current account balance *B*, which is equal to the market value of imports less the market value of exports, net official transfers and net private remittances[28] from abroad:

$$B_t = (\pi_M)(M_t) - (\pi_E)(E_t) - FT_t - Re_t \tag{5.23}$$

The three energy pathways in Chapter 4 produced cost projections of the energy system towards 2050 and the CGE model would use these projections for the implementation of user-defined economic shocks such as those applied to investment. These shocks would subsequently require adjustments in order for the model to return to an equilibrium state. There are a number of policy response adjustments that could be applied in this scenario such as tax adjustments, trade policy and government savings. The impact of the three energy mix pathways, the financial shocks they induce and the economic adjustments towards equilibrium are the subject of further testing and analysis later in this chapter.

[28] Net private remittances for the CGE model is the sum of net factor income and net private transfers of primary and secondary income.

5.5 Econometric models and data used for estimation

The vector error correction model (VECM) is used to estimate the long run equilibrium and short run dynamics from the economic relationships discussed in section 5.2. The variables in each VECM are treated as endogenous and each of the endogenous variables in the VECM is defined by the value of its own lag as well as the current and lagged values of the remaining endogenous variables within a multivariate, multiequation framework. The variables in four of the five VECMs relationships (equations 5.24 to 5.27) are converted to their natural logarithms in order for the estimated coefficients to be interpreted as elasticities. The five economic relationships that need to be estimated in the following VECM groups:

i. Export-led growth (ELG) / Growth-led export (GLE) hypotheses
ii. Import-led growth (ILG) / Growth-led import (GLI) hypotheses
iii. The effect of tax shocks on economic growth
iv. The effect of fiscal consolidation on economic growth
v. The effect of GDP on the current account balance

The testing of the ELG/GLE and ILG/GLI hypotheses are based on the specification from Wong (2008) and Jarra (2013):

$$\begin{bmatrix} \Delta\ln Export_t \\ \Delta\ln GDP_t \\ \Delta\ln House_t \\ \Delta\ln Govt_t \end{bmatrix} = \begin{bmatrix} \alpha_1 \\ \alpha_2 \\ \alpha_3 \\ \alpha_4 \end{bmatrix} \beta_j' * \begin{bmatrix} \ln Export_{t-1} \\ \ln GDP_{t-1} \\ \ln House_{t-1} \\ \ln Govt_{t-1} \end{bmatrix} + \sum_{i=1}^{p} \begin{bmatrix} \gamma_{i11} & \gamma_{i12} & \gamma_{i13} & \gamma_{i14} \\ \gamma_{i21} & \gamma_{i22} & \gamma_{i23} & \gamma_{i24} \\ \gamma_{i31} & \gamma_{i32} & \gamma_{i33} & \gamma_{i34} \\ \gamma_{i41} & \gamma_{i42} & \gamma_{i43} & \gamma_{i44} \end{bmatrix} * \begin{bmatrix} \Delta\ln Export_{t-i} \\ \Delta\ln GDP_{t-i} \\ \Delta\ln House_{t-i} \\ \Delta\ln Govt_{t-i} \end{bmatrix} + \begin{bmatrix} c_1 \\ c_2 \\ c_3 \\ c_4 \end{bmatrix} + \begin{bmatrix} \varepsilon_2 \\ \varepsilon_2 \\ \varepsilon_3 \\ \varepsilon_4 \end{bmatrix} \quad (5.24)$$

$$\begin{bmatrix} \Delta\ln Import_t \\ \Delta\ln GDP_t \\ \Delta\ln House_t \\ \Delta\ln Govt_t \end{bmatrix} = \begin{bmatrix} \alpha_1 \\ \alpha_2 \\ \alpha_3 \\ \alpha_4 \end{bmatrix} \beta_j' * \begin{bmatrix} \ln Import_{t-1} \\ \ln GDP_{t-1} \\ \ln House_{t-1} \\ \ln Govt_{t-1} \end{bmatrix} + \sum_{i=1}^{p} \begin{bmatrix} \gamma_{i11} & \gamma_{i12} & \gamma_{i13} & \gamma_{i14} \\ \gamma_{i21} & \gamma_{i22} & \gamma_{i23} & \gamma_{i24} \\ \gamma_{i31} & \gamma_{i32} & \gamma_{i33} & \gamma_{i34} \\ \gamma_{i41} & \gamma_{i42} & \gamma_{i43} & \gamma_{i44} \end{bmatrix} * \begin{bmatrix} \Delta\ln Import_{t-i} \\ \Delta\ln GDP_{t-i} \\ \Delta\ln House_{t-i} \\ \Delta\ln Govt_{t-i} \end{bmatrix} + \begin{bmatrix} c_1 \\ c_2 \\ c_3 \\ c_4 \end{bmatrix} + \begin{bmatrix} \varepsilon_2 \\ \varepsilon_2 \\ \varepsilon_3 \\ \varepsilon_4 \end{bmatrix} \quad (5.25)$$

where $Export$ is exports, $Import$ is imports, GDP is gross domestic product at market prices, $House$ is household consumption and $Govt$ is government consumption. The term α_i is a $4 \times r$ matrix of speed of adjustment parameters, $\beta_j^{'} = \beta_1,\ \beta_2, \dots, \beta_{K-1}$ is a matrix of long run cointegration parameters, γ_{ij} is a 4×4 matrix of short run parameters with a p lag order, c_i is a 4×1 vector of intercept parameters and ε_i is a 4×1 vector of error terms. For example, if equation (5.24) had two cointegrating vectors, then $\alpha_i = 4 \times 2$. Equations (5.24) and (5.25) are hereafter referred to as VECM 1a and 1b respectively.

The effect of the UK Government's tax hikes and cuts on GDP is tested in VECM 2 and is based on the following model specifications used in Mamatzakis (2005) and Birhanu (2016):

$$\begin{bmatrix} \Delta\ln GDP_t \\ \Delta\ln dirTax_t \\ \Delta\ln indTax_t \end{bmatrix} = \begin{bmatrix} \alpha_1 \\ \alpha_2 \\ \alpha_3 \end{bmatrix} \beta_j' * \begin{bmatrix} \ln GDP_{t-1} \\ \ln dirTax_{t-1} \\ \ln indTax_{t-1} \end{bmatrix} + \sum_{i=1}^{p} \begin{bmatrix} \gamma_{i11} & \gamma_{i12} & \gamma_{i13} & \gamma_{i14} \\ \gamma_{i21} & \gamma_{i22} & \gamma_{i23} & \gamma_{i24} \\ \gamma_{i31} & \gamma_{i32} & \gamma_{i33} & \gamma_{i34} \end{bmatrix} * \begin{bmatrix} \Delta\ln GDP_{t-i} \\ \Delta\ln dirTax_{t-i} \\ \Delta\ln indTax_{t-i} \end{bmatrix} + \begin{bmatrix} c_1 \\ c_2 \\ c_3 \end{bmatrix} + \begin{bmatrix} \varepsilon_2 \\ \varepsilon_2 \\ \varepsilon_3 \end{bmatrix} \quad (5.26)$$

where $dirTax$ is government revenue from direct taxes and $indTax$ is government revenue from indirect taxes on domestic goods and services.

The next VECM assesses the effect of the UK Government's revenue and current expenditure position on GDP and is based on the variables used in the model specification in Mody and Rebucci (2006):

$$\begin{bmatrix} \Delta\ln GDP_t \\ \Delta\ln totTax_t \\ \Delta\ln nonTax_t \\ \Delta\ln WGS_t \\ \Delta\ln Interest_t \\ \Delta\ln SubTr_t \end{bmatrix} = \begin{bmatrix} \alpha_1 \\ \alpha_2 \\ \alpha_3 \\ \alpha_4 \\ \alpha_5 \\ \alpha_6 \end{bmatrix} \beta_j' * \begin{bmatrix} \Delta\ln GDP_{t-1} \\ \Delta\ln totTax_{t-1} \\ \Delta\ln nTax_{t-1} \\ \Delta\ln WGS_{t-1} \\ \Delta\ln Interest_{t-1} \\ \Delta\ln SubTr_{t-1} \end{bmatrix}$$

$$+ \sum_{i=1}^{p} \begin{bmatrix} \gamma_{i11} & \gamma_{i12} & \gamma_{i13} & \gamma_{i14} & \gamma_{i15} & \gamma_{i16} & \gamma_{i17} \\ \gamma_{i21} & \gamma_{i22} & \gamma_{i23} & \gamma_{i24} & \gamma_{i25} & \gamma_{i26} & \gamma_{i27} \\ \gamma_{i31} & \gamma_{i32} & \gamma_{i33} & \gamma_{i34} & \gamma_{i35} & \gamma_{i36} & \gamma_{i37} \\ \gamma_{i41} & \gamma_{i42} & \gamma_{i43} & \gamma_{i44} & \gamma_{i45} & \gamma_{i46} & \gamma_{i47} \\ \gamma_{i51} & \gamma_{i52} & \gamma_{i53} & \gamma_{i54} & \gamma_{i55} & \gamma_{i56} & \gamma_{i57} \\ \gamma_{i61} & \gamma_{i62} & \gamma_{i63} & \gamma_{i64} & \gamma_{i65} & \gamma_{i66} & \gamma_{i67} \end{bmatrix} * \begin{bmatrix} \Delta\ln GDP_{t-i} \\ \Delta\ln totTax_{t-i} \\ \Delta\ln nTax_{t-i} \\ \Delta\ln WGS_{t-i} \\ \Delta\ln Interest_{t-i} \\ \Delta\ln SubTr_{t-i} \end{bmatrix} + \begin{bmatrix} c_1 \\ c_2 \\ c_3 \\ c_4 \\ c_5 \\ c_6 \end{bmatrix} + \begin{bmatrix} \varepsilon_2 \\ \varepsilon_2 \\ \varepsilon_3 \\ \varepsilon_4 \\ \varepsilon_5 \\ \varepsilon_6 \end{bmatrix} \quad (5.27)$$

where $totTax$ is total tax revenue, $nonTax$ is non-tax revenue, WGS is the current government expenditure on wages, goods and services, $Interest$ is the current government expenditure on public debt interest and $SubTr$ is the current government expenditure on subsidies and transfers. Equation (5.27) is hereafter referred to as VECM 3.

The variables in the VECM that estimates the effect of GDP on the current account follows the variables used in Arghyrou and Chortareas (2016) and Thomas (2015). The variables in this model are not converted to their natural logarithms as there are a number of negative values within the current account and net trade time series. The model is defined by the following specification:

$$\begin{bmatrix} CurrAc_t \\ GDP_t \\ nTrade_t \\ exRate_t \end{bmatrix} = \begin{bmatrix} \alpha_1 \\ \alpha_2 \\ \alpha_3 \\ \alpha_4 \end{bmatrix} \beta_j' * \begin{bmatrix} CurrAc_{t-1} \\ GDP_{t-1} \\ nTrade_{t-1} \\ exRate_{t-1} \end{bmatrix} + \sum_{i=1}^{p} \begin{bmatrix} \gamma_{i11} & \gamma_{i12} & \gamma_{i13} \\ \gamma_{i21} & \gamma_{i22} & \gamma_{i23} \\ \gamma_{i31} & \gamma_{i32} & \gamma_{i33} \\ \gamma_{i41} & \gamma_{i42} & \gamma_{i43} \end{bmatrix} * \begin{bmatrix} CurrAc_{t-i} \\ GDP_{t-i} \\ nTrade_{t-i} \\ exRate_{t-i} \end{bmatrix} + \begin{bmatrix} c_1 \\ c_2 \\ c_3 \\ c_4 \end{bmatrix} + \begin{bmatrix} \varepsilon_2 \\ \varepsilon_2 \\ \varepsilon_3 \\ \varepsilon_4 \end{bmatrix} \quad (5.28)$$

where $CurrAc$ is the current account balance, $nTrade$ is net trade in goods and non-factor services and $exRate$ is the real effective exchange rate.[29]

This chapter uses UK annual time series data, which consists of 43 observations spanning from 1972 to 2014. The length of the sample period was chosen subject to the availability of data. All variables (except for the exchange rate) are expressed in billions of constant 2010 British pounds. Data for 14 out of the 15 variables from the 5 models are obtained from the World Development Indicators of the World Bank's 2016 database (World Bank, 2016). Data for the UK's real effective exchange rate is obtained from the statistics division of the Bank for International Settlements (BIS, 2016). Table 5.1 shows the data prior to the conversion of most of the times series to natural logarithms:

Table 5.1: Summary statistics of the data

Variable	Description	Model	Obs	Mean (£bn)	Std.Dev (£bn)	Min (£bn)	Max (£bn)
GDP	Gross domestic product (nominal)	1a, 1b, 2, 3 & 4	43	1,127.5	336.9	673.2	1,687.8
Export	Total exports	1a	43	305.8	96.6	186.6	493.8
Import	Total imports	1b	43	328.3	105.9	203.4	525.4
Govt	Government consumption	1a and 1b	43	228.4	66.7	143.9	341.5
House	Household consumption	1a and 1b	43	716.9	222.9	432.1	1,092.5
dirTax	Direct taxes	2	43	163.8	50.8	98.1	271.5
indTax	Taxes on goods and services	2	43	124.9	41.3	73.1	200.2
totTax	Total tax revenues	3	43	228.7	91.4	171.2	443.2
nonTax	Non-tax revenues	3	43	104.0	32.1	63.3	170.0
WGS	Wages, goods & services expense	3	43	137.1	42.8	87.9	216.0
Interest	Interest payments on govt debt	3	43	31.0	7.7	19.2	50.3
SubTr	Subsidies and transfers expense	3	43	230.9	76.9	143.5	362.8
CurrAc	Current account balance	4	43	-26.6	17.0	-81.8	-6.7
nTrade	Net trade: goods & non-factor services	4	43	-23.7	12.2	-49.8	-6.2
exRate	Real effective exchange rate	4	43	120.8	12.5	97.7	150.3

[29] The real effective exchange rate (REER) is a measure of the nominal effective exchange rate of the local currency against the weighted average of a basket of several foreign currencies and is deflated by the consumer price index in order to obtain the REER (Darvas, 2012). The REER for the UK is expressed in an index form with the base year 2010 = 100. An increase in the REER represents an appreciation in the value of the British pound against a basket of foreign currencies.

5.6 Empirical analysis 1: Cointegration and VECM

This section contributes to the empirical literature on long-term econometric projections through the analysis of the UK's economy from the viewpoint of five economic relationships. Johansen's ML estimator of cointegration analysis and the VECM methodology are implemented in order to assess the long run equilibrium relationships and short run adjustment coefficients in each of the economic relationships discussed in section 5.3. The Granger causality tests are based on the methodology in section 3.4.4 and provides indicators of the directions of causality between the variables. The structurally parsimonious models from the VECM analyses are used to generate projections of economic data up to 2050. These projections are subsequently fed into a CGE model, which is subject to different shocks from the energy mix scenarios that were estimated in Chapter 4.

5.6.1 Unit root tests for the VECM variables

In Chapter 3, we considered the properties of standard economic time series in terms of their order of integration. We also considered the methods for testing the presence of a unit root and order of integration via the augmented Dickey-Fuller "ADF" test (Dickey and Fuller, 1981) and the Dickey-Fuller Generalised Least Squares "DF-GLS" test (Elliott, Rothenberg, and Stock, 1996).

Testing a variable for its order of integration is a standard procedure in applied time series analysis and the motive behind this test lies in the necessity of knowing whether a variable exhibits a stationary process or a non-stationary process with a unit root i.e. integrated of order one or $I(1)$. If one is estimating an ordinary least squares regression with $I(1)$ variables, the least squares estimates and t-statistics would have atypical distributions, which could lead to spurious regression results. Phillips (1987) also demonstrated that any regression that models the level of variables that are $I(1)$ but are not cointegrated is a spurious relationship. Therefore, it is important to understand the time series properties of the variables in this chapter by running the ADF and DF-GLS unit root test equations from Chapter 3.

The selection of either an intercept or an intercept and trend in the unit root test is determined by the pattern of the data and its graphical representation. The lag length for the unit root test is based on the optimal lag order chosen by the Akaike Information Criteria (AIC). The ADF and DF-GLS tests are carried out using equations (3.4) and (3.6) from Chapter 3. Table 5.2 shows the unit root test results for all of the variables that are used in the 5 models:

Table 5.2: ADF and DF-GLS unit root tests for the VECM variables

Model	Variable	Included in test	ADF t-statistic	DF-GLS t-statistic
1a, 1b, 2, 3 & 4	ln *GDP*	Intercept only	-0.006 (0.953)	1.032
1a, 1b, 2, 3 & 4	Δln *GDP*	Intercept only	-4.912 (0.000) ***	-3.262 ***
1a	ln *Export*	Intercept only	-0.146 (0.937)	1.162
1a	Δln *Export*	Intercept only	-6.477 (0.000) ***	-5.751 ***
1b	ln *Import*	Intercept only	-0.127 (0.940)	1.033
1b	Δln *Import*	Intercept only	-6.173 (0.000) ***	-5.316 ***
1a and 1b	ln *Govt*	Intercept only	-0.051 (0.948)	0.735
1a and 1b	Δln *Govt*	Intercept only	-4.146 (0.002) ***	-2.869 ***
1a and 1b	ln *House*	Intercept only	0.216 (0.970)	1.020
1a and 1b	Δln *House*	Intercept only	-4.416 (0.001) ***	-3.243 ***
2	ln *dirTax*	Intercept and trend	-1.570 (0.788)	-1.788
2	Δln *dirTax*	Intercept and trend	-6.511 (0.000) ***	-6.540 ***
2	ln *indTax*	Intercept and trend	-2.988 (0.148)	-2.629
2	Δln *indTax*	Intercept and trend	-5.525 (0.000) ***	-5.534 ***
3	ln *totTax*	Intercept and trend	-1.765 (0.704)	-1.826
3	Δln *totTax*	Intercept and trend	-6.409 (0.000) ***	-6.339 ***
3	ln *nonTax*	Intercept only	-0.132 (0.939)	0.809
3	Δln *nonTax*	Intercept only	-5.536 (0.000) ***	-5.005 ***
3	ln *WGS*	Intercept and trend	-2.561 (0.299)	-6.339
3	Δln *WGS*	Intercept and trend	-4.578 (0.004) ***	-6.339 ***
3	ln *Interest*	Intercept only	-1.409 (0.569)	-6.339
3	Δln *Interest*	Intercept only	-6.376 (0.000) ***	-6.339 ***
3	ln *SubTr*	Intercept only	-0.086 (0.944)	-6.339
3	Δln *SubTr*	Intercept only	-5.530 (0.000) ***	-6.339 ***
4	*CurrAc*	Intercept only	-0.073 (0.946)	-6.339
4	Δ*CurrAc*	Intercept only	-6.079 (0.000) ***	-6.339 ***
4	*nTrade*	Intercept only	-1.555 (0.496)	-6.339
4	Δ*nTrade*	Intercept only	-7.454 (0.000) ***	-6.339 ***
4	*exRate*	Intercept	-2.501 (0.123)	-1.851 *
4	Δ*exRate*	Intercept	-4.869 (0.000) ***	-3.889 ***

3. ***, ** and * denotes *I*(1) at the 1%, 5% and 10% significance levels respectively
4. The numbers in parentheses are the probability values of the t-statistics

The ADF and DF-GLS results clearly show that all of the variables exhibit a nonstationary process at level. The slight difference is the *exRate* variable as the DF-GLS result shows that it is stationary at the 10% level of significance. However, this is not very indicative as the standard significance threshold to denote a true level stationary process is 5%. The variables further indicate that they are all stationary at first difference i.e. they are all *I*(1) variables at the 1% significance level.

The unit root test results were largely expected, given the nature of the major economic events that took place throughout the duration of the sample period. The global sovereign debt and financial crisis of 2007-08 is especially prominent across the variables as they show a significant structural break during this period. Similarly to Chapter 3, further estimations of the variables in this chapter accounts for the 2007-08 structural break with the inclusion of a break dummy variable. The next step involves the determination of the lag order for the 5 models and testing of the variables in each model for the presence of a long run cointegrated relationship.

5.6.2 Determination of the lag order and lag selection criteria

The initial preestimation test for a VECM involves the estimation of an unrestricted VAR in order to determine the appropriate p lag order, denoted as VAR(p). The selection of the true p lag order for a VAR is important as it ensures the parsimonious quality of the model's estimates. Furthermore, Lütkepohl (2005) indicated that the selection of an overfitted VAR$(p+i)$ would cause the mean square error forecasts to be inferior to forecasts from a correct VAR(p) while an underfitted VAR$(p-i)$ could result in autocorrelated residuals.

The sample period of 43 observations does not allow for the consideration of a large lag order so the appropriate lag order is tested on a maximum of three lags for models 1a, 1b, 2 and 4. For model 3, a maximum of two lags is chosen due to the larger number of variables in the model. The lag selection criteria are based on the likelihood ratio (LR) test, the Final Prediction Error (FPE) and the following information criteria: Akaike (AIC), Schwarz (SIC) and Hannan-Quinn (HQIC). The AIC is considered first in this chapter due to its consistency in selecting the appropriate lag order in small sample sizes (Lütkepohl, 2005). However, the AIC is considered alongside the remaining lag selection criteria in order to obtain an overall picture of the suitability of each lag length. The appropriate lag order is therefore based on the lag length that produces the lowest value statistic in each of the five lag selection criteria.

Table 5.3 provides a summary of the lag selection criteria and statistics for each of the five models:

Table 5.3: Lag selection criteria for the underlying VAR

Model	Lag	LogL	LR	FPE	AIC	SC	HQ
1a	0	264.54	NA	3.16E-11	-12.83	-12.49	-12.70
	1	466.68	343.63	2.89E-15	-22.13	**-21.12** *	-21.77
	2	484.47	**26.70** *	2.74E-15	-22.22	-20.53	-21.61
	3	508.56	31.31	**1.98E-15** *	**-22.63** *	-20.26	**-21.77** *
1b	0	271.02	NA	2.28E-11	-13.15	-12.81	-13.03
	1	471.83	341.37	2.24E-15	-22.39	**-21.38** *	-22.02
	2	494.09	33.40	1.69E-15	-22.70	-21.02	-22.09
	3	516.23	**28.78** *	**1.35E-15** *	**-23.01** *	-20.65	**-22.16** *
2	0	143.88	NA	2.04E-07	-6.89	-6.64	-6.80
	1	281.25	**240.39** *	3.33E-10	-13.31	**-12.68** *	**-13.08** *
	2	290.18	14.29	3.39E-10	-13.31	-12.30	-12.94
	3	301.49	16.40	**3.10E-10** *	**-13.42** *	-12.03	-12.92
3	0	356.09	NA	2.07E-15	-16.78	-16.28	-16.60
	1	600.28	393.08	8.29E-20	-26.94	**-24.93** *	**-26.21** *
	2	643.26	**56.61** *	**6.79E-20** *	**-27.28** *	-23.77	-26.00
4	0	-421.73	NA	25222.74	21.49	21.82	21.61
	1	-264.76	266.86	22.10	14.44	**15.45** *	**14.80** *
	2	-249.84	22.37	24.14	14.49	16.18	15.10
	3	-223.86	**33.77** *	**15.88** *	**13.99** *	16.36	14.85

The * and bold font denotes the appropriate lag length in each category

Based on the AIC statistics from the underlying VAR, models 1a, 1b and 4 have opted for a lag order of three and model 3 has opted for a lag order of two. This can be viewed as the settled lag order for those models as it is supported by the majority of the other lag selection criteria in each model. For model 2, AIC and FPE supports three lags while SIC, HQIC and the log likelihood ratio (LR) statistic supports one lag. Since AIC is the principal information criteria for consideration, a lag order of 3 is chosen but it is worth noting that SIC and HQIC tends to restrict the lag order as they have a stricter penalty term than AIC when additional parameters are added to the model.

5.6.3 Johansen's ML estimator for cointegration analysis

Since the p lag order for the underlying VAR is specified, the lag order for Johansen's ML estimator and VECM are also specified as a $p - 1$ lag order. This directly corresponds to a

VAR(p) order since a VECM is a VAR in differences. The trend specification for each cointegration test is determined by economic theory and graphical analysis. Based on this criteria, the trend specification for models 1a, 1b and 3 is based on case 3 of section 5.3.3 (unrestricted intercept), model 2 is based on case 4 (restricted trend) and model 4 is based on case 2 (restricted intercept).

As discussed in section 5.3.2, the rank of the coefficient matrix $\mathbf{\Pi}$ is based on the number of important eigenvalues within $\widehat{\mathbf{\Pi}}$. The eigenvalues are ordered in descending order starting with the largest eigenvalue. The null hypothesis (H_0) of no cointegrating vectors is tested on this eigenvalue against the alternative (H_1) of at least one cointegrating vector. If the null hypothesis is rejected, then the test moves onto the next largest eigenvalue and so on until the null hypothesis can longer be rejected. Two LR test statistics are produced in order to reject or not reject H_0: the trace statistic and maximum eigenvalue statistic. If the trace and/or max statistics are greater than their corresponding 5% critical values, then H_0 is rejected. This process will continue to the next eigenvalue and so on until we can no longer reject H_0. Table 5.4 shows the results for the 5 models from Johansen's cointegration test for both the trace statistic and the maximum eigenvalue statistic:

Table 5.4: Number of cointegrating vectors in each model

Model (lags)	H_0: Coint. equations	Eigen value	**Trace** Statistic	5% Crit. Value	Prob.	H_0: Coint. equations	Eigen value	**Max** Statistic	5% Crit. Value	Prob.
1a (2)	None*	0.502	64.488	47.856	0.001	None*	0.502	27.913	27.584	0.045
	At most 1*	0.447	36.575	29.797	0.007	At most 1*	0.447	23.674	21.132	0.022
	At most 2	0.255	12.901	15.495	0.119	At most 2	0.255	11.793	14.265	0.119
1b (2)	None*	0.620	74.665	47.856	0.000	None*	0.620	38.722	27.584	0.001
	At most 1*	0.440	35.944	29.797	0.009	At most 1*	0.440	23.167	21.132	0.026
	At most 2	0.244	12.777	15.495	0.123	At most 2	0.244	11.215	14.265	0.144
2 (2)	None*	0.528	53.275	42.915	0.003	None*	0.528	30.002	25.823	0.013
	At most 1	0.328	23.273	25.872	0.102	At most 1	0.328	15.872	19.387	0.151
	At most 2	0.169	7.401	12.518	0.305	At most 2	0.169	7.401	12.518	0.305
3 (1)	None*	0.720	140.523	95.754	0.000	None*	0.720	52.181	40.078	0.001
	At most 1*	0.605	88.342	69.819	0.001	At most 1*	0.605	38.050	33.877	0.015
	At most 2*	0.460	50.292	47.856	0.029	At most 2	0.460	25.235	27.584	0.097
	At most 3	0.372	25.057	29.797	0.159	At most 3	0.372	19.081	21.132	0.095
4 (2)	None*	0.757	88.024	54.079	0.000	None*	0.757	56.558	28.588	0.000
	At most 1	0.370	31.466	35.193	0.120	At most 1	0.370	18.475	22.300	0.157
	At most 2	0.215	12.991	20.262	0.365	At most 2	0.215	9.662	15.892	0.366

* denotes a rejection of the null hypothesis of the corresponding cointegration rank

The 'H_0: coint. equations' column indicates the null hypothesis of r cointegrating vectors among the variables. For models 1a and 1b, H_0: $r = 1$ is rejected at the 5% significance level but we do not reject $r = 2$ for both the trace statistic and the maximum eigenvalue statistics as they are both lower than their corresponding 5% critical values. This is also evidenced by the probability values of the trace and max statistics as they are both higher than 5%. This means that models 1a and 1b conclusively indicate the presence of two cointegrating vectors.

The trace and maximum eigenvalue results for models 2 and 4 also agree that there is one cointegrating vector within each model. However, the results for model 3 differ as the trace statistic shows the presence of 3 cointegrating vectors and the maximum eigenvalue statistic shows the presence of 2 cointegrating vectors. Based on the extensive experiments conducted in Lütkepohl et al (2000), it was found that in small sample sizes, the trace test wields a superior performance to the maximum eigenvalue test in terms of power. Furthermore, the trace test performs better with models that consist of at least 2 cointegrating vectors. Based on these findings, the trace statistic result of 3 cointegrating vectors is accepted rather than the maximum eigenvalue statistic of 2 cointegrating vectors.

5.6.4 Long run parameter estimates from the cointegrating vectors

The next stage involves the estimation of the five VECMs with the aim of initially assessing the long run coefficients of the cointegrating vectors within each VECM. The standard output from Johansen's ML estimator produces economically arbitrary restrictions on the parameter estimates. Therefore, manual restrictions are applied to the cointegration parameters in each VECM, based on economic theory. For example, model 1a consists of 4 variables (ln *GDP*, ln *Govt*, ln *Export* and ln *House*) and 2 cointegrating vectors so the β_j' matrix for model 1a would consist of the following parameters:

$$\beta_j' = \begin{pmatrix} \beta_{11} & \beta_{21} & \beta_{31} & \beta_{41} \\ \beta_{12} & \beta_{22} & \beta_{32} & \beta_{42} \end{pmatrix} \tag{5.29}$$

In order to test the ELG/GLE hypothesis in VECM 1a, the "0" identification restriction cannot be applied to ln *GDP* and ln *Export* in either of the two cointegrating vectors. The just-identified cointegrating vectors are now represented by the following modified restrictions:

$$\beta_j' = \begin{pmatrix} 1 & 0 & \beta_{31} & \beta_{41} \\ \beta_{12} & \beta_{22} & 1 & 0 \end{pmatrix} \quad (5.30)$$

The results from the just-identified cointegrating vectors for the 5 VECMs are given in Tables 5.5, 5.6 and 5.7 with their associated standard errors given in brackets:

Table 5.5: Estimates of the coefficients from the cointegrating vectors: VECMs 1a and 1b

VECM 1a	Cointegrating vector (β_1)	Cointegrating vector (β_2)	VECM 1b	Cointegrating vector (β_1)	Cointegrating vector (β_2)
ln *GDP*	1.000	-2.606 (0.418)	ln *GDP*	1.000	-2.840(0.382)
ln *Govt*	0.000	1.970 (0.498)	ln *Govt*	0.000	2.154(0.446)
ln *Export*	0.603(0.103)	1.000	ln *Import*	0.826(0.069)	1.000
ln *House*	-1.495(0.093)	0.000	ln *House*	-1.725(0.065)	0.000
C	-0.651	1.905	C	-0.472	2.475

The numbers in parentheses are the standard errors.

Table 5.5 highlights the long run estimates between GDP and its constituents in VECMs 1a and 1b. The estimates from the first cointegrating vectors in VECMs 1a and 1b show that the signs agree with the theoretical expectations concerning the ELG/GLE and IMG/GLI hypotheses. The UK's long run trade deficit is clearly explained in the first cointegrating equations in both models as a 1% increase in GDP corresponds to a 0.83% increase in imports but only a 0.6% increase in exports.

Table 5.6: Estimates of the coefficients from the cointegrating vectors: VECMs 2 and 3

VECM 2	Cointegrating vector (β_1)	VECM 3	Cointegrating vector (β_1)	Cointegrating vector (β_2)	Cointegrating vector (β_3)
ln *GDP*	1.000	ln *GDP*	1.000	0.001 (0.061)	0.000
ln *dirTax*	-0.134(0.094)	ln *totTax*	-3.783 (0.237)	1.000	-5.849(0.265)
ln *indTax*	-0.128(0.097)	ln *nonTax*	-1.897 (0.152)	-0.598 (0.055)	0.000
Trend	-0.019(0.002)	ln *WGS*	4.132 (0.316)	0.000	3.934(0.330)
C	-5.271	ln *Interest*	0.000	0.000	0.347(0.046)
		ln *SubTr*	0.000	-0.301(0.025)	1.000
		C	2.848	-1.246	7.108

The numbers in parentheses are the standard errors.

Table 5.6 highlights the long run relationship between the fiscal variables and GDP. The signs of the tax and non-tax estimates of the cointegrating vectors support expectations from theoretical models such as the Laffer curve, which suggests that real tax cuts from a certain high level corresponds to economic growth in the long run but there are marked differences in magnitudes in VECM 2 and VECM 3. There is also support of the notion that long run growth corresponds to the growth in public sector expenditure on wages, goods and services.

Table 5.7: Parameter estimates of the cointegrating vectors: VECM 4

VECM 4	Cointegrating vector (β_1)
ln GDP	1.000
CurrAc	0.003 (0.017)
nTrade	0.022 (0.012)
exRate	-0.014 (0.010)
C	-3.467 (1.489)

The numbers in parentheses are the standard errors

Table 5.7 highlights the long run relationship between GDP, the current account balance and one its constituents, net trade in goods and non-factor services. The signs correspond to the intertemporal models of a nation's current account balance but the minuscule coefficient on the current account reflects the UK's long term current account deficit.

5.6.5 Speed of adjustment coefficients, weak exogeneity and Granger causality

The five VECMs that were previously estimated are assessed for the significance of their speed of adjustment coefficients. The endogeneity status of the variables in each VECM is considered in order to determine whether they're actually weakly exogenous. We can distinguish the difference between endogenous variables that are affected by other variables in a model and exogenous variables, which can affect other variables in a model but are not themselves affected. If all of the speed of adjustment coefficients relating to an endogenous variables are equal to 0, then in the context of the VECM, the variable is deemed to be exogenous as it does not adjust to deviations from the long run equilibrium relationships that are identified in β_j'. Tables 5.8, 5.9 and 5.10 show the estimates of the speed of adjustment coefficients, goodness of fit and the weak exogeneity results from the likelihood ratio (LR) statistics for VECMs 1a and 1b:

Table 5.8: Estimates of the speed of adjustment coefficients: VECM 1a and VECM 1b

VECM 1a	Speed of adjustment coefficients		VECM 1b	Speed of adjustment coefficients	
	α_1	α_2		α_1	α_2
Δln *GDP*	0.053 (0.137)	0.089 (0.035)**	Δln *GDP*	0.000 (0.177)	0.085 (0.040)**
Δln *Govt*	-0.105 (0.178)	-0.019 (0.046)	Δln *Govt*	-0.084 (0.216)	-0.013 (0.049)
Δln *Export*	-0.871 (0.356)**	0.055 (0.092)	Δln *Import*	-1.552 (0.349)***	0.257 (0.079)***
Δln *House*	0.218 (0.142)	0.029 (0.036)	Δln *House*	0.109 (0.187)	0.025 (0.042)

1. The numbers in parentheses are the standard errors.
2. The asterisks ***, ** and * are based on the 1%, 5% and 10% significance levels

Table 5.9: Measures of Goodness of Fit for VECMs 1a and 1b

VECM 1a	Adj. R^2	S.E.	AIC	SIC	VECM 1b	Adj. R^2	S.E.	AIC	SIC
Δln *GDP*	0.626	0.013	-5.672	-5.166	Δln *GDP*	0.584	0.013	-5.565	-5.058
Δln *Govt*	0.297	0.016	-5.144	-4.638	Δln *Govt*	0.311	0.016	-5.164	-4.658
Δln *Export*	0.370	0.033	-3.755	-3.249	Δln *Import*	0.636	0.026	-4.205	-3.698
Δln *House*	0.592	0.013	-5.599	-5.093	Δln *House*	0.528	0.014	-5.455	-4.949

Table 5.10: Weakly exogenous results for α_i: VECM 1a and VECM 1b

VECM 1a	α_1	α_2	VECM 1b	α_1	α_2
	χ^2	χ^2		χ^2	χ^2
Δln *GDP*	0.175•	6.311	Δln *GDP*	0.000•	4.355
Δln *Govt*	0.360•	0.189•	Δln *Govt*	0.187•	0.073•
Δln *Export*	4.599	0.273•	Δln *Import*	17.143	8.623
Δln *House*	2.858	0.721•	Δln *House*	0.432•	0.414•

The ● symbol denotes a weakly exogenous variable at the 1%, 5% and 10% significance levels

The results in Table 5.8 show that the adjustment coefficients have a significant role to play in at least one of the four short-run equations for each VECM. Furthermore, *GDP*, *Export* and *Import* seem to have the main significant statistics over the *Govt* and *House* variables. However, there is concern about the unlikely overadjustment of *Import* in the first cointegrating equation of VECM 1b as it would suggest that the adjustment from disequilibrium is extremely rapid and would take place in less than a year. There is also an absence of a negative sign on at least one of the adjustment coefficients on the second cointegrating vector of VECM 1b. The weakly exogenous variables from the LR test in Table 5.10 roughly indicate the insignificant adjustment coefficients from Table 5.8. The weak exogeneity test confirms that *GDP* and *Import* statistically plays the most significant part in the long run equilibrium relationship.

Based on the lag order of the underlying VAR(*p*), further evidence to prove the ELG/GLE and IMG/GLI hypotheses are obtained from the Granger causality Wald test statistics in Table 5.11:

Table 5.11: Granger causality tests on the ELG/GLE and IMG/GLI hypotheses

H_0: *X* does not Granger cause *Y*	Wald test		
Models 1a and 1b	χ^2	Prob.	Result
ln *Export* does not Granger cause ln *GDP*	16.363	0.001	Reject***
ln *GDP* does not Granger cause ln *Export*	14.687	0.002	Reject***
ln Im*port* does not Granger cause ln *GDP*	16.363	0.001	Reject***
ln GDP does not Granger cause ln *Import*	14.687	0.002	Reject***

The asterisks ***, ** and * are based on the 1%, 5% and 10% significance levels

The results show that we can reject the null hypothesis of no Granger causality in the *GDP-Export* and *GDP-Import* relationship. Despite the ambiguity of the long run relationship between the variables, bidirectional causality is clearly evident throughout this test and so the widely acknowledged hypotheses ELG/GLE ($Export \leftrightarrow GDP$) and IMG/GLI ($Import \leftrightarrow GDP$) are strongly proven at the 1% level of significance in this instance.

For VECM 2, the estimates of the speed of adjustment coefficients, goodness of fit and weakly exogenous results are highlighted in Tables 5.12, 5.13 and 5.14:

Table 5.12: Estimates of the speed of adjustment coefficients: VECM 2

VECM 2	Speed of adjustment coefficients
	α_1
Δln *GDP*	-0.409 (0.124) ***
Δln *dirTax*	0.397 (0.410)
Δln *indTax*	-0.851 (0.243) ***

1. The numbers in parentheses are the standard errors
2. The asterisks ***, ** and * are based on the 1%, 5% and 10% significance levels

Table 5.13: Measures of Goodness of Fit for VECM 2

VECM 2	Adj. R^2	S.E.	AIC	SIC
Δln *GDP*	0.608	0.013	-5.675	-5.295
Δln *dirTax*	0.177	0.042	-3.287	-2.907
Δln *indTax*	0.496	0.025	-4.335	-3.955

Table 5.14: Weakly exogenous LR test on α_1

VECM 2	α_1
	χ^2
Δln *GDP*	6.670
Δln *dirTax*	0.686 •
Δln indTax1	9.134

The ● symbol denotes a weakly exogenous variable at the 1%, 5% and 10% significance levels

The results from Table 5.12 clearly show that *GDP* and indirect taxes on goods and services such as VAT and environmental taxes (*indTax*) have a very strong role to play in a relatively fast adjustment of the model towards long run equilibrium. The weakly exogenous results in Table 5.14 confirms the absence of direct taxes from the long run adjustment process. The direction of causality in the principal long run relationship is also assessed through the Granger causality results in Table 5.15:

Table 5.15: Granger causality tests on the *indTax* – *GDP* relationship

H_0: X does not Granger cause Y Model 2	Wald test χ^2	Prob.	Result
ln *indTax* does not Granger cause ln *GDP*	8.925	0.030	Reject **
ln *GDP* does not Granger cause ln *indTax*	6.002	0.112	Do not reject

The asterisks ***, ** and * are based on the 1%, 5% and 10% significance levels

The results show that we can reject the null hypothesis of no Granger causality from *indTax* to *GDP* but not the other way round. This means that unidirectional causality runs from $indTax \rightarrow GDP$ at the 5% significance level. This unidirectional relationship finds support in studies such as Scarlett (2011) and Ray et al (2012).

The speed of adjustment, goodness of fit and weakly exogenous estimates for VECMs 3 and 4 are highlighted in Tables 5.16, 5.17 and 5.18:

Table 5.16: Estimates of the speed of adjustment coefficients: VECM 3 and VECM 4

VECM 3	Speed of adjustment coefficients			VECM 4	Speed of adjust.
	α_1	α_2	α_3		α_1
Δln *GDP*	-0.305 (0.104) ***	0.825 (0.452) *	0.315 (0.112) ***	Δln *GDP*	0.025 (0.004) ***
Δln *totTax*	-0.167 (0.158)	1.510 (0.686) **	0.276 (0.171)	*CurrAc*	4.526 (2.387) *
Δln *nonTax*	-0.152 (0.159)	3.514 (0.695) ***	0.546 (0.173) ***	*nTrade*	0.593 (1.842)
Δln *WGS*	0.137 (0.105)	0.068 (0.457)	-0.122 (0.114)	*exRate*	-2.625 (1.962)
Δln *Interest*	-0.560 (0.383)	0.940 (1.668)	0.538 (0.415)		
Δln *SubTr*	0.494 (0.209) **	-1.359 (0.913)	-0.567 (0.227) **		

1. The numbers in parentheses are the standard errors.
2. The asterisks ***, ** and * are based on the 1%, 5% and 10% significance levels

Table 5.17: Measures of Goodness of Fit for VECMs 3 and 4

VECM 3	Adj. R^2	S.E.	AIC	SIC	VECM 4	Adj. R^2	S.E.	AIC	SIC
Δln *GDP*	0.342	0.018	-5.026	-4.566	Δln *GDP*	0.476	0.015	-5.365	-4.943
Δln *totTax*	0.457	0.027	-4.188	-3.728	*CurrAc*	0.180	8.118	7.238	7.661
Δln *nonTax*	0.411	0.027	-4.164	-3.704	*nTrade*	-0.053	6.267	6.721	7.143
Δln *WGS*	0.293	0.018	-5.003	-4.544	*exRate*	0.048	6.673	6.846	7.269
Δln *Interest*	0.519	0.065	-2.413	-1.953					
Δln *SubTr*	0.222	0.035	-3.619	-3.159					

Table 5.18: Weakly exogenous LR test on the speed of adjustment coefficients (α_i)

VECM 3	α_1	α_2	α_3	VECM 4	α_1
	χ^2	χ^2	χ^2		χ^2
Δln *GDP*	4.931	1.550●	9.417	Δln *GDP*	26.590
Δln *totTax*	0.581●	5.317	3.079	*CurrAc*	4.151
Δln *nonTax*	0.046●	10.927	9.198	*nTrade*	0.117●
Δln *WGS*	1.960●	0.022●	1.352●	*exRate*	1.988●
Δln *Interest*	2.555●	0.287●	1.981●		
Δln *SubTr*	2.644	1.099●	4.993		

The ● symbol denotes a weakly exogenous variable at the 1%, 5% and 10% significance levels

The Table 5.16 output from the first cointegrated vector in VECM 3 has a reasonable fit. The adjustment coefficients are statistically significant for *GDP* and government expenditure on subsidies and transfers (*SubTr*). The coefficient of -0.305 means that when GDP moves above equilibrium, it moves towards a relatively quick adjustment down towards the level of *SubTr*. Conversely, the coefficient of 0.494 means that when *GDP* moves above equilibrium, *SubTr* would quickly adjust upwards towards *GDP* at the same time as the downward adjustment of *GDP*. The second and third adjustment coefficients in VECM 3 and the adjustment coefficients in VECM 4 also show statistical significance but there is a lack of negative sign in either VECM 3 (α_2) or VECM 4 (α_1). Tables 5.19 and 5.20 show the Granger causality results for the two main long run relationships with *GDP* in VECM 3 and the principal relationship with *GDP* in VECM 4:

Table 5.19: Granger causality tests on the *nonTax–GDP* and *SubTr–GDP* relationship

H_0: *X* does not Granger cause *Y*	Wald test		
Model 3	χ^2	Prob.	Result
ln *nonTax* does not Granger cause ln *GDP*	0.899	0.638	Do not Reject
ln *GDP* does not Granger cause ln *nonTax*	2.780	0.249	Do not Reject
ln *SubTr* does not Granger cause ln *GDP*	0.545	0.762	Do not Reject
ln *GDP* does not Granger cause ln *SubTr*	11.267	0.004	Reject ***

The asterisks ***, ** and * are based on the 1%, 5% and 10% significance levels

Table 5.20: Granger causality tests on the *CurrAc* – GDP relationship

H_0: *X* does not Granger cause *Y*	Wald test		
Model 4	χ^2	Prob.	Result
ln C*urrAc* does not Granger cause ln *GDP*	2.651	0.449	Do not Reject
ln *GDP* does not Granger cause ln *CurrAc*	2.781	0.427	Do not Reject

The asterisks ***, ** and * are based on the 1%, 5% and 10% significance levels

The results show that we do not reject the null hypothesis of no Granger causality in all but one relationship in models 3 and 4. The sole direction of causality in model 3 runs strongly from $GDP \rightarrow SubTr$ at the 1% significance level. This unidirectional relationship has a strong theoretical basis for the UK, even in times of a large fiscal deficit, which suggests that there could be a political rather than an economic dynamic to this relationship.

5.6.6 Forecast evaluation of the five VECMs

In order to assess the forecasting ability of the five VECM relationships, the in-sample period is estimated from 1972 to 2010. This leaves four observations from the sample period between 2011 and 2014. These remaining observations are compared to dynamic forecasts that are generated during the same period in order to derive the forecast error, with a low forecast error for each variable and observation denoting a good forecast. A further comparative analysis is carried out by comparing the forecast errors from the unconstrained VECM with the forecast errors produced by a constrained VECM. The weak exogeneity tests in the previous section provided information on variables that do not adjust towards the long run cointegrated relationship so the speed of adjustment coefficient on the weakest variable in each constrained VECM is set to zero. The constrained VECM is useful for comparison purposes because if the weak exogeneity condition holds, there would be no losses of information on the remaining parameters that go through the forecast evaluation process.

Tables 5.21 to 5.25 show the forecast errors from each of the five VECMs for both the unconstrained and constrained VECMs. The tables also report the summary statistics from the RMSE, MAE and MAPE evaluation methods:

Table 5.21: Forecast results and evaluation for VECM 1a

VECM 1a	Variable	VECM (unconstrained)				VECM (ln *Govt* constrained)			
		2011	2012	2013	2014	2011	2012	2013	2014
Forecast error	Δln *GDP*	-0.0054	-0.0077	0.0005	0.0184	-0.0055	-0.0087	-0.0020	0.0141
	Δln *Govt*	-0.0141	-0.0114	-0.0264	-0.0203	-0.0147	-0.0150	-0.0350	-0.0340
	Δln *Export*	0.0162	-0.0080	0.0220	0.0043	0.0166	-0.0076	0.0232	0.0058
	Δln *House*	-0.0078	-0.0018	0.0047	0.0154	-0.0079	-0.0030	0.0019	0.0111

Evaluation of Forecasts: 2011 to 2014	Variable	VECM (unconstrained)			VECM (ln *Govt* constrained)		
		RMSE	MAE	MAPE	RMSE	MAE	MAPE
	Δln *GDP*	0.0032	0.0007	0.0101	**0.0027 ↓**	**0.0007 ↓**	**0.0095 ↓**
	Δln *Govt*	**0.0058 ↓**	**0.0017 ↓**	**0.0289 ↓**	0.0081	0.0023	0.0394
	Δln *Export*	**0.0044 ↓**	**0.0012 ↓**	**0.0190 ↓**	0.0046	0.0012	0.0200
	Δln *House*	0.0027	0.0007	0.0151	**0.0021 ↓**	**0.0006 ↓**	**0.0080 ↓**

The ↓ and **bold** font denotes the lower (more desirable) forecast evaluation statistic between the unconstrained and constrained VECM

Table 5.22: Forecast results and evaluation for VECM 1b

VECM 1b	Variable	VECM (unconstrained)				VECM (ln *House* constrained)			
		2011	2012	2013	2014	2011	2012	2013	2014
Forecast error	Δln *GDP*	-0.0019	-0.0098	0.0070	0.0291	-0.0004	-0.0041	0.0205	0.0496
	Δln *Govt*	-0.0103	-0.0096	-0.0224	-0.0167	-0.0098	-0.0077	-0.0178	-0.0094
	Δln *Import*	0.0148	-0.0224	0.0242	0.0065	0.0168	-0.0149	0.0424	0.0331
	Δln *House*	-0.0041	-0.0037	0.0112	0.0254	-0.0024	0.0027	0.0260	0.0476

Evaluation of Forecasts: 2011 to 2014	Variable	VECM (unconstrained)			VECM (ln *House* constrained)		
		RMSE	MAE	MAPE	RMSE	MAE	MAPE
	Δln *GDP*	**0.0048 ↓**	**0.0011 ↓**	**0.0151 ↓**	0.0082	0.0017	0.0235
	Δln *Govt*	0.0048	0.0014	0.0236	**0.0036 ↓**	**0.0010 ↓**	**0.0179 ↓**
	Δln *Import*	**0.0056 ↓**	**0.0016 ↓**	**0.0253 ↓**	0.0089	0.0025	0.0401
	Δln *House*	**0.0043 ↓**	**0.0010 ↓**	**0.0148 ↓**	0.0083	0.0018	0.0263

The ↓ and **bold** font denotes the lower (more desirable) forecast evaluation statistic between the unconstrained and constrained VECM

Table 5.23: Forecast results and evaluation for VECM 2

VECM 2	Variable	VECM (unconstrained)				VECM (ln *dirTax* constrained)			
		2011	2012	2013	2014	2011	2012	2013	2014
Forecast error	Δln *GDP*	0.0012	0.0002	0.0034	0.0023	0.0004	-0.0005	0.0001	-0.0061
	Δln *dirTax*	0.0074	-0.0282	0.0068	0.0149	-0.0038	-0.0485	-0.0292	-0.0388
	Δln *indTax*	0.0168	0.0236	0.0252	0.0015	0.0155	0.0233	0.0220	-0.0081

Evaluation of Forecasts: 2011 to 2014	Variable	VECM (unconstrained)			VECM (ln *dirTax* constrained)		
		RMSE	MAE	MAPE	RMSE	MAE	MAPE
	Δln *dirTax*	**0.0007 ↓**	**0.0002 ↓**	**0.0022 ↓**	0.0009	0.0002	0.0022
	Δln *GDP*	**0.0051 ↓**	**0.0013 ↓**	**0.0246 ↓**	0.0105	0.0028	0.0514
	Δln *indTax*	0.0059	**0.0016 ↓**	**0.0299 ↓**	**0.0056 ↓**	0.0016	0.0306

The ↓ and **bold** font denotes the lower (more desirable) forecast evaluation statistic between the unconstrained and constrained VECM

Table 5.24: Forecast results and evaluation for VECM 3

VECM 3	Variable	VECM (unconstrained)				VECM (ln *WGS* constrained)			
		2011	2012	2013	2014	2011	2012	2013	2014
Forecast error	Δln *GDP*	0.0050	-0.0014	-0.0056	0.0034	-0.0055	-0.0247	-0.0454	-0.0486
	Δln *totTax*	0.0109	-0.0171	-0.0192	0.0220	0.0101	-0.0141	-0.0225	0.0202
	Δln *nonTax*	-0.0009	-0.0473	0.0276	0.0088	-0.0129	-0.0769	-0.0236	-0.0597
	Δln *WGS*	-0.0025	0.0124	-0.0037	0.0209	-0.0185	-0.0205	-0.0558	-0.0466
	Δln *Interest*	0.0073	-0.0549	-0.0453	-0.0653	0.0138	-0.0576	-0.0808	-0.1227
	Δln *SubTr*	0.0022	0.0366	0.0194	0.0200	0.0003	0.0410	0.0342	0.0464

Evaluation of Forecasts: 2011 to 2014	Variable	VECM (unconstrained)			VECM (ln *WGS* constrained)		
		RMSE	MAE	MAPE	RMSE	MAE	MAPE
	Δln *GDP*	**0.0013 ↓**	**0.0004 ↓**	**0.0048 ↓**	0.0109	0.0029	0.0388
	Δln *totTax*	0.0054	0.0016	0.0267	**0.0053 ↓**	**0.0016 ↓**	**0.0258 ↓**
	Δln *nonTax*	**0.0085 ↓**	**0.0020 ↓**	**0.0387 ↓**	0.0154	0.0040	0.0786
	Δln *WGS*	**0.0038 ↓**	**0.0009 ↓**	**0.0171 ↓**	0.0119	0.0033	0.0610
	Δln *Interest*	**0.0148 ↓**	**0.0040 ↓**	**0.1036 ↓**	0.0242	0.0064	0.1634
	Δln *SubTr*	**0.0070 ↓**	**0.0018 ↓**	**0.0311 ↓**	0.0108	0.0028	0.0487

The ↓ and **bold** font denotes the lower (more desirable) forecast evaluation statistic between the unconstrained and constrained VECM

Table 5.25: Forecast results and evaluation for VECM 4

VECM 4	Variable	VECM (unconstrained)				VECM (ln *nTrade* constrained)			
		2011	2012	2013	2014	2011	2012	2013	2014
Forecast error	Δln *GDP*	-0.0147	-0.0127	0.0038	0.0221	-0.0154	-0.0144	0.0010	0.0188
	Δ*CurrAc*	14.1636	0.3981	-9.8519	-12.1799	14.9460	1.7240	-7.9870	-9.7231
	Δ*nTrade*	11.7784	5.5970	1.4773	5.4600	12.5451	6.9398	3.4994	8.1579
	Δ*exRate*	8.0879	12.6795	10.6659	18.2036	8.2941	13.3354	11.6408	19.4349

Evaluation of Forecasts: 2011 to 2014	Variable	VECM (unconstrained)			VECM (ln *ntrade* constrained)		
		RMSE	MAE	MAPE	RMSE	MAE	MAPE
	Δln *GDP*	0.0045	0.0012	0.0168	**0.0043 ↓**	**0.0012 ↓**	**0.0156 ↓**
	Δ*CurrAc*	3.2212	0.8510	1.5543	**2.9910 ↓**	**0.7995 ↓**	**1.4634 ↓**
	Δ*nTrade*	**2.1677 ↓**	**0.5654 ↓**	**1.4609 ↓**	2.5715	0.7242	1.7998
	Δ*exRate*	**3.9512 ↓**	1.1543	**1.2396 ↓**	4.2037	**1.2257 ↓**	1.3285

The ↓ and **bold** font denotes the lower (more desirable) forecast evaluation statistic between the unconstrained and constrained VECM

Concerning the forecast errors, a negative statistic indicates an overpredicted forecast and a positive statistic indicates an underpredicted forecast, with zero indicating a perfect forecast. The results show that the unconstrained VECMs have a stronger forecast performance than the constrained VECMs as the unconstrained VECMs have lower forecast errors and evaluation statistics in models 1a, 1b, 2 and model 3. The constrained VECM 4 performs only slightly better than the unconstrained VECM 4 but unlike the other VECMs, the comparatively large forecast errors in VECM 4 are due to the non-conversion of the variables to their natural logarithms. In most cases, the differences between the unconstrained and constrained forecast errors for VECMs 1a, 1b, 2 and model 3 are usually ≤0.015, which implies that they are close to each other in terms of their forecast accuracy.

5.6.7 The British economy in 2050

The next stage involves the estimation of long run econometric projections towards 2050, using the parsimonious VECMs that were previously estimated. The forecast evaluation results in section 5.6.6 show that the unconstrained VECM produces the stronger of the two forecasts, so it will be used in this section to estimate the long run projections of the economic and fiscal data. The projected data for 2050 forms a critical part of the next section in this chapter as the projected values are fed into a CGE model. An assessment is then carried out on the economic impact of the three energy pathways in 2050, based on the projected energy-related data from Chapter 4, namely the Fusion Pathway, the National Grid pathway and the Friends of the Earth pathway.

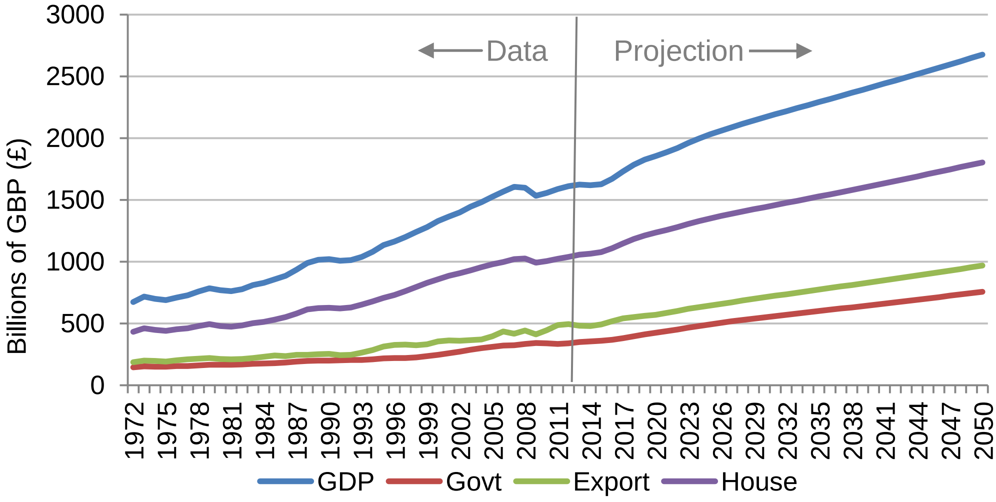
A major consideration in the estimation of long run economic and fiscal projections that have an energy focus is the inclusion of past and projected oil prices as an exogenous series (Fouré et al; 2010). This section uses real crude oil price data from BP's Statistical Review of World Energy from 1972 to 2015 based on 2015 USD (BP, 2016) and projected real crude oil price data from the UK's Department of Business, Energy and Industrial Strategy (BEIS) from 2016 to 2040 based on 2016 USD (BEIS, 2016). The models assume that crude oil prices would continue to grow at an average rate from 2041 to 2050.

However, there is still the problem of the global financial crisis of 2008-09 as the long run projections do not permit the inclusion of a break dummy variable within the model. There is a possibility of using a pre-financial crisis year such as 2006 but the financial crisis involved the collapse in production through liquidity constraints on debt and investment as well as an overall drop in income. These factors are likely to have induced a long-term effect on economic output and may skew the projections to an unrealistic path. Therefore, the projections follow Fouré et al (2010) by using the IMF forecast for GDP between the autumn of 2011 to 2012, with adjustments made accordingly for the constituents of GDP (IMF, 2011). This is a relatively mild feature as the assumption is that the gap in economic output would have narrowed by then. As a result, the long run projections now span from 2013 to 2050[30].

[30] The projections do not consider the numerous publications of various economic scenarios that could arise from the UK's decision to withdraw from the European Union in the 2016 referendum. This is due to the uncertainty surrounding the future UK-EU trade relationship and the relatively strong economic growth forecasts for 2017 from several financial services institutions, highlighted in HM Treasury (2017).

Figure 5.1 and 5.2 shows the existing and projected data from VECMs 1a and 1b. Figure 5.3, 5.4 and 5.5 also shows the existing and projected data from VECMs 2, 3 and 4 but the projected GDP variable is omitted from these graphs as the focus is on the other projections. All variables are projected in constant 2010 GBP:

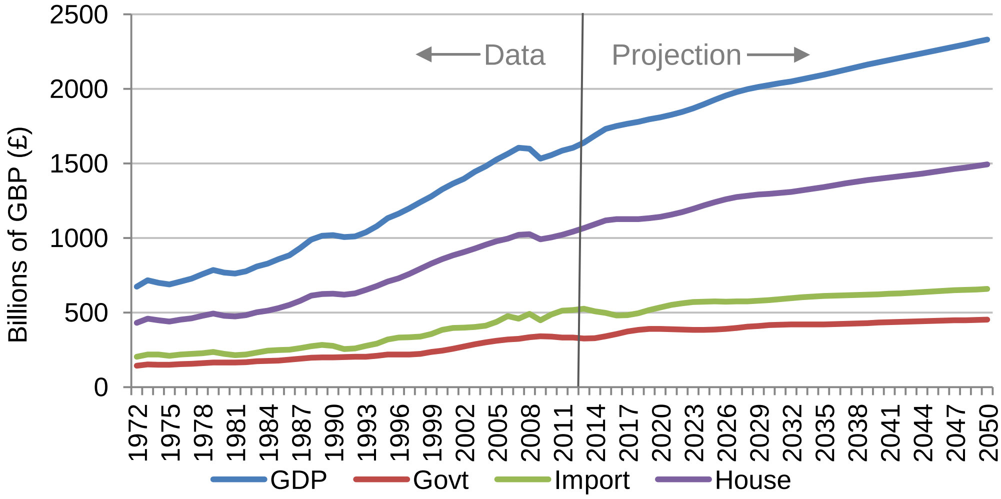
Figure 5.1: Past and projected GDP and its constituents (VECM 1a): 1972 - 2050



Source: Data from 1972 - 2011 (World Bank, 2016) and 2011 - 2012 (IMF, 2011)

Projections from 2013 - 2050 (Author's calculations)

Figure 5.2: Past and projected GDP and its constituents (VECM 1b): 1972 - 2050

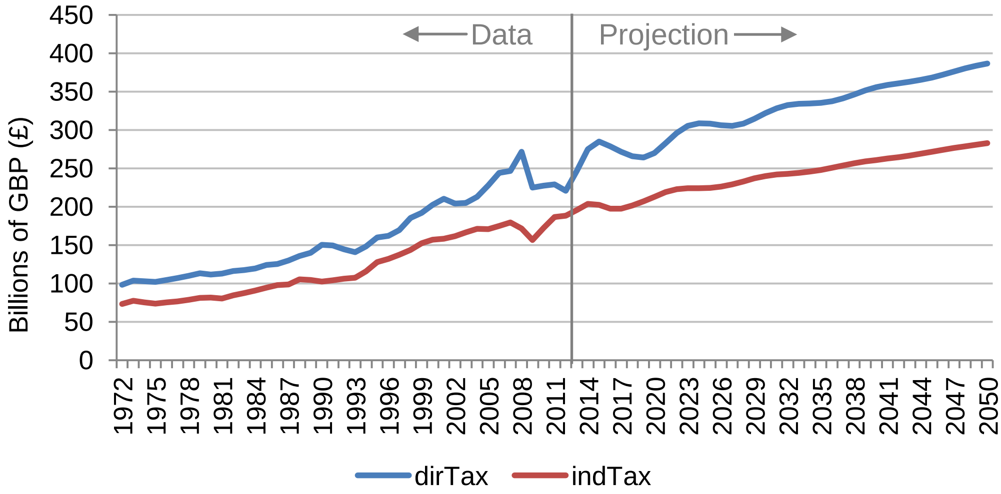


Source: Data from 1972 - 2011 (World Bank, 2016) and 2011 - 2012 (IMF, 2011)

Projections from 2013 - 2050 (Author's calculations)

Figure 5.1 and 5.2 shows the steady expansion of economic growth during the life of the projection. There's an initial slight lift in the GDP projection during the first 5 years prior to stabilisation. The long run curve shows signs of a dynamic economy, with a 72% increase in GDP between 2010 and 2050. The success of the economy filters through to the constituents of GDP as the net trade balance (export less imports) improves from a deficit of 2.8% of GDP in 2010 to a deficit of 0.2% of GDP in 2050. Household and government consumption enjoy consistent growth and but their curves slightly diverge from each other during the latter part of the projection.

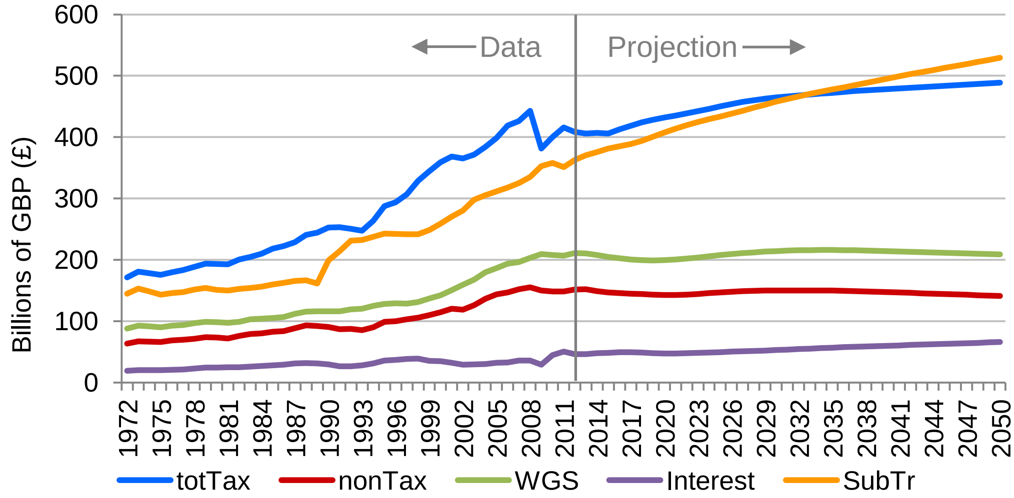
Figure 5.3: Past and projected direct and indirect taxes (VECM 2): 1972 - 2050



Source: Data from 1972 - 2011 (World Bank, 2016) and 2011 - 2012 (IMF, 2011)
Projections from 2013 - 2050 (Author's calculations)

Direct taxes in Figure 5.3 shows a cyclical pattern of three significant dips between 1990 and 2010 and these are reflected in the first 15 years of the projection, with a stable rise of the curve towards 2050. However, both direct and indirect taxes have fallen as a percentage of GDP in real terms as the drop in direct taxes between 2010 and 2050 is 1.8% and the drop in indirect taxes is 0.9%. The long run connection in Figure 5.3 between GDP growth and tax decreases correspond to the cointegration results in Table 5.6.

Figure 5.4: Past and projected fiscal variables (VECM 3): 1972 - 2050

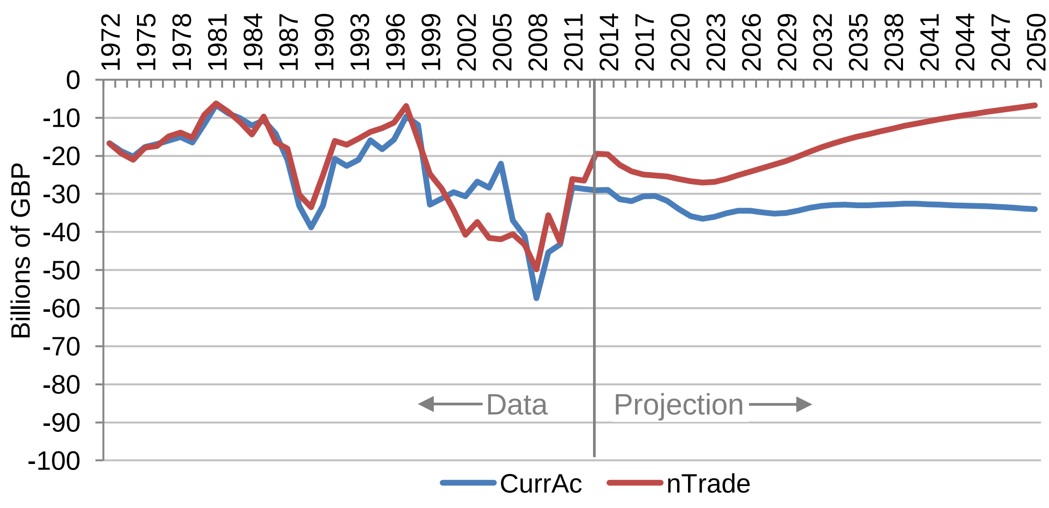


Source: Data from 1972 - 2011 (World Bank, 2016) and 2011 - 2012 (IMF, 2011)

Projections from 2013 - 2050 (Author's calculations)

Figure 5.4 shows that total taxes roughly reflects the pattern of its individual components in Figure 5.3, with a steady inclining curve and a slight bow shape. Fiscal policy during the projected period does not adequately tackle the burden of increasing subsidies and transfers, which are projected to exceed total tax revenues by approximately 2035. Non-tax revenues are not expected to grow at all over the course of the projection period. The lack of adequate revenue growth to cover the government's current expenditure means that increased borrowings are required to cover the budget deficit, which is reflected in the interest payments as they are 47% higher in 2050 than they were in 2010.

Figure 5.5: Past and projected trade variables (VECM 4): 1972 – 2050



Source: Data from 1972 - 2011 (World Bank, 2016) and 2011 - 2012 (IMF, 2011)

Projections from 2013 - 2050 (Author's calculations)

Figure 5.5 shows two significant components of the UK's balance of payments: the current account balance and its constituent, net trade in goods and non-factor services. The current account experiences a slight dip for a few years after 2020, and stabilises at a balance below the £30 billion mark throughout the remainder of the projected period. On the other hand, the net trade balance experiencing an upturn after 2023 that takes it to levels not seen since the year prior to the change in the political regime in 1997. The widening gap between the net trade and current account balance is a reflection of the large gap that first appeared at approximately 2002 and is primarily made up of the growth in net private transfers to non-UK residents and from UK residents to people and entities abroad.[31]

5.7 Empirical analysis 2: Computable general equilibrium model

5.7.1 Trade elasticities

The first stage of the analysis consists of an estimation of the parameters that are related to international trade, namely the transformation elasticity Ω from the CET equation and the substitution elasticity σ from the CES equation. Estimates of these parameters are required as they help to determine the optimal ratio between the exported good and the domestically sold good as well as between the imported good and the demanded domestic good respectively. There is no consensus in the literature in relation to the value to set for the transformation elasticities for exports and substitution elasticities for imports as even single countries have wide-ranging elasticities that are estimated for different sample periods at different points in time. For example, Devarajan, Go and Li (1991) from the World Bank published the export and import elasticities for 87 countries, with each country showing a broad range of trade elasticities that are based on the different econometric methods that were used.

The approach in this section recognises that the CET export elasticity might be affected by long or short run lags in supply behaviour as well as transient changes in trade policies, which can be complicated to assess without additional microeconomic data. Nevertheless, the long run trade elasticities are estimated using the autoregressive distributed lag (ARDL) method of

[31] Net private transfers consist of net primary income and net secondary income. Net primary income on the balance of payments comprises the receipts and payments of employee wages to non-UK residents as well as the receipts and payments of investment income of direct, portfolio and other types of investment (World Bank, 2016). Net secondary income on the other hand comprises the current transfers that are unilaterally made without anything received in return such as money transfers, UK foreign aid and donations.

cointegration analysis as it can adequately estimate the simultaneity between economic growth, prices and trade. Alongside the assumption of imperfect substitutability between domestic and foreign products, the model assumes that price uniformity holds, and that trade and price elasticities related to economic growth are constant over time.

The model that is used to explain the relationship between foreign economic activity (*USgdp*), UK exports (*export*) and relative export prices (*rexpp*) follows Hooper et al (2000) and is based on the following unrestricted error correction form of the ARDL model specification that was previously described in Chapter 3:

$$\Delta \ln USgdp_t = \beta_0 + \sum_{\mathrm{i}=1}^{p} \beta_{1\mathrm{i}} \Delta\ln USgdp_{t-i} + \sum_{\mathrm{i}=0}^{q} \beta_{2\mathrm{i}} \Delta\ln export_{t-i} + \sum_{\mathrm{i}=0}^{q} \beta_{3\mathrm{i}} \Delta \ln rexpp_{t-i}$$
$$+\lambda_1 \ln USgdp_{t-1} + \lambda_2 \ln export_{t-1} + \lambda_3 \ln rexpp_{t-1} + \varepsilon_{1t} \quad (5.31)$$

where ε is the error term. All variables are converted to their natural logarithms and the *rexpp* variable is measured as the ratio between the export price index and the GDP deflator for country *X*, both expressed in USD (index year 2010 = 100). The United States represents country *X* in this section due to the size of its economy and the extent of its trade relationship with the UK so *rexpp* = $\ln\left(\frac{UKepx * USdxy}{USde}\right)$, where *UKepx* is the UK export price index in GBP, *USdxy* is the currency index for the US dollar, commonly known as the US dollar index and *USde* is the US GDP deflator in USD.

The model that is used to explain the relationship between the UK's domestic economic activity (*UKgdp*), UK imports (*import*) and relative import prices (*rimpp*) is based on the following unrestricted error correction form of the ARDL model:

$$\Delta \ln UKgdp_t = \beta_0 + \sum_{\mathrm{i}=1}^{p} \beta_{1\mathrm{i}} \Delta\ln UKgdp_{t-i} + \sum_{\mathrm{i}=0}^{q} \beta_{2\mathrm{i}} \Delta\ln import_{t-i} + \sum_{\mathrm{i}=0}^{q} \beta_{3\mathrm{i}} \Delta \ln rimpp_{t-i}$$
$$+\lambda_1 \ln UKgdp_{t-1} + \lambda_2 \ln import_{t-1} + \lambda_3 \ln rimpp_{t-1} + \varepsilon_{1t} \quad (5.32)$$

All variables are converted to their natural logarithms and the *rimpp* variable is measured as the natural logarithm of the ratio between the UK's import price index (*UKipx*) and the GDP deflator (*UKde*): $\ln\left(\frac{UKipx}{UKde}\right)$, with both variables expressed in GBP (index year 2010 = 100).

The two ARDL models use annual time series data, which consists of 32 observations spanning from 1983 to 2014. The length of the sample period was chosen subject to the availability of data. Price indices for the UK's exports and imports are obtained from the UK Balance of Payments: the Pink Book (ONS, 2016a). Data for the US dollar index is obtained from Macrotrends (2016). Data for the UK's GDP deflator is obtained from the UK National Accounts, the Blue Book (ONS, 2016b). Finally, data for UK GDP, imports and exports as well as US GDP and the US GDP deflator are obtained from the World Development Indicators (World Bank, 2016)

Due to the duration of sample period, a lag length of 1 is chosen. Following Hooper et al (2000), the estimates of trade elasticities are deemed viable if they produce non-negative coefficients, are as close to unity as possible and are not subject to autocorrelated residuals. Similarly to the previous section in this chapter, the global financial crisis of 2007-08 is deemed to have led to a structural break in the data, which is accounted for by the inclusion of a break dummy variable dv.

The unit root test results in Appendix 5.1 shows that we cannot reject the null hypothesis of a unit root for the variables i.e. all variables are $I(1)$. Table 5.26 provides a summary of the ARDL lag selection criteria based on AIC and Table 5.27 shows the results of the ARDL-bounds test for cointegration:

Table 5.26: AIC selection criteria for trade models

Model rank	Model with ln *export*		Model with ln *import*	
	AIC	Specification	AIC	Specification
1	-5.961	ARDL(1, 0, 0)	-5.920	ARDL(1, 1, 1)
2	-5.907	ARDL(1, 1, 0)	-5.869	ARDL(1, 1, 0)
3	-5.897	ARDL(1, 0, 1)	-5.868	ARDL(1, 0, 0)

Table 5.27: Bounds test of ARDL trade models

Model	Significance level	10%	5%	1%	F-Stat	Result
ARDL(1, 0, 0)	$I(0)$ Bound	2.63	3.10	4.13	31.044	Cointegration***
ln *export*	$I(1)$ Bound	3.35	3.87	5.00		
ARDL(1, 1, 1)	$I(0)$ Bound	2.63	3.10	4.13	11.923	Cointegration***
ln *import*	$I(1)$ Bound	3.35	3.87	5.00		

***, ** and * are based on the 1%, 5% and 10% significance levels respectively

The AIC lag selection criteria shows that the optimum models for further testing and analysis are the ARDL(1, 0, 0) for the export elasticity and ARDL(1, 1, 1) for the import elasticity. The calculated *F*-statistics in Table 5.27 are higher than the upper bounds at the 10%, 5% and 1% significance levels. This means that we reject the null hypothesis of no cointegration at all levels of significance. The results therefore show that there is a long run cointegrated relationship among the variables for both models. Table 5.28 shows the extent of the export and price elasticities in the long run:

Table 5.28: Long run coefficients from the unrestricted error correction representation

Dep. variable: ln *USgdp*	ARDL(1, 0, 0) with ln *export*	Dep. variable: ln *UKgdp*	ARDL(1, 1, 1) with ln *import*
ln *export*	0.812(0.085) ***	ln *import*	1.025(0.249) ***
ln *rexpp*	-0.214(0.079) ***	ln *rimpp*	0.073(0.187)
dv	-0.105(0.033) ***	*dv*	-0.167(0.091) *
C	9.648(2.566) ***	*C*	0.680(6.621)

1. The numbers in parentheses are the standard errors.
2. The asterisks ***, ** and * are based on the 1%, 5% and 10% significance levels

The coefficients for the export and import elasticities are economically significant as they have the right signs and are close to unity. They are also statistically significant at the 1% level. The results show that a 1% increase in US GDP corresponds to a 0.8% increase in UK exports and a 1% increase in UK GDP corresponds to slightly more than a proportional increase in imports. The relative export price coefficient is also economically and statistically significant, with a wrong sign estimated for the statistically insignificant relative import price coefficient but both coefficients are not subject to further use as they do not enter into the CGE model.

The estimated trade elasticities are comparable to the previous Hooper et al (2000) estimates for Canada, France, Germany and Japan. Similarly to the previous France and Germany results, the relative price elasticities do not collectively meet the Marshall-Lerner condition[32], which stipulates that an exchange rate devaluation or depreciation of the local currency could only improve the balance of trade position if $\ln rexpp + \ln rimpp > 1$ (in absolute terms). Table 5.29 shows the models' diagnostic tests for autocorrelation, normality, heteroskedasticity and functional form:

[32] Boyd et al (2001) provides a comprehensive test of the Marshall-Lerner condition by producing estimates from a VECM, a cointegrated vector ARDL (VARDL) and a single equation cointegrated ARDL. The final model is chosen for our analysis of the *import* and *export* models due to the presence of a single cointegrating vector among the variables in both models.

Table 5.29: Diagnostic tests for ARDL trade models

Model	Autocorrelation (p-value)	Functional form F-stat (p-value)	Normality (p-value)	Heteroskedasticity (p-value)
ARDL(1, 0, 0): ln *export*	0.447 (0.504)	0.249 (0.622)	2.331(0.312)	3.569 (0.468)
ARDL(1, 1, 1): ln *import*	1.065 (0.302)	1.011 (0.325)	1.571(0.456)	2.725 (0.842)

The numbers in parentheses are the probability values (p-values)

The results show that both models pass all of the residual diagnostic and functional form tests. The results are statistically and economically robust and the export and import elasticities can now enter the CGE model.

5.7.2 Economic impact of the Friends of the Earth and Fusion power pathways in 2050

The 2050 projections from the five VECMs are entered into the CGE model. Each VECM assessed the relationship between several variables and GDP but the projections produced final GDP figures for 2050 that were moderately different to each other. The GDP value to be used in the CGE model for 2050 is based on the VECM 1b projection (model with *GDP*, *Govt*, *Import* and *House*). The projected variables from VECMs 2, 3 and 4 are taken as a percentage of their respective GDP projection and multiplied by the GDP projection from VECM 1b in order to standardise the values for the CGE model. The values of three additional variables in 2050 are also included: GDP at factor cost (GDP at market value + subsidies on products – indirect taxes), investment and government capital expenditure. Due to the stable average values of subsidies on products and capital expenditure between 1972 and 2014, the model assumes in 2050 that subsidies on products are 1% of GDP and capital expenditure is 4.74% of GDP. The investment data is derived from GDP and is simply calculated from the following projected values for 2050: *Investment* = *GDP* – *Govt* – *House* – *Export* + *Import*.

The CGE model now considers the economic impact of two estimated energy mix pathways in 2050: The Friends of the Earth and the Fusion Pathways. The approach is similar to Moore (2011), who used the Salter-Swan CGE framework to model the economic impact of two climate change scenarios on projected economic data for 2050. The National Grid Pathway is taken as the reference to which the other two pathways are measured against as it is deemed to be an expert pathway from a multinational energy company and FTSE 100 constituent[33].

[33] The reference pathway could also be construed as the established scenario where there is no current consideration for a change in the capital and primary energy inputs to an alternative strategy. Investors and energy generators in Friends of the Earth and Fusion Pathway are subsequently able to adjust the composition of the energy mix over the course of the projection period due to price signals, greater energy efficiencies and improved technologies.

The capital, operating and fuel costs of the Friends of the Earth and Fusion Pathways act as a shock to the reference pathway due to their diverging values. The capital cost shocks are applied as a percentage increase or decrease to aggregate investment, which consists of capital investment from the representative industry and government as well as the relevant level of capital investment from the representative household. The operating and fuel cost shocks are only applied to government expenditures on wages, goods and services (WGS). Two types of adjustment are applied to the shocks in both pathways in order to maintain the same levels of a critical element of the economy. Table 5.30 shows a summary of the shocks, adjustments and rationale for the adjustment:

Table 5.30: Shocks, adjustments and rationale for the CGE model

Shock	Adjustment	Rationale for adjustment in CGE model
Aggregate investment	Current account balance	Maintains the indirect tax rate No change in government expense on WGS
	Indirect taxes	Prevents a deterioration of the current account deficit No change in government expense on WGS
Govt expense: WGS	Current account balance	Maintains the indirect tax rate Maintains existing levels of aggregate investment
	Indirect taxes	Prevent a deterioration of the current account deficit Maintains existing levels of aggregate investment

The undiscounted annual capital cost of the Friends of the Earth Pathway by 2050 is £210.5bn, whereas the discounted value uses the HM Treasury (2011) Green Book rate of 3% for project and programme costs in 2050. The discounted annual capital cost (2010 prices) of £64.5bn is £17.5bn higher than the discounted reference pathway and represents a +6.3% shock on the aggregate investment value in 2050. This large capital cost outlay is based on the high overall outlay on electrification through increased renewable energy generation and decarbonised transport. This pathway reaches a decarbonisation target of 96% in 2050 in comparison to 1990 levels, which is significantly higher than the minimum decarbonisation target set by the UK Government's 2008 climate commitment of 80% compared to 1990 levels.

For comparison purposes, the Fusion pathway meets the 2050 decarbonisation target with an 81% reduction in GHG emissions compared to 1990 levels. The undiscounted annual capital cost of this pathway by 2050 is £153.5bn, whereas the discounted annual capital cost (2010 prices) of £47.1bn is £2bn lower than the discounted reference pathway and represents a -0.8% shock on the aggregate investment value in 2050. Table 5.31 shows the economic impact of the capital cost shocks and adjustments in the Friends of the Earth and Fusion Pathways:

Table 5.31: Shocks, adjustments and economic impacts - Energy capital costs

2050 energy mix pathways: Capital costs	Friends of the Earth Pathway		Fusion Pathway	
Shock: Aggregate Investment (%)	6.3		-0.8	
Financial adjustment to shock (%)	Current account -77.19	Indirect taxes 16.27	Current account 9.71	Indirect taxes -2.03
Economic impacts (% change)				
Volume of exports	-0.85	0.00	0.11	0.00
Volume of import	2.27	0.00	-0.29	0.00
Supply & demand: Domestic good	0.52	0.00	-0.07	0.00
Supply & demand: Composite good	1.19	0.00	-0.15	0.00
Export to dom. sold good ratio (*X* :1)	0.61	0.62	0.62	0.62
Import to dom. demand good ratio (*X* :1)	0.64	0.62	0.62	0.62
Sales price of composite good	1.04	1.69	-0.13	-0.21
Price of domestic good	1.70	0.00	-0.21	0.00
Subsidies on products	1.04	0.00	-0.13	0.00
GDP at factor cost	1.05	0.00	-0.13	0.00
GDP at market prices	1.18	1.71	-0.15	-0.69
Total Income - Household	1.06	0.00	-0.13	0.00
Aggregate consumption	0.02	-1.66	0.00	0.21
Total tax revenue	1.56	6.87	-0.20	-0.86
Non-tax revenue	1.04	0.00	-0.13	0.00
Other govt current expenditure	0.47	0.00	-0.06	0.00
Aggregate savings	7.41	8.10	-0.93	-1.01
Government savings	-0.41	-17.26	0.05	6.96
Change in indirect tax (£)		40,378m		-5,032m

5.7.2.1 Impact of the current account adjustment on the investment shock

The economic impact results are expressed as a percentage change of the National Grid reference case for comparison purposes. The 6.3% shock on aggregate investment for the Friends of the Earth Pathway demonstrates that in order to maintain the same indirect tax rate and government expenditure on WGS, demand and supply of the composite good would need to increase by 1.19%. The optimal ratio of the export/import good to the domestic good is 61% to 39% and 64% to 36%, which means that the volume of imports would need to increase by 2.27% and exports would need to decrease by 0.85%. This has a substantial effect on the already large current account deficit as it would increase further by 77.19%.

The strength of demand for imported goods means that the economy is subject to inflationary pressures, which overheats the economy and translate into higher prices. Higher demand also increases the profitability for the representative industry through its transition from a predominantly producer focus towards a retail focus, which leads to higher earnings and savings for the household. The burden of increased capital expenditure would mean that government revenues from direct taxes and non-tax sources would need to rise substantially. Total tax revenues would therefore need to increase by 1.56% and non-tax revenues by 1.04%. Although the aggregate savings in the economy has increased significantly by 7.41%, the government's increased capital expenditure on the energy system has led to a slight increase in the budget deficit, which is reflected in a 0.41% decrease in government savings.

The -0.8% shock on aggregate investment in the Fusion Pathway means that GDP at factor cost, which represents the price of aggregate output, declines slightly by 0.13%. GDP at market prices in this pathway is less than in the Friends of the Earth Pathway due to substantially lower investment in the energy system. However, the 0.29% decrease in import demand, the 0.11% increase in exports and lower overall prices imply that economic growth in the Fusion Pathway is on a sustainable path. Total tax and non-tax revenues experience a slight decrease so the government is not able to substantially improve its fiscal position beyond the 0.05% increase in its savings.

5.7.2.2 Impact of the indirect tax adjustment on the investment shock

The results for the indirect tax adjustment show that the optimal ratio of the export/import good to the domestic good is 62% to 38% in favour of the export/import good. In order to prevent an increasing current account deficit and government expenditure on WGS, the Friends of the Earth Pathway demonstrates that the 6.3% shock on aggregate investment would require a corresponding rise in total indirect taxes of 16.27%, which amounts to approximately £40.4bn. The increased capital expenditure on energy also means that the government has a substantial reduction in savings of 17.26%, thereby providing a significant increase in the budget deficit. Inevitably, the high indirect tax increase is reflected in the percentage increase in the sales price of the composite good, which experiences and even higher increase than in the previous current account adjustment at 1.69%.

Environmental taxes form a significant part of the indirect tax rise and consist of an aggregate composition of predominantly *ad varolem* taxes on energy, transportation, pollution and miscellaneous resources. Environmental taxes in 2010 were 23% of the total indirect tax figure and if this share is proportionally applied to 2050, then the extra environmental tax outlay in addition to the reference case figure would be £9.29bn. This equates to an extra £619m environmental tax to industry for every 1% of CO_2 emissions over and above the 81% emission reduction target that was safely met by the Fusion Pathway. The Friends of the Earth Pathway results are also consistent with Bovenberg and de Mooij (1994) in that they challenge the notion of the second dividend from the double dividend hypothesis. This is because the £9.29bn increase in environmental taxes does not lead to the alleviation of direct taxes in the CGE model.

The adjustment to indirect taxes in the Fusion Pathway is -2.03%, which equates to a total indirect tax reduction of £5.03bn and an increase in government savings of 6.96%. In addition to the boost in government resources, this adjustment provides a relief to industry through the levying of cheaper environmental taxes as they are reduced by £467m. The savings to industry is passed onto the sales price of the composite good, which is marginally lower at 0.21%. However, stable demand, lower prices and reduced energy capital investment have led to a slight decline to GDP at market price at -0.69%.

5.7.2.3 Impact of shocks on the government's WGS expenditure

The government's share of total operating and fuel costs of 16.5% is based on the ratio of WGS to household consumption. Therefore the shocks on the government's WGS expenditure are -0.25% and -0.17% for the Friends of the Earth and Fusion Pathways respectively. Table 5.32 shows the economic impact of the operating and fuel cost shocks and adjustments in the Friends of the Earth and Fusion Pathways:

Table 5.32: Shocks, adjustments and economic impacts - Operating and fuel costs

2050 energy mix pathways: Operating and fuel costs	Friends of the Earth Pathway		Fusion Pathway	
Shock: Govt expense – WGS (%)	-0.25		-0.17	
Financial adjustment to shock (%)	Current account 5.60	Indirect taxes -1.17	Current account 1.16	Indirect taxes -0.78
Economic impacts (% change)				
Volume of exports	0.02	0.00	0.01	0.00
Volume of import	-0.05	0.00	-0.03	0.00
Supply & demand: Domestic good	-0.01	0.00	-0.01	0.00
Supply & demand: Composite good	-0.03	0.00	-0.02	0.00
Export to dom. sold good ratio (*X* :1)	0.62	0.62	0.62	0.62
Import to dom. demand good ratio (*X* :1)	0.62	0.62	0.62	0.62
Sales price of composite good	-0.02	-0.04	-0.02	-0.03
Price of domestic good	-0.04	0.00	-0.03	0.00
Subsidies on products	-0.02	0.00	-0.05	0.00
GDP at factor cost	-0.02	0.00	-0.05	0.00
GDP at market prices	-0.03	-0.12	-0.06	-0.03
Total Income - Household	-0.02	0.00	-0.02	0.00
Aggregate consumption	0.00	0.04	0.00	0.03
Total tax revenue	-0.03	-0.15	-0.02	-0.10
Nontax revenue	-0.02	0.00	-0.05	0.00
Other govt current expenditure	-0.01	0.00	-0.02	0.00
Aggregate savings	-0.02	-0.04	-0.02	-0.03
Government savings	-0.95	-0.95	-0.95	-0.95
Change in indirect tax (£)		-885.7m		-602.4m

Both economic shocks indicate that the optimal ratio of the export/import good to the domestic good is approximately 62% to 38% in favour of export and import goods. The economic impacts for both pathways show a degree of similarity due to the low magnitude of the current account shocks on government expenditure on WGS. The difference between the growth in imports and growth in exports is higher in The Friends of the Earth Pathway than in the Fusion Pathway but the actual volumes of trade and prices are similar. Tax revenues are lower in the Friend of the Earth Pathway but government savings decrease by 0.95%, which is the same as the Fusion Pathway due to the similar costs of primary energy inputs.

The higher negative adjustment on indirect taxes in the Friends of the Earth Pathway tells a similar story in that there is a £283.4m reduction in indirect tax revenues over the Fusion Pathway and overall tax revenues are lower. Government savings for the Fusion Pathway decreases by 0.95%, which is the same as the Friends of the Earth Pathway. In general, the impact of both shocks would result in a slightly weaker economic growth in the Friends of the Earth Pathway but household consumption remains similar to the Fusion Pathway.

5.8 Conclusion

This chapter assessed the potential economic impact of fusion power within the context of an future energy mix pathway that provided a more favourable cost outlay than the Friends of the Earth Pathway, with the National Grid Pathway acting as the reference scenario. Five economic relationships that encapsulated the UK's economic activity were based on the theoretical relationships that were established in the economic literature. A multivariate econometric analysis of these relationships was carried out, using Johansen's ML estimator method of cointegration and VECM for short and long run analyses. Forecast evaluations preceded the econometric projections from the VECM relationships towards 2050, which subsequently formed the basis of the future economic climate during the commercialisation period of fusion power. Finally, the competing energy mix pathways were applied as shocks to aggregate investment and government current expenditure, with the policy response adjustments resulting in wider economic implications.

The estimations resulted in a number of significant contributions to the empirical literature in the cointegration/VECM and CGE modelling field. However, the main contributions to the cointegration/VECM literature comes in the form of the five multivariate projections for the UK's economic activity towards 2050, which moved away from the previous 2050 studies that focused on univariate methods as they did not capture the long run synergistic interdependencies between the variables under consideration. From the CGE modelling perspective, the main empirical contribution can be found in the unique application of shocks to the CGE model from the two innovative energy mix pathways, which invoked competing policy response adjustments to the current account balance and environmental taxes via the indirect tax variable. This filled a gap in the literature as most CGE studies in this field apply environmental taxes as the principal shock rather than as an adjustment to a shock as highlighted by Bowen and Stern (2010).

The findings from Johansen's ML estimator of cointegration, Granger causality and VECM estimates shows that the export-led-growth/growth-led export and import-led-growth/growth-led-import hypotheses are proven, with bidirectional causality shown in all relationships and a strong long run equilibrium relationship especially shown where exports and imports are the dependent variables. Long run equilibrium and short run causal relationships were also proven for the other economic relationships in VECMs 2, 3 and 4. The constrained VECMs with the restricted weakly exogenous adjustment coefficients showed weaker statistics from the forecast evaluation exercise. This prompted the sole use of the unconstrained VECMs in the formation of econometric projections to 2050. These projections provided new insights, which were especially apparent in the fiscal variables from VECM 3 as they showed the precarious path of the UK's budget deficit and potential burden of a sovereign debt crisis for future generations. The 2050 projections subsequently acted as the economic backdrop in the CGE model for the shocks and adjustments that manifested from the competing energy mix pathways.

The findings from the projected CGE model show that the 6.3% shock on aggregate investment from the Friends of the Earth energy pathway in 2050 triggered a large adjustment in indirect taxes and its environmental tax constituent. This prompted a moderate increase in economic growth as the environmental tax was recycled back into the economy. However, this caused both inflationary pressures due to higher prices and an immediate risk to industrial productivity due the extra £619m environment tax burden for every 1% of CO_2 emissions above the 81% emissions abatement target that was already met by the Fusion Pathway.

The results from the Friends of the Earth Pathway shock also follow Bovenberg and de Mooij (1994) by challenging the notion of a double dividend from environmental taxes through its lack of alleviation of the direct tax burden. The shock on aggregate investment from the Fusion Pathway induces near static growth due to the lower investment in energy capital costs but prices are marginally lower and environmental taxes are reduced by £467m over the National Grid reference pathway. The lower environmental taxes burden provides a boost to industry through higher retention of profits and increased confidence in production. The policy response adjustment to the current account balance also results in a higher level of industrial confidence in the Fusion Pathway through a 0.11% increase in exports as opposed to the 0.85% decrease in exports from the Friends of the Earth Pathway.

In his tribute to the late Sir Clive Granger, Taylor (2012) pondered the future of academic publishing within the field of econometrics by stating that "*to look forward, it is initially helpful to look backwards*". The same applies to the estimation of forecasts and long run econometric projections because reasonable expectations of future economic phenomena could only be expected when the estimates are based on accurate past and present data of a sufficient sample size. Forecasts form an essential ingredient in the holistic approach to time series analysis so it is crucial that forecasts are robustly based on the linkage between established theoretical relationships and appropriate data. However, Phillips (2004) indicated that forty years of extensive improvements in econometric modelling have done little to improve the predictive quality of forecasts, even in the short run. Indeed, the predictive quality of forecasts decreases further as the projected time period increases. Nevertheless, econometric forecasts and projections that are estimated with theoretically robust modelling frameworks would provide a hypothetical and tolerable direction of travel and would provide policy makers with useful information to assist in their decision making processes.

The most obvious future area of research regarding the CGE modelling of the competing energy mixes would involve the disaggregation of various sectors of industry. The Salter-Swan framework consists of a transparent structure that systematically demonstrates how shocks and policy adjustments affect the wider economy. Its structure operates in a similar fashion to multisector models but lacks detail as to whether environmental tax adjustments have a distortionary effect on the most polluting industries. Although not necessary for the scope of this chapter, future research could focus on the effect of further shocks to the CGE model from variables such as aggregate output and government transfers. The future energy system may also benefit from sensitivity tests on shocks to the real effective exchange rate and export price adjustments in order to determine any additional benefits that would filter into the industrial sector.

CHAPTER 6

CONCLUSION

This thesis investigates the role that fusion power might potentially play during the estimated period of initial commercialisation of 2045 – 2050, based on the "Case 1" schedule estimated by Ward et al (2004). This potential commercialisation period also receives support from a group of scientists from the EURATOM/UKAEA Fusion Association, on the basis that the inclusion of buttresses would reduce the overall risk of the first commercial power plant (Cook et al, 2005). The extensive estimates in this thesis are justified given the high import dependency from foreign sources of energy, the gradual depletion of finite fossil fuels, the migration of the UK's energy system towards full electrification and the need for future energy sources that significantly contribute towards the 2050 target of an 80% reduction in GHG emissions relative to 1990 levels.

The importance of the above factors must be weighed against the configuration of a future energy system that must not be viewed as "cost prohibitive" due the limited budgets that are held by investors, energy companies, the UK Government and other energy stakeholders. The key to maintaining the high goodwill towards the realisation of fusion power lies with the government's commitment to manage an acceptable level of R&D spending, a prime example being the resources committed to the ITER power plant programme, whose budget of €4.6bn in 2004 nearly tripled to a budget of €13bn as of today (ITER, 2014a). Nevertheless, the main objective of this thesis is to produce an overall framework that addresses the need to understand the potential role of fusion power within a future economic context while providing the technical rigour behind various estimates through the use of established econometric and techno-economic energy models.

In Chapter 1, we considered the key role that energy plays in the global economy. The downsides of the current global energy production and consumption path were highlighted and the option of a future role for fusion power within the future energy mix was considered. The technical, historical and economic aspects of fusion power were discussed in the literature review (Chapter 2), with the aim of placing fusion power within the context of the current energy mix. However, the estimated commercialisation phase of fusion power is close to three decades away so it is currently impossible to apply econometric modelling techniques that would assess its performance against other variables within the energy-economy-environment nexus. Chapter 3 addressed this gap in the empirical body of knowledge by providing a guideline of the potential future effect of fusion power on CO_2 emissions abatement, using nuclear fission as an example. Nuclear fission was chosen as a guideline as there were similarities between the two electricity generation technologies. These similarities are apparent in the nuclear reactions that occur for energy generation, complex power plant technology, the capital-intensive nature of the power plants and the long construction periods towards electricity generation.

A single equation, multivariate econometric method was used to estimate the nuclear-GDP-CO_2 nexus, which was also estimated in limited sources of the energy-economic-environment literature. The model also included environmental taxes as a comparative analysis was sought between nuclear electricity generation and punitive government action in relation to their effect on CO_2 emissions abatement while taking other economic variables into account such as industrial electricity consumption. The ARDL-bounds test method of cointegration analysis was therefore used to estimate the long and short run elasticities between the independent variables and the dependent variable, CO_2 emissions with a sample size of 40 years chosen based on the availability of data.

Other models that were estimated include the environmental Kuznets curve (EKC), which assesses the turning point during the sample period when the ratio of CO_2 emissions decreases as a percentage of GDP, and two Granger causality tests. It was found that CO_2 emissions corresponds more strongly in the long and short run to punitive increases in environmental taxes than to electricity generated from nuclear fission. However, this would have the knock-on effect on reducing overall industrial electricity consumption, with its implication of higher energy bills for households and businesses.

The Granger causality tests also show a stronger, bidirectional causal relationship between CO_2 emissions and environmental taxes with an EKC turning point of 1995 to 1999, both of which are either side of the 1997 Kyoto Protocol. The estimates from nuclear fission inevitably lack a stronger correspondence to CO_2 emissions due to safety issues and a lack of commitment from energy companies in the last 30 years (apart from Sizewell B in Somerset) as well as the looming retirement of ageing power plants. Therefore, the implication for fusion power in these estimates is that a safe and consistent supply of electricity from commercialised fusion power plants is required in order for it to correspond more strongly to CO_2 emissions abatement in the future.

A number of contributions to the empirical literature on the CO_2-GDP-nuclear nexus study were made in Chapter 3 such as the inclusion of trade and industrial electricity consumption within a multivariate group. Furthermore, Chapter 3 provides a first of a kind comparative analysis between electricity generated from nuclear fission against the UK Government's punitive action against GHG emissions through the inclusion of aggregate environmental taxes. Unique insights were gained from the comparable Granger causality tests (Wald and MWald) and the impact of environmental taxes on the EKC hypothesis, using CO_2 emissions as the measure of environmental degradation. The research questions in Chapter 1 were addressed and the estimated results demonstrated the technical robustness of the econometric modelling techniques.

Chapter 4 assessed the potential role of fusion power within the future energy mix through the estimates that were generated from the Department of Energy and Climate Change (DECC) 2050 Energy Calculator. The 2050 Energy Calculator is a bottom-up, techno-economic energy model that is used for the generation of future energy scenarios. The estimated future scenarios are based on the underlying energy demand, energy supply, economic and emissions assumptions, which addresses one of the research questions in Chapter 1 as they are hypothetically plausible. The Fusion Pathway consisted of a configuration of the future energy mix that integrated the projections from commercialised fusion power. The Fusion Pathway was compared to two expert pathways from Friends of the Earth and National Grid plc as it would provide comparatively different views from an environmental preservation and corporate perspective.

All scenarios were able to generate projections of the energy mix that met the 80% reduction in GHG emissions target based on 1990 levels, with the Friends of the Earth Pathway going much further with a 96% reduction in GHG emissions. It was found that the Friends of the Earth Pathway provided the most surplus electricity over and above the demand level in 2050, which could be stored and/or exported. However, despite the low fuel costs due the higher percentage of renewables, this pathway sacrifices cost containment as it is by far the most capital-intensive pathway. The implication is that much higher levels of investment and debt are required to finance this pathway and it seemingly would not offer an adequate return on investment. The National Grid Pathway provided an intermediate cost route but the Fusion Pathway offered the strongest overall savings between the three pathways. The Fusion Pathway addressed another research question in Chapter 1 by providing a more favourable annual capital cost of the entire energy system by 2050 at £153.5bn. This competitive energy pathway is £6.4bn cheaper than the National Grid Pathway and £57bn cheaper than the Friends of the Earth Pathway[34].

This chapter provides a unique contribution to the empirical literature through the extensive recalibration of the 2050 Energy Calculator in order to consider the impact of fusion power within the future energy mix, with a commercialisation year of 2045. Indeed, the recalibration of the 2050 Energy Calculator pre-empted the government's likely integration of fusion power in a future update of the model. This is based on the following statement by HM Government (2011a) in their 2050 Pathways Analysis: "*the Government is committed to supporting ongoing research both at the Joint European Torus at the Culham Science Centre and also the ITER fusion reactor, currently under construction in France. The most ambitious vision for fusion predicts that, if developed successfully to commercial scale, it could be capable of supplying high levels of low carbon electricity, providing a major contribution to energy needs. We will keep this sector under review for future updates of the 2050 Calculator*".

Chapter 5 assessed the impact of commercialised fusion power on the future projected variables of the British economy. The multiequation, multivariate assessment involved the use of Johansen's ML estimator for cointegration analysis and VECM in order to estimate five theoretical relationships that provide a representative picture of the UK's economic and fiscal activity. Forecast evaluations were conducted and projections of the economic variables were made until 2050, which provided a backdrop for the estimation of the CGE model with the Salter-Swan theoretical framework. The capital expenditure projections from the Fusion Pathway and Friends of the Earth Pathway were subsequently applied as shocks to aggregate investment in the CGE model, with policy response adjustments from the current account balance and environmental taxes via the indirect tax variable. The wider economic impacts of

[34] The capital costs of the energy system consists of (1) energy infrastructure and plant costs (2) costs incurred on agricultural land for bioenergy (3) costs incurred for energy efficiencies and appliances in domestic and commercial buildings (4) costs incurred for industrial processes and (5) capital costs related to transportation vehicles.

these two energy mix pathways were subsequently assessed in areas such as consumption, prices, trade and government savings.

The findings from the econometric part demonstrate that all of the theoretical relationships between GDP and the fiscal and economic variables were largely proven and the forecast evaluations from the unconstrained VECMs where stronger than those from the constrained VECMs that contained the restriction on the weakly exogenous adjustment coefficients. The Friends of the Earth Pathway shows that the 6.3% shock to aggregate investment and the policy response to the current account has a negative effect on the trade balance. GDP is marginally increased due the increase in investment but there are inflationary pressures in the economy that translate into higher prices. From a supply side perspective in the model, this corresponds to an increase in total taxation. The Fusion Pathway capital expenditure shock of -0.8% on investment and policy response to the current account balance improves the current account deficit, lowers prices and has a relatively stable effect on GDP.

When assessing the second policy response adjustment in the form of environmental taxes (via the indirect tax variable), the £9.29bn increase in environmental taxes for the Friends of the Earth Pathway amounts to an extra £619m in environmental taxes for every 1% of CO_2 emissions over and above the 81% decarbonisation target that was already met by the Fusion Pathway. The hit that industry takes with the higher environmental tax is transferred to the sales price of the composite good, which increases by 1.69%. On the other hand, the environmental tax burden for industry in the Fusion Pathway is reduced by £467m and the sales price of the composite good is reduced by 0.21%. However, it remains open as to whether a continuous reduction in environmental taxes beyond 2050 would weaken the government's deterrent against CO_2 emissions. A possible solution would be an environmental tax that is sufficient in its deterrent attribute but fair enough to maintain confidence in industrial production and supply.

A number of significant contributions to the literature were made but the major contribution to the cointegration/VECM empirical literature comes in the form of an estimation of five theoretical relationships, which sought to provide a representative picture of the UK's economic activity as well as the econometric projections towards 2050. The empirical use of the CGE model also contributes to the literature on the Salter-Swan framework by providing a comparative analysis between the impact of the Friends of the Earth Pathway and the Fusion

Pathway towards the decarbonisation target in 2050, with the econometric projections providing the economic climate in 2050. The capital expenditure shocks to investment and the comparative policy responses to the current account and environmental taxes (via the indirect tax variable) finds a unique placement for itself within the CGE literature on the Salter-Swan framework. The research questions in Chapter 1 were addressed through the detailed output that was derived from the cointegration, VECM and CGE model analyses and the rigorous modelling processes were justified by the generation of viable estimates with plausible inferences.

The integration of the theoretical frameworks and the empirical estimates from the econometric and techno-economic energy models affirms the vital role that fusion power could play during the potential period of commercialisation in the middle of this century. The use of different modelling tools is indeed a key contributory area of this thesis as it provides a holistic approach into the analysis of several different aspects of fusion power generation. Care was taken in thesis to ensure that the econometric specifications in the single and multiequation approaches were theoretically consistent and empirically credible. The comparative pathways of the UK's 2050 energy mix also provide an important gauge that enables comparisons to be carried out against the well-researched opinions set out by experts. This thesis supports the principle of a continued effort towards the fast or semi-fast track option in order for the commercialisation period of fusion to coincide with the decarbonisation target year of 2050. Therefore, the empirical research in this thesis would assist policy makers in any determination that they may have to strengthen their R&D annual budgets and strategic drive towards the eventual realisation of commercialised fusion power.

However, there are important limitations to the research that needs to be taken into consideration. Although the nuclear-GDP-CO_2 nexus estimation provided a strong empirical basis, it will take many decades before a similar type of analysis could be conducted for commercialised fusion power so caution should be taken as to what extent the inferences are applicable to fusion power. For Chapter 4, the levelised costs of electricity (LCOE) calculation produced electricity price estimates that were competitive but this does not translate into the effect on energy bills as other factors that are not built into the 2050 Energy Calculator need to be taken into consideration such as taxes and subsidies. As previously stated in the literature review, the global fusion research and development programme has absorbed a significant amount of funds but these are not added to the 2050 Energy Calculator in 2045 or 2050, despite the potential for such future costs to be capitalised on the eventual realisation of commercialised fusion power. As the model is user-driven rather than market-driven, price interactions between demand levels are not taken into consideration i.e. there is no elasticity of demand response to relative changes on the cost of electricity generation. The use of cost optimisation models such as TIMES (The Integrated MARKAL-EFOM System) may add value to future research as they are able to estimate the demand responses to different prices.

The projections of the UK's economy in 2050 from Chapter 5 were only intended to provide a backdrop for estimation purposes rather than a highly accurate picture of what the economy would look like in 2050. Indeed, the famous Box and Draper (1987) phrase "*all models are wrong, but some are useful*" is even more applicable to econometric projections that are estimated into the very long run due to the greater level of uncertainty in the future stochastic path of time series variables. There are a number of similarities between the results that emanate from the multisector CGE models and the Salter-Swan three-good framework. However, future areas of research could be made on the competing energy mix pathways based on highly disaggregated CGE models where the production activities and the energy inputs are categorised by sector. Alongside the disaggregation of sectors, future research should also aim at disaggregating environmental taxes into categories such as transports taxes or into any of the large individual taxes such as Renewable Energy Obligations. This is in order to obtain a better understanding of the distortionary effect of specific tax adjustments levied to industries that emit varying levels of greenhouse gases.

APPENDICES

Chapter 3 appendices

3.1 ARDL models for EKC estimation

General ARDL models and models with *nuc* for EKC estimation

Variable	ARDL(1, 1, 0, 1, 0) General model	ARDL(1, 1, 0, 1, 0, 1) General with ln *trade*	ARDL(1, 0, 1, 0) ln *nuc* only	ARDL(1, 0, 1, 0, 0) ln *nuc* and ln *trade*
ln co_2(-1)	0.177 (0.187)	0.097 (0.209)	0.569 (0.158)	0.599 (0.168)
ln gdp	5.601 (4.262)	6.804 (5.023)	4.571 (4.602)	6.229 (5.503)
ln gdp(-1)	-0.596 (0.271)	-0.751 (0.297)		
(ln $gdp)^2$	-0.252 (0.212)	-0.307 (0.254)	-0.197 (0.231)	-0.286 (0.281)
(ln $gdp)^2$(-1)			-0.039 (0.014)	-0.038 (0.015)
ln nuc	-0.062 (0.057)	-0.049 (0.059)	-0.048 (0.045)	-0.054 (0.047)
ln $nuc(-1)$	0.115 (0.060)	0.109 (0.061)		
ln $entax$	-0.338 (0.112)	-0.382 (0.118)		
ln $trade$		-0.097 (0.125)		0.062 (0.110)
ln $trade(-1)$		0.158 (0.116)		
$break\ dv$	-0.034 (0.008)	-0.038 (0.008)	-0.024 (0.007)	-0.024 (0.008)
$intercept$	-20.912 (20.753)	-25.948 (24.876)	-21.127 (22.727)	-29.645 (27.494)
Adjusted R-squared	0.954	0.954	0.942	0.941
S.E. of regression	0.028	0.028	0.032	0.032

The numbers in parentheses are the standard errors.

ARDL models with ln *entax* for EKC estimation

Variable	ARDL(1, 0, 1, 0) ln *entax* only	ARDL(1, 0, 1, 0, 1) ln *entax* and ln *trade*	ARDL(1, 0, 1, 0, 1, 0) ln *entax*, ln *trade* and ln *indelec*
ln co_2(-1)	0.268 (0.182)	0.197 (0.198)	-0.297 (0.166)
ln gdp	6.760 (3.229)	8.855 (3.840)	1.078 (3.058)
(ln $gdp)^2$	-0.298 (0.163)	-0.400 (0.196)	-0.029 (0.154)
(ln $gdp)^2$(-1)	-0.040 (0.013)	-0.048 (0.014)	-0.035 (0.010)
ln $entax$	-0.285 (0.100)	-0.323 (0.103)	-0.319 (0.073)
ln $trade$		-0.082 (0.121)	-0.286 (0.093)
ln $trade(-1)$		0.169 (0.116)	0.195 (0.083)
ln $indelec$			0.529 (0.095)
$break\ dv$	-0.033 (0.008)	-0.038 (0.008)	-0.033 (0.006)
$intercept$	-30.314 (15.524)	-40.659 (18.830)	1.058 (15.302)
Adjusted R-squared	0.952	0.952	0.976
S.E. of regression	0.029	0.029	0.021

The numbers in parentheses are the standard errors.

3.2 Output from VAR models for Granger causality analysis

VAR(p) model for Granger causality analysis

Variables	$\ln co_2$	$\ln gdp$	$\ln nuc$	$\ln entax$	$\ln trade$	$\ln indelec$
$\ln co_2$(-1)	-0.663 (0.280)	-0.201 (0.170)	0.055 (0.899)	-0.666 (0.350)	-0.473 (0.551)	-0.610 (0.352)
$\ln co_2$(-2)	-0.735 (0.268)	-0.051 (0.163)	0.284 (0.862)	0.169 (0.336)	0.037 (0.528)	-0.416 (0.337)
$\ln gdp$(-1)	0.493 (0.392)	1.263 (0.238)	-2.420 (1.262)	-0.337 (0.491)	0.910 (0.774)	0.891 (0.493)
$\ln gdp$(-2)	-1.044 (0.372)	-0.410 (0.225)	2.097 (1.195)	0.291 (0.465)	-0.489 (0.733)	-0.965 (0.467)
$\ln nuc$(-1)	0.029 (0.060)	0.055 (0.036)	0.564 (0.192)	0.017 (0.075)	0.112 (0.118)	0.129 (0.075)
$\ln nuc$(-2)	0.032 (0.065)	-0.017 (0.039)	0.133 (0.209)	0.156 (0.081)	-0.123 (0.128)	-0.005 (0.082)
$\ln entax$(-1)	-0.721 (0.184)	-0.017 (0.112)	0.703 (0.593)	0.810 (0.231)	0.247 (0.363)	-0.285 (0.232)
$\ln entax$(-2)	0.224 (0.137)	0.012 (0.083)	0.246 (0.440)	-0.211 (0.171)	-0.290 (0.270)	0.000 (0.172)
$\ln trade$(-1)	-0.525 (0.145)	-0.088 (0.088)	0.437 (0.466)	0.100 (0.181)	0.725 (0.286)	-0.503 (0.182)
$\ln trade$(-2)	0.489 (0.130)	0.132 (0.079)	-1.177 (0.417)	-0.017 (0.162)	-0.038 (0.255)	0.524 (0.163)
$\ln indelec$(-1)	0.714 (0.205)	0.080 (0.124)	0.465 (0.660)	-0.164 (0.257)	0.049 (0.405)	1.159 (0.258)
$\ln indelec$(-2)	0.066 (0.205)	-0.109 (0.124)	-0.001 (0.658)	0.119 (0.256)	-0.167 (0.403)	-0.257 (0.257)
intercept	13.922 (2.616)	1.687 (1.586)	3.136 (8.410)	3.360 (3.274)	0.067 (5.156)	4.697 (3.288)
break dv	-0.062 (0.011)	-0.009 (0.007)	0.041 (0.035)	-0.013 (0.014)	-0.018 (0.022)	-0.039 (0.014)
Adj. R-squared	0.962	0.995	0.922	0.983	0.968	0.924
S.E. of equation	0.026	0.016	0.084	0.033	0.051	0.033
AIC	-4.182	-5.183	-1.846	-3.733	-2.825	-3.724
SIC	-3.578	-4.580	-1.243	-3.130	-2.221	-3.121

The numbers in parentheses are the standard errors.

Augmented VAR($p + m$) for Granger causality analysis

Variables	$\ln co_2$	$\ln gdp$	$\ln nuc$	$\ln entax$	$\ln trade$	$\ln indelec$
$\ln co_2$(-1)	-0.866 (0.344)	-0.194 (0.215)	0.565 (1.184)	-0.536 (0.357)	0.023 (0.536)	-0.030 (0.387)
$\ln co_2$(-2)	-1.191 (0.418)	0.041 (0.261)	1.198 (1.438)	0.304 (0.433)	1.270 (0.651)	0.370 (0.470)
$\ln gdp$(-1)	0.472 (0.419)	1.327 (0.261)	-1.862 (1.442)	-0.266 (0.435)	1.657 (0.653)	0.851 (0.471)
$\ln gdp$(-2)	-0.551 (0.615)	-0.847 (0.383)	-0.127 (2.115)	0.039 (0.637)	-2.088 (0.957)	-0.926 (0.692)
$\ln nuc$(-1)	0.001 (0.068)	0.066 (0.042)	0.480 (0.233)	0.032 (0.070)	0.146 (0.105)	0.114 (0.076)
$\ln nuc$(-2)	-0.020 (0.082)	0.003 (0.051)	0.198 (0.283)	0.232 (0.085)	-0.059 (0.128)	0.146 (0.092)
$\ln entax$(-1)	-0.834 (0.236)	-0.018 (0.147)	0.582 (0.811)	0.738 (0.244)	0.151 (0.367)	-0.018 (0.265)
$\ln entax$(-2)	0.167 (0.255)	0.006 (0.159)	0.992 (0.875)	-0.098 (0.264)	0.927 (0.396)	0.514 (0.286)
$\ln trade$(-1)	-0.621 (0.156)	-0.079 (0.097)	0.473 (0.536)	0.195 (0.161)	0.487 (0.242)	-0.557 (0.175)
$\ln trade$(-2)	0.503 (0.211)	0.093 (0.132)	-0.699 (0.726)	-0.223 (0.219)	0.862 (0.328)	0.842 (0.237)
$\ln indelec$(-1)	0.819 (0.241)	0.066 (0.150)	0.123 (0.830)	-0.530 (0.250)	0.082 (0.376)	0.978 (0.271)
$\ln indelec$(-2)	0.106 (0.296)	-0.039 (0.184)	-0.251 (1.018)	0.387 (0.307)	-1.174 (0.461)	-0.351 (0.333)
intercept	19.854 (5.010)	1.812 (3.122)	-12.08 (17.224)	-1.614 (5.191)	-12.905 (7.795)	-6.354 (5.632)
break dv	-0.084 (0.021)	-0.013 (0.013)	0.112 (0.071)	0.004 (0.021)	0.036 (0.032)	-0.001 (0.023)
$\ln co_2$(-3)	-0.495 (0.339)	-0.155 (0.211)	1.653 (1.164)	0.708 (0.351)	0.656 (0.527)	0.408 (0.381)
$\ln gdp$(-3)	-0.472 (0.438)	0.348 (0.273)	1.956 (1.506)	0.164 (0.454)	1.283 (0.682)	0.509 (0.492)
$\ln nuc$(-3)	0.076 (0.076)	-0.030 (0.048)	0.153 (0.262)	0.027 (0.079)	-0.150 (0.119)	-0.214 (0.086)
$\ln entax$(-3)	-0.130 (0.152)	-0.012 (0.095)	0.014 (0.523)	0.094 (0.157)	-0.610 (0.236)	-0.354 (0.171)
$\ln trade$(-3)	-0.098 (0.172)	0.070 (0.107)	-0.294 (0.591)	0.371 (0.178)	-0.623 (0.267)	-0.304 (0.193)
$\ln indelec$(-3)	0.272 (0.232)	-0.049 (0.145)	-0.700 (0.798)	-0.495 (0.241)	0.426 (0.361)	-0.297 (0.261)
Adj. R-squared	0.961	0.995	0.907	0.988	0.980	0.940
S.E. equation	0.026	0.016	0.089	0.027	0.040	0.029
AIC	-4.168	-5.115	-1.699	-4.097	-3.284	-3.934
SIC	-3.298	-4.244	-0.828	-3.226	-2.413	-3.064

The numbers in parentheses are the standard errors.

Chapter 4 appendices

4.1 Estimates of capital, operating, fuel and total costs: Fusion Pathway

UK's Energy Mix - Fusion pathway		Intermediate estimate of capital costs (£m)								
Category	**Description**	**2010**	**2015**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Electricity	Combustion + CCS	-	301	179	383	780	1,026	1,026	1,026	1,026
Electricity	Conventional thermal plant	90	612	828	501	2	-	2,286	-	-
Electricity	Distributed solar PV	14	-	-	-	-	-	-	-	-
Electricity	Electricity Exports	-	-	-	-	-	-	-	-	124
Electricity	Electricity grid distribution	1,036	855	1,393	2,116	2,093	2,109	2,149	2,104	2,383
Electricity	Electricity imports	-	-	-	-	-	-	-	-	-
Electricity	Fusion power	-	-	-	-	-	-	-	1,649	1,649
Electricity	Geothermal	-	14	39	153	593	154	12	45	172
Electricity	Hydroelectric	106	26	26	18	18	8	8	8	8
Electricity	Micro wind	15	86	114	-	-	-	-	-	-
Electricity	Nuclear fission	-	-	1,919	3,522	3,446	3,369	3,293	3,293	3,293
Electricity	Offshore wind	728	2,339	3,352	5,417	5,149	5,057	4,964	4,871	4,723
Electricity	Onshore wind	960	847	833	819	-	-	-	-	-
Electricity	Storage, demand shifting, backup	-	133	282	1,053	986	708	441	-	105
Electricity	Wave and Tidal	2	6	90	140	-	-	6	82	167
Fossil Fuels	Balancing imports - Coal	-	-	-	-	-	-	-	-	-
Fossil Fuels	Balancing imports - Gas	-	-	-	-	-	-	-	-	-
Fossil Fuels	Balancing imports - Oil	-	-	-	-	-	-	-	-	-
Fossil Fuels	Fossil fuel transfers	1,223	705	721	719	702	630	513	383	340
Fossil Fuels	Indigenous production - Coal	-	-	-	-	-	-	-	-	-
Fossil Fuels	Indigenous production - Gas	-	-	-	-	-	-	-	-	-
Fossil Fuels	Indigenous production - Oil	-	-	-	-	-	-	-	-	-
Bioenergy	Agriculture and land use	-	-	-	-	-	-	-	-	-
Bioenergy	Agriculture and land use	-	-	-	-	-	-	-	-	-
Bioenergy	Bioenergy imports	-	-	-	-	-	-	-	-	-
Bioenergy	Biomatter to fuel conversion	1,422	1,669	1,090	756	745	759	774	790	708
Bioenergy	Energy from waste	-	-	-	-	-	-	-	-	-
Bioenergy	Marine algae	-	-	-	-	-	-	-	-	-
Bioenergy	Waste arising	2,506	2,724	3,123	3,106	3,265	3,488	3,475	3,582	3,766
Other	Geosequestration	-	-	-	-	-	-	-	-	-
Other	Storage of captured CO2	-	110	243	401	694	1,032	1,322	1,516	1,639
Buildings	Commercial heating and cooling	-	-	-	-	-	-	-	-	-
Buildings	Comm. lighting, appliances, and catering	93	274	268	263	249	220	210	210	211
Buildings	Distributed solar thermal	-	-	-	-	-	-	-	-	-
Buildings	District heating effective demand	38	23	22	22	22	22	22	22	22
Buildings	Domestic heating	9,273	6,982	11,679	14,474	17,160	20,237	23,153	26,591	30,234
Buildings	Domestic insulation	20,555	21,491	21,051	19,217	17,960	22,047	23,089	23,738	24,889
Buildings	Dom. lighting, appliances, and cooking	2,724	2,977	3,118	3,233	3,333	3,559	3,741	3,932	4,166
Industry	Industrial processes	4	5	5	32	58	132	249	381	549
Industry	Petroleum refineries	391	368	349	331	317	306	298	291	286
Transport	Bikes	913	960	1,025	1,074	1,123	1,170	1,216	1,262	1,308
Transport	Conventional cars and buses	49,180	45,737	47,576	18,243	4,153	18,141	16,160	7,741	3,443
Transport	Domestic aviation	516	520	604	628	622	632	617	615	609
Transport	Domestic freight	4,225	4,725	4,427	4,266	4,114	3,964	3,817	3,673	3,531
Transport	Electric cars and buses	-	2,590	3,679	13,608	17,708	31,199	37,203	41,796	45,510
Transport	Fuel cell cars and buses	-	-	-	-	-	-	-	-	-
Transport	H2 Production	-	-	-	-	-	-	-	-	-
Transport	Hybrid cars and buses	92	2,345	3,312	44,517	59,364	23,077	16,749	20,454	18,492
Transport	International aviation	-	-	-	-	-	-	-	-	-
Transport	International shipping (maritime bunkers)	-	-	-	-	-	-	-	-	-
Transport	Rail	128	97	148	128	136	130	125	125	125
Total	**Total**	**96,234**	**99,519**	**111,495**	**139,140**	**144,790**	**143,178**	**146,917**	**150,182**	**153,481**

Source: Author's calculations

UK's Energy Mix - Fusion pathway		Intermediate estimate of operating costs (£m)								
Category	**Description**	**2010**	**2015**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Electricity	Combustion + CCS	-	59	112	204	397	651	905	1,160	1,416
Electricity	Conventional thermal plant	3,252	2,687	2,348	1,814	1,232	887	658	-	-
Electricity	Distributed solar PV	1	0	-	-	-	-	-	-	-
Electricity	Electricity Exports	-	-	-	-	-	-	-	-	0
Electricity	Electricity grid distribution	1,129	1,060	1,143	1,385	1,561	1,697	1,810	1,882	2,007
Electricity	Electricity imports	-	-	-	-	-	-	-	-	-
Electricity	Fusion power	-	-	-	-	-	-	-	330	660
Electricity	Geothermal	-	2	8	30	121	146	146	146	146
Electricity	Hydroelectric	166	179	192	200	209	213	218	222	226
Electricity	Micro wind	1	8	17	17	17	17	17	17	17
Electricity	Nuclear fission	842	641	692	1,058	1,669	2,157	2,767	3,378	3,988
Electricity	Offshore wind	99	478	1,030	1,928	2,721	3,221	3,548	3,519	3,519
Electricity	Onshore wind	54	92	130	152	114	76	38	0	0
Electricity	Storage, demand shifting, backup	79	80	86	273	456	625	736	633	501
Electricity	Wave and Tidal	0	1	23	57	57	-	-	-	-
Fossil Fuels	Balancing imports - Coal	-	-	-	-	-	-	-	-	-
Fossil Fuels	Balancing imports - Gas	-	-	-	-	-	-	-	-	-
Fossil Fuels	Balancing imports - Oil	-	-	-	-	-	-	-	-	-
Fossil Fuels	Fossil fuel transfers	4	4	3	3	2	2	1	1	1
Fossil Fuels	Indigenous production - Coal	-	-	-	-	-	-	-	-	-
Fossil Fuels	Indigenous production - Gas	-	-	-	-	-	-	-	-	-
Fossil Fuels	Indigenous production - Oil	-	-	-	-	-	-	-	-	-
Bioenergy	Agriculture and land use	-	-	-	-	-	-	-	-	-
Bioenergy	Agriculture and land use	0	0	0	0	0	0	0	0	0
Bioenergy	Bioenergy imports	-	-	-	-	-	-	-	-	-
Bioenergy	Biomatter to fuel conversion	546	1,127	1,929	2,561	2,822	3,072	3,354	3,661	3,971
Bioenergy	Energy from waste	186	248	317	362	410	447	486	526	567
Bioenergy	Marine algae	-	-	-	-	-	-	-	-	-
Bioenergy	Waste arising	4,782	5,115	5,459	5,682	5,910	6,062	6,215	6,370	6,527
Other	Geosequestration	-	-	-	-	-	-	-	-	-
Other	Storage of captured CO2	-	4	10	18	36	62	92	123	157
Buildings	Commercial heating and cooling	-	-	-	-	-	-	-	-	-
Buildings	Comm. lighting, appliances, and catering	-	-	-	-	-	-	-	-	-
Buildings	Distributed solar thermal	-	-	-	-	-	-	-	-	-
Buildings	District heating effective demand	7	7	7	7	7	7	7	7	7
Buildings	Domestic heating	5,015	5,262	5,173	5,030	4,833	4,652	4,441	4,196	3,914
Buildings	Domestic insulation	-	-	-	-	-	-	-	-	-
Buildings	Dom. lighting, appliances, and cooking	-	-	-	-	-	-	-	-	-
Industry	Industrial processes	478	497	516	539	562	589	620	653	689
Industry	Petroleum refineries	805	763	723	693	669	650	636	625	617
Transport	Bikes	747	789	841	884	927	967	1,006	1,045	1,084
Transport	Conventional cars and buses	55,214	54,394	55,070	41,093	25,693	24,270	22,563	17,251	11,910
Transport	Domestic aviation	246	276	318	361	401	443	481	521	563
Transport	Domestic freight	6,500	6,899	6,756	6,613	6,470	6,327	6,183	6,040	5,896
Transport	Electric cars and buses	-	742	1,455	4,556	7,307	12,317	16,428	19,583	21,890
Transport	Fuel cell cars and buses	-	-	-	-	-	-	-	-	-
Transport	H2 Production	-	-	-	-	-	-	-	-	-
Transport	Hybrid cars and buses	25	1,117	2,280	21,627	38,802	31,659	24,872	22,742	20,577
Transport	International aviation	-	26	138	202	236	267	259	271	262
Transport	International shipping (maritime bunkers)	-	15	168	399	736	927	1,145	1,394	1,677
Transport	Rail	8,421	8,475	8,768	8,995	9,069	9,099	9,016	8,903	8,764
Total	**Total**	**88,598**	**91,046**	**95,712**	**106,744**	**113,447**	**111,510**	**108,648**	**105,197**	**101,552**

Source: Author's calculations

UK's Energy Mix - Fusion pathway		Intermediate estimate of fuel costs (£m)								
Category	**Description**	**2010**	**2015**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Electricity	Combustion + CCS	-	-	-	-	-	-	-	-	-
Electricity	Conventional thermal plant	-	-	-	-	-	-	-	-	-
Electricity	Distributed solar PV	-	-	-	-	-	-	-	-	-
Electricity	Electricity Exports	-	-	-	(0)	-	-	-	(3,034)	(7,313)
Electricity	Electricity grid distribution	-	-	-	-	-	-	-	-	-
Electricity	Electricity imports	-	-	-	-	-	-	-	-	-
Electricity	Fusion power	-	-	-	-	-	-	-	-	-
Electricity	Geothermal	-	-	-	-	-	-	-	-	-
Electricity	Hydroelectric	-	-	-	-	-	-	-	-	-
Electricity	Micro wind	-	-	-	-	-	-	-	-	-
Electricity	Nuclear fission	65	55	59	91	143	185	237	290	342
Electricity	Offshore wind	-	-	-	-	-	-	-	-	-
Electricity	Onshore wind	-	-	-	-	-	-	-	-	-
Electricity	Storage, demand shifting, backup	-	-	-	-	-	-	-	-	-
Electricity	Wave and Tidal	-	-	-	-	-	-	-	-	-
Fossil Fuels	Balancing imports - Coal	2,580	1,344	737	(364)	(602)	(668)	(607)	(700)	(697)
Fossil Fuels	Balancing imports - Gas	4,558	6,323	8,028	9,282	9,137	6,945	4,598	4,074	3,601
Fossil Fuels	Balancing imports - Oil	1,614	3,742	7,910	10,105	11,722	14,284	15,819	16,325	16,074
Fossil Fuels	Fossil fuel transfers	-	-	-	-	-	-	-	-	-
Fossil Fuels	Indigenous production - Coal	1,031	665	765	864	482	482	482	482	482
Fossil Fuels	Indigenous production - Gas	9,413	7,721	6,854	5,991	5,167	3,998	3,094	2,394	1,852
Fossil Fuels	Indigenous production - Oil	25,382	15,967	15,999	15,175	13,905	10,760	8,326	6,442	4,985
Bioenergy	Agriculture and land use	418	1,283	2,702	3,797	4,400	4,973	5,624	6,337	7,054
Bioenergy	Agriculture and land use	-	-	-	-	-	-	-	-	-
Bioenergy	Bioenergy imports	507	1,029	1,570	2,108	1,551	1,896	2,240	2,585	3,393
Bioenergy	Biomatter to fuel conversion	-	-	-	-	-	-	-	-	-
Bioenergy	Energy from waste	-	-	-	-	-	-	-	-	-
Bioenergy	Marine algae	-	-	-	-	-	-	-	-	-
Bioenergy	Waste arising	-	-	-	-	-	-	-	-	-
Other	Geosequestration	-	-	-	-	-	-	-	-	-
Other	Storage of captured CO2	-	-	-	-	-	-	-	-	-
Buildings	Commercial heating and cooling	-	-	-	-	-	-	-	-	-
Buildings	Comm. lighting, appliances, and catering	-	-	-	-	-	-	-	-	-
Buildings	Distributed solar thermal	-	-	-	-	-	-	-	-	-
Buildings	District heating effective demand	-	-	-	-	-	-	-	-	-
Buildings	Domestic heating	-	-	-	-	-	-	-	-	-
Buildings	Domestic insulation	-	-	-	-	-	-	-	-	-
Buildings	Dom. lighting, appliances, and cooking	-	-	-	-	-	-	-	-	-
Industry	Industrial processes	-	-	-	-	-	-	-	-	-
Industry	Petroleum refineries	-	-	-	-	-	-	-	-	-
Transport	Bikes	-	-	-	-	-	-	-	-	-
Transport	Conventional cars and buses	-	-	-	-	-	-	-	-	-
Transport	Domestic aviation	-	-	-	-	-	-	-	-	-
Transport	Domestic freight	-	-	-	-	-	-	-	-	-
Transport	Electric cars and buses	-	-	-	-	-	-	-	-	-
Transport	Fuel cell cars and buses	-	-	-	-	-	-	-	-	-
Transport	H2 Production	-	-	-	-	-	-	-	-	-
Transport	Hybrid cars and buses	-	-	-	-	-	-	-	-	-
Transport	International aviation	-	-	-	-	-	-	-	-	-
Transport	International shipping (maritime bunkers)	-	-	-	-	-	-	-	-	-
Transport	Rail	-	-	-	-	-	-	-	-	-
Total	**Total**	**45,568**	**38,128**	**44,623**	**47,049**	**45,907**	**42,854**	**39,813**	**35,195**	**29,773**

Source: Author's calculations

UK's Energy Mix - Fusion pathway		Intermediate estimate of total costs (£m)								
Category	**Description**	**2010**	**2015**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Electricity	Combustion + CCS	-	360	291	586	1,177	1,677	1,932	2,186	2,443
Electricity	Conventional thermal plant	3,343	3,299	3,176	2,315	1,235	887	2,944	-	-
Electricity	Distributed solar PV	15	0	-	-	-	-	-	-	-
Electricity	Electricity Exports	-	-	-	(0)	-	-	-	(3,034)	(7,188)
Electricity	Electricity grid distribution	2,165	1,915	2,536	3,501	3,655	3,806	3,959	3,987	4,389
Electricity	Electricity imports	-	-	-	-	-	-	-	-	-
Electricity	Fusion power	-	-	-	-	-	-	-	1,979	2,309
Electricity	Geothermal	-	15	47	183	714	300	157	190	318
Electricity	Hydroelectric	272	205	218	218	227	222	226	230	234
Electricity	Micro wind	15	94	132	17	17	17	17	17	17
Electricity	Nuclear fission	908	696	2,670	4,671	5,257	5,711	6,297	6,960	7,623
Electricity	Offshore wind	827	2,817	4,382	7,345	7,870	8,278	8,512	8,390	8,242
Electricity	Onshore wind	1,014	939	963	971	114	76	38	0	0
Electricity	Storage, demand shifting, backup	79	213	368	1,327	1,442	1,333	1,177	633	606
Electricity	Wave and Tidal	2	6	113	198	57	-	6	82	167
Fossil Fuels	Balancing imports - Coal	2,580	1,344	737	(364)	(602)	(668)	(607)	(700)	(697)
Fossil Fuels	Balancing imports - Gas	4,558	6,323	8,028	9,282	9,137	6,945	4,598	4,074	3,601
Fossil Fuels	Balancing imports - Oil	1,614	3,742	7,910	10,105	11,722	14,284	15,819	16,325	16,074
Fossil Fuels	Fossil fuel transfers	1,227	708	724	722	704	632	515	384	341
Fossil Fuels	Indigenous production - Coal	1,031	665	765	864	482	482	482	482	482
Fossil Fuels	Indigenous production - Gas	9,413	7,721	6,854	5,991	5,167	3,998	3,094	2,394	1,852
Fossil Fuels	Indigenous production - Oil	25,382	15,967	15,999	15,175	13,905	10,760	8,326	6,442	4,985
Bioenergy	Agriculture and land use	418	1,283	2,702	3,797	4,400	4,973	5,624	6,337	7,054
Bioenergy	Agriculture and land use	0	0	0	0	0	0	0	0	0
Bioenergy	Bioenergy imports	507	1,029	1,570	2,108	1,551	1,896	2,240	2,585	3,393
Bioenergy	Biomatter to fuel conversion	1,968	2,796	3,020	3,318	3,567	3,831	4,128	4,451	4,679
Bioenergy	Energy from waste	186	248	317	362	410	447	486	526	567
Bioenergy	Marine algae	-	-	-	-	-	-	-	-	-
Bioenergy	Waste arising	7,287	7,839	8,581	8,789	9,175	9,549	9,690	9,952	10,292
Other	Geosequestration	-	-	-	-	-	-	-	-	-
Other	Storage of captured CO2	-	114	252	419	730	1,094	1,414	1,639	1,796
Buildings	Commercial heating and cooling	-	-	-	-	-	-	-	-	-
Buildings	Comm. lighting, appliances, and catering	93	274	268	263	249	220	210	210	211
Buildings	Distributed solar thermal	-	-	-	-	-	-	-	-	-
Buildings	District heating effective demand	45	29	29	29	29	28	28	28	28
Buildings	Domestic heating	14,289	12,244	16,852	19,503	21,993	24,889	27,593	30,787	34,148
Buildings	Domestic insulation	20,555	21,491	21,051	19,217	17,960	22,047	23,089	23,738	24,889
Buildings	Dom. lighting, appliances, and cooking	2,724	2,977	3,118	3,233	3,333	3,559	3,741	3,932	4,166
Industry	Industrial processes	483	501	521	571	620	721	869	1,034	1,238
Industry	Petroleum refineries	1,196	1,131	1,072	1,024	986	957	934	916	903
Transport	Bikes	1,659	1,749	1,866	1,958	2,050	2,137	2,222	2,307	2,392
Transport	Conventional cars and buses	104,394	100,132	102,645	59,336	29,846	42,411	38,723	24,992	15,353
Transport	Domestic aviation	762	796	921	988	1,023	1,075	1,098	1,136	1,172
Transport	Domestic freight	10,724	11,624	11,183	10,879	10,584	10,291	10,000	9,713	9,427
Transport	Electric cars and buses	-	3,332	5,135	18,164	25,015	43,516	53,631	61,379	67,400
Transport	Fuel cell cars and buses	-	-	-	-	-	-	-	-	-
Transport	H2 Production	-	-	-	-	-	-	-	-	-
Transport	Hybrid cars and buses	117	3,461	5,592	66,144	98,166	54,737	41,621	43,196	39,069
Transport	International aviation	-	26	138	202	236	267	259	271	262
Transport	International shipping (maritime bunkers)	-	15	168	399	736	927	1,145	1,394	1,677
Transport	Rail	8,549	8,572	8,916	9,123	9,204	9,230	9,141	9,028	8,889
Total	**Total**	**230,399**	**228,693**	**251,831**	**292,933**	**304,144**	**297,542**	**295,378**	**290,574**	**284,805**

Source: Author's calculations

4.2 Estimates of greenhouse gas emissions: Fusion Pathway

Emissions

Emissions as % of base year, adjusted so that 2007 matches actuals

	IPCC Sector (2007 Actuals, GHG Inv.)		**2007**	**2010**	**2015**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
1A	Fuel Combustion											
1B	Fugitive Emissions from Fuels											
1	Fuel Combustion	68%	68%	66%	61%	54%	44%	34%	31%	28%	27%	26%
2	Industrial Processes	3%	4%	4%	3%	3%	3%	3%	3%	3%	3%	3%
3	Solvent and Other Product Use	-	-	-	-	-	-	-	-	-	-	-
4	Agriculture	5%	6%	5%	5%	5%	5%	5%	5%	4%	4%	4%
5	LULUCF	(0%)	(0%)	0%	1%	1%	1%	1%	1%	1%	0%	0%
6	Waste	3%	3%	2%	2%	2%	2%	1%	1%	1%	1%	1%
7	Other	-	-	-	-	-	-	-	-	-	-	-
X1	Int'l Aviation & Shipping	5%	7%	6%	6%	7%	7%	7%	8%	8%	8%	8%
X2	Bioenergy credit		(1%)	(2%)	(3%)	(5%)	(8%)	(8%)	(9%)	(10%)	(11%)	(13%)
X3	Carbon capture		-	-	(0%)	(1%)	(2%)	(3%)	(5%)	(7%)	(8%)	(10%)
	Total	**85%**	**85%**	**81%**	**75%**	**66%**	**52%**	**41%**	**35%**	**28%**	**24%**	**19%**
	Excluding international bunkers	82%	81%	78%	71%	61%	47%	35%	28%	21%	16%	11%
	Adjustment factor:		**1.028**					**% reduction 1990-2050**				**81%**

Sector	**2007**	**2010**	**2015**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Hydrocarbon fuel power generation	200	192	173	144	100	54	30	12	7	9
Nuclear power generation	0	0	0	0	0	0	0	0	0	0
National renewable power generation	0	0	0	0	0	0	0	0	0	0
Distributed renewable power generation	0	0	0	0	0	0	0	0	0	0
Bioenergy	-10	-12	-23	-41	-60	-63	-69	-82	-89	-100
Agriculture and waste	66	62	60	59	58	56	53	49	45	42
Electricity distribution, storage, and balancing	0	0	0	0	0	1	1	1	1	1
H2 Production	0	0	0	0	0	0	0	0	0	0
Heating	84	86	83	72	62	52	43	33	24	13
Lighting and appliances	3	3	3	2	2	2	2	2	2	1
Industry	93	92	90	87	85	82	79	76	72	68
Transport	187	176	167	158	135	113	113	110	105	98
Food consumption [UNUSED]	0	0	0	0	0	0	0	0	0	0
Geosequestration	0	0	0	0	0	0	0	0	0	0
Fossil fuel production	34	31	27	24	21	18	17	16	15	14
Transfers	4	4	4	4	3	3	2	2	1	1
District heating	0	0	0	0	0	0	0	0	0	0
Total	662	633	584	510	408	319	271	219	183	148
Emissions in the time period (up to and incl. year above)		2561	3018	2698	2243	1773	1451	1200	989	810
Cumulative emissions		2561	5579	8278	10521	12294	13745	14945	15933	16744

Modelled emissions

	IPCC Sector	Actuals, GHG Inv.								Mt CO2e		
1A	Fuel Combustion	533	515	500	465	413	335	263	235	215	204	199
1B	Fugitive Emissions from Fuels	13	12	11	10	9	8	6	5	4	3	3
1	Fuel Combustion	546	527	511	475	422	343	268	240	219	207	202
2	Industrial Processes	28	28	27	26	25	24	24	23	22	22	21
3	Solvent and Other Product Use	-	-	-	-	-	-	-	-	-	-	-
4	Agriculture	43	43	42	39	37	36	36	35	35	34	34
5	LULUCF	(2)	(2)	3	5	7	9	9	8	5	2	1
6	Waste	23	23	15	14	14	12	10	9	8	7	6
7	Other		-	-	-	-	-	-	-	-	-	-
X1	Int'l Aviation & Shipping	43	53	46	50	53	55	58	61	63	63	62
X2	Bioenergy credit		(10)	(12)	(23)	(41)	(60)	(63)	(69)	(82)	(89)	(100)
X3	Carbon capture		-	-	(3)	(7)	(12)	(22)	(36)	(51)	(64)	(78)
	Total	**681**	**662**	**633**	**584**	**510**	**408**	**319**	**271**	**219**	**183**	**148**
	Excluding international bunkers	638	610	587	534	457	352	261	210	157	120	86

Source: Author's calculations

4.3 Estimates of primary energy sources and use: Fusion Pathway

Energy source / use charts												
Use	TWh / year	2007 (Consistent)	**2007**	**2010**	**2015**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
T.01	Road transport	503	491	462	415	369	282	204	190	176	157	141
T.02	Rail transport	16	16	18	18	17	17	16	15	15	14	13
T.03	Domestic aviation	9	9	9	10	11	12	13	13	14	14	14
T.04	National navigation	19	19	27	26	26	26	27	27	27	28	28
T.05	International aviation	153	153	125	141	156	165	173	183	187	188	180
T.06	International shipping	29	54	57	56	51	53	55	57	59	61	63
	Transport	**729**	**742**	**699**	**665**	**632**	**555**	**487**	**486**	**478**	**462**	**439**
I.01	**Industry**	**443**	**485**	**472**	**459**	**447**	**438**	**430**	**424**	**420**	**417**	**415**
H.01	**Heating & cooling**	**545**	**498**	**505**	**482**	**468**	**459**	**450**	**444**	**441**	**440**	**442**
L.01	**Lighting & appliances**	**184**	**176**	**170**	**167**	**164**	**161**	**159**	**160**	**162**	**164**	**166**
F.01	**Food consumption**	**59**	**-**	**-**	**-**	**-**	**-**	**-**	**-**	**-**	**-**	**-**
	Total	**1,960**	**1,901**	**1,846**	**1,774**	**1,710**	**1,613**	**1,525**	**1,515**	**1,500**	**1,484**	**1,463**
Source												
N.01	Nuclear fission	163	164	161	135	146	223	351	454	583	711	840
R.01	Solar	1	0	0	0	-	-	-	-	-	-	-
R.02	Wind	7	6	14	38	72	123	163	189	200	191	191
R.03	Tidal	-	-	0	0	0	0	0	-	-	-	-
R.04	Wave	-	-	-	0	0	0	0	-	-	-	-
R.05	Geothermal	-	-	-	0	0	1	6	7	7	7	7
R.055	Fusion power	-	-	-	-	-	-	-	-	-	80	161
R.06	Hydro	5	4	5	6	6	6	7	7	7	7	7
Y.02	Elec. oversupply (imports)	5	0	-	-	0	(0)	-	-	0	(41)	(100)
	Elec, solar, marine & net imports	**181**	**174**	**181**	**179**	**224**	**354**	**528**	**657**	**796**	**955**	**1,106**
R.07	**Environmental heat**	**-**	**-**	**-**	**-**	**30**	**59**	**88**	**119**	**150**	**184**	**220**
W.01	Waste	14	46	45	74	126	160	171	174	179	185	189
A.01	Agriculture	58	5	6	21	37	54	72	97	123	151	182
Y.01	Biomass oversupply (imp.)	26	4	9	16	24	32	19	23	27	31	35
	Agric, waste & biomatter imports	**99**	**55**	**60**	**111**	**187**	**246**	**262**	**294**	**329**	**367**	**406**
Y.04	Coal oversupply (imports)	330	346	320	259	123	(54)	(80)	(89)	(81)	(93)	(93)
Q.01	Coal reserves	146	124	128	128	128	128	64	64	64	64	64
	Coal	**475**	**470**	**448**	**387**	**251**	**74**	**(16)**	**(25)**	**(17)**	**(29)**	**(29)**
Q.02	Oil reserves	887	976	803	647	502	388	300	232	180	139	108
Y.05	Oil & petroleum oversupply (imports)	80	(75)	51	152	248	259	253	309	342	353	347
Y.03	Petroleum oversupply	(61)	-	-	-	-	-	-	-	-	-	-
	Oil & petroleum products	**907**	**901**	**854**	**798**	**750**	**647**	**554**	**541**	**522**	**492**	**455**
Y.06	Gas oversupply (imports)	215	247	313	406	449	459	406	308	204	181	160
Q.03	Gas reserves	834	731	646	496	383	296	229	177	137	106	82
	Natural gas	**1,049**	**978**	**959**	**902**	**832**	**756**	**635**	**486**	**341**	**287**	**242**
	Total Primary Supply	**2,711**	**2,578**	**2,501**	**2,377**	**2,274**	**2,135**	**2,050**	**2,072**	**2,122**	**2,256**	**2,400**
Conversion loss, distribution & own use												
X.01	Conversion losses	561	556	540	493	458	415	413	439	498	639	793
X.02	Distribution losses & own use	187	121	115	110	107	108	112	117	124	134	144
	Supply net of losses	**1,962**	**1,901**	**1,846**	**1,774**	**1,710**	**1,613**	**1,525**	**1,515**	**1,500**	**1,484**	**1,463**

Source: Author's calculations

4.4 Estimates of electricity generation and installed capacity: Fusion Pathway

Electricity Generation

TWh		2007	2010	2015	2020	2025	2030	2035	2040	2045	2050
Biomass/Coal power stations	276.5	314.8	300.8	273.6	245.6	191.7	119.8	60.6	10.3	-	-
Domest. space heating & hot water	-	-	-	-	-	-	-	-	-	-	-
Commercial heating and cooling	-	-	-	-	-	-	-	-	-	-	-
Conventional	**276.5**	**314.8**	**300.8**	**273.6**	**245.6**	**191.7**	**119.8**	**60.6**	**10.3**	**-**	**-**
CCS Power	**-**	**-**	**-**	**5.1**	**10.8**	**19.5**	**38.0**	**62.3**	**86.9**	**111.6**	**136.5**
Nuclear fission	**57.2**	**57.5**	**52.6**	**44.2**	**47.7**	**72.9**	**115.0**	**148.7**	**190.7**	**232.8**	**274.9**
Onshore wind	4.5	5.0	10.3	17.5	24.8	29.0	21.8	14.6	7.3	0.1	0.1
Offshore wind	0.8	1.0	4.1	20.0	45.6	92.2	139.9	173.3	190.9	189.3	189.3
Hydroelectric power stations	4.1	4.1	5.3	5.7	6.2	6.4	6.7	6.9	7.0	7.1	7.3
Tidal & Wave	-	-	0.0	0.0	0.2	0.5	0.5	-	-	-	-
Geothermal electricity	-	-	-	0.1	0.4	1.5	5.8	7.0	7.0	7.0	7.0
Fusion power	-	-	-	-	-	-	-	-	-	26.3	52.6
Solar PV	-	0.0	0.0	0.0	-	-	-	-	-	-	-
Non-thermal renewable gen.	**9.4**	**10.1**	**19.8**	**43.4**	**77.1**	**129.6**	**174.8**	**201.8**	**212.3**	**229.9**	**256.3**
Electricity imports	**5.2**	**-**	**-**	**-**	**-**	**-**	**-**	**-**	**-**	**-**	**-**
Total	**348.4**	**382.4**	**373.2**	**366.3**	**381.2**	**413.8**	**447.6**	**473.3**	**500.2**	**574.3**	**667.7**
Electricity exports	-	0.0	-	-	0.0	(0.0)	-	-	0.0	(41.4)	(99.9)
Electricity used in UK, before losses and district heat demand	348.4	382.4	373.2	366.3	381.2	413.8	447.6	473.3	500.2	532.8	567.8

GW installed capacity	2007	2010	2015	2020	2025	2030	2035	2040	2045	2050
Unabated thermal generation	62.6	58.4	47.7	42.2	32.2	19.5	9.7	1.5	-	-
Oil / Biofuel	4.1	4.1	-	-	-	-	-	-	-	-
Coal / Biomass	28.1	28.1	23.4	17.1	8.6	1.8	0.6	0.6	-	-
Gas / Biogas	30.3	26.2	24.3	25.2	23.6	17.7	9.1	0.9	-	-
CCS Power	-	-	0.9	1.7	3.1	5.9	9.7	13.4	17.2	20.9
Nuclear fission	11.0	10.0	7.2	6.8	10.4	16.4	21.2	27.2	33.2	39.2
Onshore wind	2.1	3.9	6.7	9.4	11.0	8.3	5.5	2.8	0.0	0.0
Offshore wind	0.4	1.3	6.5	14.1	26.3	37.1	43.9	48.4	48.0	48.0
Hydroelectric power stations	1.3	1.6	1.7	1.9	1.9	2.0	2.1	2.1	2.1	2.2
Wave	-	-	0.0	0.1	0.2	0.2	-	-	-	-
Tidal Stream	-	0.0	0.0	0.0	0.0	0.0	-	-	-	-
Tidal Range	-	-	-	-	-	-	-	-	-	-
Geothermal electricity	-	-	0.0	0.1	0.2	0.8	1.0	1.0	1.0	1.0
Fusion power	-	-	-	-	-	-	-	-	3.6	7.2
Solar PV	0.0	0.0	0.0	-	-	-	-	-	-	-
Standby / peaking gas	-	-	-	-	7.0	13.8	20.1	24.2	20.4	15.3
Total generation	**77.4**	**75.3**	**70.7**	**76.2**	**92.3**	**104.1**	**113.2**	**120.6**	**125.5**	**133.8**

Source: Author’s calculations

4.5 Estimates of bioenergy production and use: Fusion Pathway

Bio-energy - Production and Use												
Production												
Domestic			**2007**	**2010**	**2015**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
V.a	V.03	Solid hydrocarbons	14.5	20.2	39.8	81.7	133.9	160.7	185.8	214.3	245.4	276.6
V.a	V.04	Liquid hydrocarbons	1.3	0.4	0.4	0.4	0.5	0.5	0.5	0.5	0.6	0.6
V.a	V.05	Gaseous hydrocarbons	22.0	18.2	33.0	48.1	52.8	52.6	52.7	53.0	53.2	53.5
Imports												
V.b	V.03	Solid hydrocarbons	4.4	6.5	10.1	13.6	17.2	-	-	-	-	-
V.b	V.04	Liquid hydrocarbons	-	2.1	6.2	10.3	14.4	18.5	22.7	26.8	30.9	35.0
V.b	V.05	Gaseous hydrocarbons	-	-	-	-	-	-	-	-	-	-
Total												
V.b	V.03	Solid hydrocarbons	18.9	26.7	49.9	95.4	151.1	160.7	185.8	214.3	245.4	276.6
V.b	V.04	Liquid hydrocarbons	1.3	2.4	6.6	10.7	14.9	19.0	23.2	27.3	31.4	35.6
V.b	V.05	Gaseous hydrocarbons	22.0	18.2	33.0	48.1	52.8	52.6	52.7	53.0	53.2	53.5
Hydro-carbon use by sector and Bio-energy share												
Solid Hydrocarbon consumption			**496**	**482**	**445**	**357**	**236**	**157**	**174**	**211**	**231**	**263**
Share of biomass to total solid hydrocarbon consump.			4%	6%	11%	27%	64%	103%	107%	101%	106%	105%
I.b	CCS Power		0	0	7	21	35	64	102	140	176	209
I.a	Biomass/Coal power stations		427	414	374	274	141	33	14	14	0	0
XI	Industry		55	54	54	54	53	53	53	53	53	53
IX	Heating		14	13	9	8	7	5	4	3	1	0
Liquid Hydrocarbon consumption			**905**	**856**	**805**	**761**	**662**	**573**	**564**	**549**	**523**	**491**
Share of Bioliquids to total liquid hydrocarbon consump.			0%	0%	1%	1%	2%	3%	4%	5%	6%	7%
XII	Transport		733	691	657	620	528	445	442	432	412	384
XI	Industry		82	80	77	75	73	70	68	66	64	62
XV.a	Petroleum refineries		56	53	50	48	46	44	43	42	41	41
Gaseous Hydrocarbon consumption			**989**	**966**	**925**	**871**	**798**	**676**	**527**	**383**	**331**	**288**
Share of Biogas to total gaseous hydrocarbon consump.			2%	2%	4%	6%	7%	8%	10%	14%	16%	19%
IX.a	Domestic space heating and hot water		324	340	332	292	256	218	182	146	110	73
IX.c	Commercial heating and cooling		78	77	76	65	54	44	33	23	12	0
XI	Industry		150	148	145	142	140	135	131	127	123	119
I.a	Biomass/Coal power stations		351	328	304	315	295	222	114	11	0	0
I.b	CCS Power		0	0	6	6	11	23	37	51	65	79

Source: Author’s calculations

Chapter 5 appendices

5.1 Unit root tests for CGE trade elasticity variables (ADF and DF-GLS)

Variable	Included in test	ADF t-statistic	DF-GLS t-statistic
ln *USgdp*	Intercept only	-1.466(0.537)	0.627
Δln *USgdp*	Intercept only	-3.789(0.008)***	-2.501**
ln *export*	Intercept only	-0.647(0.846)	0.378
Δln *export*	Intercept only	-5.690(0.000)***	-5.767***
ln *rexpp*	Intercept only	-1.262(0.634)	-0.583
Δln *rexpp*	Intercept only	-5.085(0.000)***	-4.215***
ln *UKgdp*	Intercept only	-1.413(0.563)	-0.052
Δln *UKgdp*	Intercept only	-3.350(0.022)***	-3.413***
ln *import*	Intercept only	-0.825(0.798)	0.292
Δln *import*	Intercept only	-5.519(0.000)***	-5.495***
ln *rimpp*	Intercept only	-1.308(0.613)	-0.883
Δln *rimpp*	Intercept only	-4.337(0.002)***	-4.150***

1. ***, ** and * denotes $I(1)$ at the 1%, 5% and 10% significance levels respectively
2. The numbers in parentheses are the probability values of the t-statistics

5.2 ARDL regression output for CGE trade elasticity variables

Dep. variable ln *USgdp*	ARDL(1, 0, 0) with ln *export*
ln *USgdp*(-1)	0.715(0.070)
ln *export*	0.231(0.051)
ln *rexpp*	-0.061(0.034)
dv	-0.030(0.007)
C	2.751(1.208)
Adj. R-squared	0.998
S.E. of regression	0.011

Dep. variable ln *UKgdp*	ARDL(1, 1, 1) with ln *import*
ln *UKgdp*(-1)	0.813(0.082)
ln *import*	0.325(0.053)
ln *import*(-1)	-0.133(0.068)
ln *rimpp*	-0.045(0.036)
ln *rimpp*(-1)	0.059(0.034)
dv	-0.031(0.009)
C	0.127(1.283)
Adj. R-squared	0.997
S.E. of regression	0.011

The numbers in parentheses are the standard errors.

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