Essays on Sustainable Consumption and Green Development

by

Wong Siang Leng

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Certified by:

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Supervisor: Asst. Prof Chia Wai-Mun

Certified by:

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Co-Supervisor: Asst. Prof Chang Youngho

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Executive Summary

This thesis aims to contribute empirically the importance of renewable energy to economic growth. Renewable energy brings environmental sustainability but its influence on economic growth remains highly controversial.

This thesis contributes to the literature of renewable energy and economic growth through the discussions of three related and yet distinct issues: (i) What is the contribution of renewable energy consumption and R&D to economic growth? (ii) How different types of energy consumption and energy R&D respond towards changes in economic growth and oil prices? (iii) Is there any causal relationship between energy consumption and energy R&D?

Chapter 1 provides an overview of the literature and the motivation of this thesis. The relationship between energy and economic growth is discussed.

A central puzzle in energy economics is to deal with the relationship between energy consumption and economic growth and recently, studies have begun to explore the importance of renewable energy consumption in promoting economic growth but neglected the influence of energy R&D on economic growth. Chapter 2 of this thesis hence fills this gap and examines the relationship between both energy consumption and energy R&D with economic growth. Using the Fully-Modified Ordinary Least Squares (FMOLS) estimator and a Dynamic Ordinary Least Squares (DOLS) estimator, this chapter finds that while capital stock and fossil fuels are the key factors driving economic growth, both renewable energy consumption and renewable energy R&D have the potential to promote real output, especially amongst the countries without oil reserves. The research

results from this chapter will also be published in a journal article entitled "Energy consumption, energy R&D and real GDP in OECD countries with and without oil reserves" in *Energy Economics*.

While Chapter 2 examines the renewable energy and economic growth nexus, Chapter 3 studies the short-run and long-run elasticities of various energy consumption and energy R&D to change in oil prices and income. Using the Nerlove Partial Adjustment Model (NPAM), this chapter finds that economic growth is the main factor to promote cleaner forms of energy consumption, from coal to oil, gas and renewable energy.

Energy consumption and energy R&D could have potential bilateral causality and Chapter 4 goes a step further in the examination of the factors which promote energy consumption or energy R&D by also examining the dynamic relationship between energy consumption and energy R&D, which is found missing in literature. As gas consumption becomes more important and climatic policies could also play a role in influencing energy consumption or R&D, gas prices and time dummies are included in the regressions. To facilitate the shift towards renewable energy-based economies, this chapter shows that countries could implement policies such as subsidies for renewable energy R&D and removal of subsidies for fossil fuel-related R&D. Parts of this chapter will be published in *Energy Policy,* entitled "Energy consumption and energy R&D in OECD: Perspectives from oil prices and economic growth".

Chapter 5 summarizes the key findings of this thesis and explores the potential of future extension.

Chapter 1

Introduction

This thesis contributes empirically to the literature of renewable energy and economic growth through the discussion of three distinct and yet related issues: (1) What is the contribution of renewable energy to economic growth? (2) How do different types of energy consumption and energy R&D respond towards changes in economic growth and oil prices? (3) What is the relationship between energy consumption and energy R&D?

The thesis is different from the existing literature in three dimensions. First, the thesis clearly distinguishes the potential differences between energy consumption and energy R&D which has often been overlooked by the existing literature. While energy consumption represents the demand side of the energy market, energy R&D, on the other hand, influences the supply side of the energy market and should be clearly distinguished. The role of energy R&D, which may be an important element that drives technological advancement, on economic growth, has been somehow overlooked. However, R&D investment has been long recognized as engine of total productivity growth, first demonstrated by the theoretical work of Romer (1990) and Grossman and Helpman (1991b) and later the empirical work of Griliches (1992). Economic intuition on the causal relationship between energy R&D and economic growth is less clear cut. On the one hand, other things being equal, higher level of energy

R&D results in more developed and efficient production processes. Therefore, promoting energy R&D enhances economic growth through higher total productivity. On the other hand, channeling limited resources to energy R&D may imply less are now available for other factors of production and therefore lowering economic growth. The ambiguity in economic intuition on this matter has made the energy R&D-economic growth nexus an essential empirical matter.

Second, instead of exploring the above-mentioned issues by looking into an individual country or a group of countries as a whole, this thesis clear distinguishes the potential differences that could arise due to the countries' different levels of oil endowments by disaggregating countries into those with and without oil reserves. For instance, in the investigation of energy consumption-economic growth nexus (or energy R&D-economic growth nexus), the absence of clear consensus regarding the direction of causality can be attributed to many factors ranging from different economic structures and development stage within a country to different econometric techniques used. Within the same country group, countries often exhibit similar characteristics and converge to the same steady-state income levels. As a result, one could expect that energy consumption and energy R&D could have homogeneous (heterogeneous) contributions to economic growth within (between) the country groups. Although oil remains the main energy source for most countries, the responses of countries with and without oil reserves to higher oil prices and OPEC supply restrictions differ. As compared to countries with oil reserves which could still depend on their own oil reserves, countries without oil reserves are energy importers and are likely to be more affected by the immediate reduction in energy resources. Compared to their counterparts who have no oil reserves, countries with oil reserves do not face threat to their energy security. As a result, it becomes meaningful to explore the underlying reasons that attribute to the differences in the direction of causality by clearly classifying countries into those with and without oil reserves. Countries with similar oil reserves and endowment are expected to exhibit similar characteristics and therefore show similar dynamic linkages between energy consumption (energy R&D) and economic growth. As Sachs and Warner (1995, 2001) demonstrated that economic growth is related to their natural resources endowment, this study investigates whether economic growth could also be related to the energy endowment.

Third, in the process of addressing the above-mentioned issues, the thesis also looks into the importance of renewable energy consumption and renewable energy R&D. Despite the fact that renewable energy is considered to be one of the fastest rising sources of energy for many countries, studies that employ modern advances in time series econometrics and causality analysis to examine the above-mentioned issues are scarce. The 1970s energy crises and increasing concerns on climatic change in recent years have caused structural changes in the energy market, promoting the use and development o alternative forms of energy. Renewable energy and nuclear energy are potential candidates to overcome sustainable challenges in the global energy market. However, despite the inexhaustible and clean features of renewable energy which could bring about energy and environment security, countries continue to rely heavily on fossil fuels, making little progress towards the switch in using and developing renewable energy. Countries cast doubts on the capacity and efficiency of renewable energy in meeting future energy demand, perceiving renewable energy as less efficient and more costly due to the lock-in technology trajectories of fossil fuels. These translate into an opposing force for the shift towards renewable energy-based economies. To date, published literature on the causal relationship between renewable energy consumption and economic growth remain scarce (Apergis and Paynes, 2010 and 2011).

In summary, the thesis aims to re-examine the (1) energy consumption-economic growth nexus, (2) response of energy consumption towards changes in economic growth and oil prices and (3) relationship between energy consumption and energy R&D of 20 OECD countries by clearly distinguishing the difference in energy consumption and energy R&D and the countries' different levels of oil endowments. The thesis also looks specifically into the rising role of renewable energy in examining the three issues.

OECD countries are chosen and examined in this thesis for two main reasons. First, OECD countries are identified as the leading countries which seek to take a more pro-active position in promoting sustainable economic growth and innovating new alternative energy technologies. Developing countries look upon them and follow their incentives and frameworks which successfully drive alternative energy. In the event that renewable energy promotes economic growth in OECD countries, many other countries are also encouraged to have coordinated actions towards higher renewable energy usage. Second, data from OECD countries are more complete and readily available as compared to the developing countries.

To examine the potential causal relationship between renewable energy consumption and R&D on economic growth, this thesis uses the Fully-Modified Ordinary Least Squares (FMOLS) and the Dynamic Ordinary Least Squares (DOLS) regressions with attempt to clearly disentangle the effect of renewable energy and fossil fuels on output in Chapter 2. Existing studies often focused on whether renewable energy consumption drives economic growth, in the absence of fossil fuel consumption (see Apergis and Payne, 2010 and 2011) and the results are usually mixed. Not including the fossil fuel consumption variable could potentially cause omitted variable bias and affect the causality results of renewable energy consumption and economic growth. The results of this chapter show that while capital stock and fossil fuels are the key factors driving economic growth, renewable energy promotes real output, especially amongst countries without oil reserves. Chapter 2 also uses the Two-Stage-Least Squares (2SLS) regressions following Stock and Watson (2003) to account for endogeneity and separate the movements of variables that are uncorrelated with error terms.

In sharp contrast with other work in the energy consumption-growth literature, this thesis acknowledges the influence of energy technologies on income. In order to reflect the total energy innovations that could bring about economic growth, Chapter 2 accounts for both earlier and newly invested energy R&D. The calculation of accumulated energy R&D follows the study of Bitzer and Stephan (2007), including a creation and destruction process.

The results of this thesis in Chapter 2 show that energy R&D, indeed, plays an important role in driving economic growth. In fact, fossil fuel R&D drives economic growth by a larger magnitude as compared to fossil fuel consumption. OECD countries, when classified in terms of their endowment, appear to have different responses to different types of energy R&D. Real output of countries with oil reserves (without oil reserves) are more responsive to fossil fuel R&D (renewable energy R&D) than countries without oil reserves (with oil reserves).

Current literature focuses on the potential benefits of renewable energy but overlook the factors that contribute to the growth in the consumption of renewable energy or cleaner forms of energy and the reduction in the consumption of fossil fuels worldwide. Generally, countries with and without fossil fuels are expected to have their own distinct growth process and there is no universal growth model applicable to all countries. Countries with and without oil reserves could also experience different energy market structures and have diverse factors which promote renewable energy and reduce fossil fuels.

Fluctuations in oil prices coupled with rising income are two major trends which could pose potential changes to the energy landscape worldwide. These could have influence over the role of crude oil as the major source of energy for most economies and promote renewable energy usage in the market. Little interest is devoted to investigate whether there are substitutions away to other forms of energy consumption (including renewable energy) and effort to increase energy efficiency with higher levels of energy R&D. Much interest is devoted to investigate the change in oil consumption, but not other types of energy consumption, with respect to changes in oil prices and income. Earlier studies such as Narayan and Wong (2009) and Cooper (2003) have found oil consumption to be rather inelastic with respect to changes in oil prices.

Using the Nerlove Partial Adjustment Model (NPAM) on the OECD countries, Chapter 3 investigates whether there is a change in energy landscape from both the perspective of energy consumption and energy R&D with changes in oil prices and economic growth. The results show that oil price hike is not effective to stimulate cleaner forms of energy consumption as the OECD countries shall remain heavily dependent on oil. However, oil price hike is a contributing factor to higher energy R&D though it is comparatively less influential in terms of magnitude on both energy consumption and energy R&D than economic growth. Economic growth is the main driver to promote cleaner forms of energy, from coal to oil, gas and renewable energy. It also contributes to higher levels of energy R&D.

Understanding the dynamic linkages between energy consumption and energy R&D of both fossil fuels and renewable energy would facilitate the climate mitigation policies which seek to increase renewable energy consumption or R&D and decrease fossil fuel consumption or R&D. In evaluating the question on what promotes renewable energy and reduces fossil fuels, Chapter 4 takes a step further by taking into account the potential bilateral relationship between energy consumption and energy R&D. Energy consumption and energy R&D are found not to be independent of one another. Energy R&D can be a tool to reduce fossil fuel consumption and increase renewable energy consumption. To reduce fossil fuel consumption and facilitate the shift towards renewable energy-based economies, countries could implement policies such as subsidies for renewable energy R&D and removal of subsidies for fossil fuel-related R&D. Higher energy consumption, on the other hand, can promote energy R&D as it leads to the depletion of energy sources and companies have to invest in energy R&D to improve their energy efficiency. Besides analyzing the potential bilateral relationship between energy consumption and energy R&D, gas prices and time dummies are also included in the regressions for analysis. Gas consumption is perceived to be growing in importance and gas prices indeed affect the respective energy consumption. There is increasing climatic policies which take place after 1992, and they do have substantial influence on energy consumption and energy R&D.

Findings from Chapters 2 - 5 suggest that renewable energy consumption and renewable energy R&D are closely related with income. Chapter 5 summarizes the findings of this thesis and discusses some interesting extensions for future research.

Chapter 2

Energy Consumption, Energy R&D and Real GDP in OECD Countries with and without Oil Reserves[1]

2.1 Introduction

One of the central puzzles in energy economics is perhaps to deal with the relationship between energy consumption and economic growth. Since the pioneering work of Kraft and Kraft (1978) which finds a uni-directional long-run relationship running from GDP to energy consumption in the US for the period of 1947-1974 through a standard Granger (1969) test, there has been a large body of published literature focusing on the causality linkages between energy consumption and economic growth.

Despite hundreds of follow-up papers, there seems to be little or no consensus regarding the direction of causality between energy consumption and

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[1] Note: An earlier version of this chapter was presented in the 35th IAEE International Conference (Energy Markets Evolution under Global Constraints: Assessing Kyoto and Looking Forward) and the Singapore Economic Review Conference (SERC) 2011. The key content of this chapter will also be published in *Energy Economics* (forthcoming).

economic growth. The absence of clear consensus regarding the direction of causality can be attributed to many factors ranging from different structure and development stage within a country to different econometric techniques used. Determining the direction of causality has crucial implications for countries in terms of designing and planning of future environmental and energy strategies. A bi-directional causality between energy consumption and economic growth implies that excessive energy protection that reduces energy consumption may consequently hinder economic growth. Absence of causality between energy consumption and economic growth or uni-directional causal relationship running from real GDP to energy consumption allows policy makers to design energy policies that are independent and have little adverse effect on economic growth. Uni-directional causal relationship running from energy consumption to economic growth implies the significance of energy conservation policies in depressing economic growth.

Many studies have attempted to complement previous studies by examining the relationship of various sources of energy consumption and economic growth such as nuclear energy consumption and economic growth (Chu and Chang, 2012; Wolde-Rufael and Menyah, 2010; Payne and Taylor, 2010; Yoo and Ku, 2009; Yoo and Jung, 2005), oil consumption and economic growth (Chu and Chang, 2012), coal consumption and economic growth (Li and Leung, 2012), electricity consumption and economic growth (Bildirici and Kayikçi, 2012; Ahamad and Islam, 2011), diesel consumption and economic growth (Tamba et al., 2012). Despite the fact that renewable energy is considered to be one of the fastest rising sources of energy for many countries, studies that employ modern advances in time series econometrics of cointegration and causality analysis to test for the causal relationship between renewable energy consumption and economic growth are scarce (Apergis and Payne, 2010, 2011 and 2012).

Even though Apergis and Payne (2010, 2011 and 2012) extend this line of research to determine the degree to which renewable energy consumption influences growth to the case of 20 OECD, the studies pay less attention to the potential differences that could take place due to countries' oil endowments. Since different countries may respond differently to energy consumption, this chapter tries to fill this gap by examining the relationship between energy consumption and economic growth on two groups of OECD countries: with and without oil reserves. Besides, this thesis also extends this strand of literature by examining not only the relationship between renewable energy consumption and economic growth but also the relationship between fossil fuel consumption and economic growth.

Within the framework of energy-growth nexus, the relationship between energy R&D and economic growth is overlooked though much attention has been paid on the relationship between energy consumption and economic growth. In the theoretical work of economic growth, there is one strand of literature that perpetuates growth through the accumulation of knowledge either through learning-by-doing (Romer, 1986; Stokey, 1988; Young, 1991) or investments in research and development (R&D) (Romer, 1990; Grossman and Helpman, 1991; Aghion and Howitt, 1992). Economic theory indeed emphasizes the importance of the accumulation of R&D in explaining growth. According to the endogenous growth model which is pioneered by Romer (1986), R&D sectors create technological innovation with the use of human capital and existing knowledge stock. While past studies did not clearly distinguish the differences between energy consumption and energy R&D, they are indeed distinct and should be treated differently. With what follows, instead of looking only at the conventional energy consumption-growth nexus, this chapter also examines the potential dynamic relationship between energy R&D (both fossil fuel and renewable energy) and economic growth.

One contribution of this chapter to existing literature is the introduction of accumulated energy R&D, which accounts for both R&D depreciation rates and past energy R&D investments. This chapter calculates accumulated energy R&D through a creation and destruction process to reflect the total energy innovations. Distinction between both the estimates of renewable energy R&D and fossil fuel R&D is also made. Estimation of cumulative renewable energy R&D only starts from 1980 whereas estimation of cumulative fossil fuel R&D is captured at an earlier date since 1860. Renewable energy R&D is assumed to be scarce before 1980.

The purpose of this chapter is to examine two sets of causal relationship between (1) capital stock, energy consumption and real GDP and (2) capital stock, energy R&D and real GDP using a panel-based Fully-Modified Ordinary Least Squares (FMOLS) and Dynamic Ordinary Least Squares (DOLS) for 20 OECD countries over the period of 1980-2010. Since different responses are expected for different groups of countries to changes in energy consumption and energy R&D, the sample is further divided into two groups: OECD countries with oil reserves and without oil reserves. Similarly energy consumption and energy R&D are also further divided into two types: fossil fuel energy and renewable energy. Before estimating these dynamic relationships between energy consumption or energy R&D with GDP, this chapter attempts to prevent endogeneity and omitted variable bias with the use of two-stage-least-squares and instrumental variables to segregate and determine the true predicted effects of one variable on another.

The contributions of this chapter are manifold. First, it deals with the endogeneity of regressors and accounts for both the integration and cointegration properties of data. Second, instead of looking at a group of OECD countries as a whole, this chapter considers a mix of OECD countries but comprising both with and without oil reserves which most studies paid less attention to. Third, most importantly, this chapter goes beyond the conventional energy consumption-growth nexus to study the role of energy R&D on economic growth.

The rest of the chapter is organized as follows. Section 2.2 provides a brief literature review of related studies on energy-consumption nexus. Section 2.3 outlines the importance of energy R&D in driving economic growth. Section 2.4 discusses the behavioral differences which countries of different oil endowment may have in terms of their types and levels of energy consumption and R&D. Section 2.5 discusses the data and the calculation of both capital stock and energy R&D. Section 2.6 provides the econometric methodology which includes tests for endogeneity, unit root, and cointegration. Section 2.7 provides the interpretation of the Fully-Modified Ordinary Least Squares (FMOLS) and Dynamic Ordinary Least Squares (DOLS) results. Section 2.8 conducts a robustness check on the variables. Section 2.9 presents the concluding remarks.

2.2 Overview of Existing Literature Review

Energy is perceived as a necessary input in production and Ayres et al. (2013) show that energy is a much more important factor of production than what its small cost share indicate. In general, economic growth could also be driven by many other non-energy related factors such as increase in trade openness and literacy rate. Nonetheless, the role of energy as an ingredient to economic growth has been well recognized and any economic growth has to be accompanied by higher energy usage. Higher oil prices and increasing risks of energy crisis raise the level of concern for energy security, especially amongst the countries without oil endowment. Countries have to search for solutions to improve on their energy efficiency or turn to alternative sources of energy, prompting them to invest in both fossil fuel R&D and renewable energy R&D. As countries grow richer, some of them eventually become more concern about the environment and begin to substitute away from the dirty fuels.

In the field of energy economics, a large number of papers have examined the role of energy consumption on economic growth. Payne (2010) found 101 papers investigating on such relationship since the first published paper in 1978 and many studies such as Stern (1993, 2000) and Ghali and El-Sakka (2004) show that energy consumption is important for production. This study, unlike earlier ones, not only examines the role of energy consumption, it also narrows down to the relationship between energy R&D and economic growth. Energy R&D, being part of the technological advancement, determines the effectiveness and efficiency in tapping and utilizing energy; hence, is also closely connected with GDP.

Scholars have moved on from analyzing the basic bi-variate models with only energy consumption and GDP to multivariate models which could include labor and capital. Recent works by Apergis and Payne (2011, 2012) have also moved on to differentiate between renewable and non-renewable energy consumption. Our study adds on to this field by differentiating between renewable energy and fossil fuels with the exclusion of nuclear energy. Nuclear energy is excluded because it could not be easily quantified by GDP. Capital stock is also included in our study for the estimations.

Existing studies often considered single countries (see as Stern, 1993, 2000 and Oh and Lee, 2004) and the studies by Lee and Lee (2010) and Ertugrul and Alper (2012) are the few which examined OECD countries. In a departure from existing studies, this study selects 20 OECD countries and divides them into those with and without oil reserves for further analyses. Countries with similar endowment are expected to display similar characteristics and economic structures, and have the similar dynamic linkages between energy and GDP.

Studies have commonly employed cointegration test, vector error correction model (see Apergis and Payne, 2009 and Odhiambo, 2009) or the Toda and Yamamoto (1995) methodology (e.g. see Lee and Chien, 2010 and Wolde-Rufael, 2009) to reveal such relationships to reveal the relationship between energy and GDP. Recently, studies such as Managi and Okimoto (2013) have also applied the Markov Chain Monte Carlo (MCMC) methodology to investigate the relationship between oil prices and stock. This study, though conducts the usual cointegration test and reports the results with the FMOLS and DOLS estimation, attempts to account for structural changes and potential of endogeneity within the models.

2.3 Importance of Energy R&D

In the field of energy economics, a large number of papers have examined the role of energy consumption but failed to account for the role of energy R&D on economic growth, leaving the relationship between energy R&D and economic growth remains largely unanswered. However, investments in R&D (research and development) are recognized as engines of total factor productivity (TFP) growth as the contributions of R&D to economic growth have been demonstrated through both theoretical (Romer, 1990; Grossman and Helpman, 1991a) and empirical (Griliches, 1992) studies. This implies that energy R&D, which forms part of R&D, could also promote the national productivity. Energy R&D is the focus of this thesis as it is a widely-emphasized subject as compared to non-energy R&D, especially at a time where public attention focuses much on energy planning topics such as future energy supply and clean energy technologies.

To date, evidence is not clear-cut whether the causal relationship between energy R&D and economic growth is a bilateral one or unilateral one. Energy R&D could cause what is largely known as energy innovation-driven growth. Other things being equal, higher levels of energy R&D result in more developed and efficient production processes or production capacity, and promote energy technologies which could be statistically and quantitatively important in providing a potential source of productivity growth. On the other hand, energy needs increase as countries become more developed, which prompts countries to enhance their respective efficiency in terms of energy generation and usage with higher levels of energy R&D investments. Energy R&D becomes a viable option to ensure the higher energy demands from new investments and activities within the economy are met.

The past few decades witnessed a few structural changes in the energy landscape where all countries in the world experienced a steep deterioration in the supply of energy, increasing population and growing economy. Increments in the investment levels of energy R&D become critical to enhance the countries' energy technologies to overcome the obstacles that restrict or lower their energy supply. This secures the energy for continued economic growth at less volatile energy prices. As fossil fuel reserves decline, countries are also exploring into the option of renewable energy, encouraging them to raise their levels of renewable energy R&D in addition to their fossil fuel R&D. Such changes in them cause higher levels of renewable energy R&D which could potentially influence the industrial processes, and hence economic growth.

2.4 Relevance of Oil Endowment

Within the same country group, countries often exhibit similar behavioral characteristics and converge to the same steady-state income levels. Often, country groups have similar factors which contribute to economic growth and one could expect that energy consumption and R&D could have homogeneous (heterogeneous) contributions to economic growth within (between) country groups. Although oil remains the main energy source for most countries, the responses of countries with and without oil reserves to higher oil prices and OPEC supply restrictions differ. As compared to countries with oil reserves which could still depend on their own oil supply, countries without oil reserves are energy import reliant and could be largely affected by the immediate reduction in energy resource. Countries with oil reserves do not face threat to their energy security like the countries without oil reserves, where the countries without oil reserves have to resort to alternative forms of energy or increase their energy efficiency with higher energy R&D for continued economic growth. As Sachs and Warner (1995, 2001) demonstrated that economic growth is related to their natural resources endowment, this Chapter investigates whether economic growth could also be related to the energy endowment.

Adoption of renewable energy could have a more quantitative effect on economic growth in countries without oil reserves as it adds an additional layer of energy security and lowers implicit energy costs for the production processes. Countries without oil reserves are hence more prone to intensive climate policy goals with more subsidies on renewable energy technologies and taxes on carbon-intensive sectors. These countries shape their energy landscape with more energy diversification, which includes the strategy of using overall more renewable energy consumption and less fossil fuel consumption to minimize their vulnerability to oil price and oil supply shocks. A fundamental barrier to renewable energy for countries with oil reserves is that they will take advantage of their natural endowments intensively, hence crowding out renewable energy-related activities. de Ferranti et al. (2002) concluded that countries such as Australia, Canada and the United States base their development on their natural resources whereas Torres et al. (2012) discover similar case in Norway.

Broadly speaking, countries with and without oil reserves behave differently and the presence of oil endowment could be perceived as a double-edged sword with both benefits and costs. It is best to distinguish both groups of countries from each other. The paper by Frankel (2010) believes in resource curse whereby the endowment of oil could cause crowding out of other manufacturing sectors and is hence detrimental to growth. With oil endowment, it also subjects the countries to excessive macroeconomic instability with fluctuations in oil prices and poor institutions.

2.5 Data Description

In this chapter, annual data of 20 OECD countries from 1980 to 2010 are used. According to BP Statistical Review of World Energy, among these 20 OECD countries, 7 countries are countries with oil reserves while the remaining 13 countries are countries without oil reserves. The 7 countries with oil reserves are Australia, Canada, Denmark, Italy, Norway, UK and US while the 13 countries without oil reserves are Austria, Belgium, Finland, France, Ireland, Japan, the Netherlands, New Zealand, Portugal, Spain, Sweden, Switzerland and Turkey. Statistics on real output, economically active population, gross fixed capital formation, fossil fuel consumption are obtained from World Development Indicators (WDI). Data on fossil fuel and renewable energy R&D are gathered from International Energy Agency (IEA). Data on renewable energy consumption are calculated by subtracting fossil fuel consumption and nuclear energy consumption from total energy consumption. Table 2.1 summarizes the descriptions of the variables used. Several aspects of the data are worth highlighting. We notice that compared to the mean of fossil fuel consumption (R&D) per labor, the mean of renewable energy consumption (R&D) per labor over the given period is lower in general for both groups of countries with and without oil reserves suggesting the dependence of OECD countries on fossil fuels as the main source of energy. Besides, it is also noted that OECD countries with oil reserves tend to have higher fossil fuel consumption per labor than OECD countries without oil reserves.

Table 2.1: Descriptive Statistics.

Variables	OECD Countries			With Oil Reserves			Without Oil Reserves		
	Mean	Std.Dev.	Obs.	Mean	Std.Dev.	Obs.	Mean	Std.Dev.	Obs.
Gdp (thousands 2000 US$)	31.8	13.0	620	36.5	10.7	217	29.3	13.4	403
Cap (thousands 2000 US$)	114.6	52.7	620	123.3	33.5	217	109.9	60.0	403
Fos^C (tonnes)	4.7	2.1	620	6.3	2.3	217	3.9	1.4	403
Ren^C (tonnes)	1.0	1.0	620	1.1	1.2	217	1.0	0.9	403
Fos^R (thousands 2000 US$)	306.0	3745.6	599	774.9	6201.7	217	39.7	136.2	382
Ren^R (thousands 2000 US$)	136.4	1742.1	597	342.5	2881.0	217	18.7	60.6	380

Note: Gdp, Cap, Fos^C, Ren^C, Fos^R, and Ren^R represent GDP per labor, capital stock per labor, fossil fuel consumption per labor, renewable energy consumption per labor, accumulated fossil fuel R&D per labor and accumulated renewable energy R&D per labor, respectively.

The past invested capital stock and energy R&D are still contributing towards economic growth. This chapter attempts to account for both newly and past invested capital and energy R&D, hence both capital stock and accumulated fossil fuel R&D and renewable energy R&D are calculated and used for analyses. The derivation of capital stock and accumulated energy R&D are shown in later sections of this chapter.

2.5.1 Calculation of Capital Stock

According to Kamps (2006), we can use the perpetual method to calculate the capital stock at the beginning of the next period (K_{t+1}).

$$K_{t+1} = K_t + I_t - D_t \tag{2.1}$$

where K_{t+1} is depedent on (i) the capital stock at the beginning of the current period (K_t), (ii) the gross investment in the current period (I_t), and (iii) the depreciation in the current period (D_t).

If the capital stock depreciates at a constant rate (δ), equation (2.1) is expressed as:

$$K_{t+1} = (1 - \delta)K_t + I_t \tag{2.2}$$

Reiterative substitution of equation (2.2) in equation (2.3) show that the past gross investments decline in quantity over time, but they will continue to remain as part of the capital stock.

$$K_{t+1} = \sum_{i=0}^{\infty}(1 - \delta)^i I_{t-i} \tag{2.3}$$

Early data on past gross investments is unavailable and hence, we need to calculate capital stock using the equation (2.3) expressed. Equation (2.3) could be re-expressed as below:

$$K_{t+1} = (1-\delta)^t K_1 + \sum_{i=0}^{t-1} (1-\delta)^i I_{t-i} \tag{2.4}$$

where K_1 is the initial capital stock at the beginning of period 1. Equation (2.4) requires assumption of three things: an estimation of the gross investment flows, the initial capital stock (which is 1980 in this study), and the depreciation rates. Kamps (2006) mentions that its methodology draws in a large part on OECD (2001) and the U.S. Bureau of Economic Analysis (1999). It is comparable to Jacob et al (1997), where Jacob et al (1997) estimate capital stocks by industrial activity according to the ISIC.

This study is similar to Jacob et al. (1997) and Kamps (2006) in terms of estimation of initial capital stock. The investments are artificially constructed and capital stock is assumed to grow linearly from the start of the period to the observed level. To obtain the initial stock, this study first estimates the gross investment from 1860 to 1960 by assuming that investment increased by 4 percent a year. The gross investment of the countries grows by an average 4 percent from 1960 to 2010. Although it is unlikely that growth rates are consistent before and after 1960, but this methodology ensures equal treatment across countries. The weightage of past gross investments also reduce to lower than 10 percent in the average OECD country.

2.5.1.1 Calculation of Depreciation Rates

The calculation of depreciation rates in this chapter is an average of the depreciation rates of Kamps (2006). Following Kamps (2006), we have the scrapping rate expressed in equation (2.5) as the proportion of depreciation over total capital stock in time period t.

$$s_t = \frac{D_t}{K_t} \cdot 100 \tag{2.5}$$

For the depreciation rates, Musgrave (1992) and Nadiri and Prucha (1996) have estimated the depreciation rates of physical stocks to be around 3.4 percent and 5.9 percent, respectively. Kamps (2006) uses different depreciation rates for different items, with time-varying depreciation rates for the public capital stock and the private nonresidential capital stock and constant depreciation rates for the private residential capital stock. In this chapter, we assume that capital stock has an annual growth rate of 4 percent since 1875 and the rate of depreciation gradually increases from 2.75 percent[2] (for the period before 1960) to 4.66 percent[3]. The rate of depreciation is calculated as the average rates of depreciation amongst government, non-residential and residential assets, adopted from Kamps (2006). The depreciation rates for t from 1980 to 2010 can be expressed as:

$$\delta_t = 2.75 * (\frac{4.66}{2.75})^{\frac{1}{50}})^{(t-2010+50)} \tag{2.6}$$

Capital stock, accumulated fossil fuel R&D and renewable energy R&D are calculated. It is first assumed that the trend for the period 1980-2010 is the same as the trend for the period of 1860-1979. Then, capital stock and accumulated energy R&D for 1860-2010 are assumed to evolve according to:

$$\begin{aligned} K_{t+1}^S &= \sum_{i=1860}^{t-1} [\prod_{k=i+1}^{t} (1-\delta_k)](1-\frac{\delta_i}{2})I_i \qquad (2.7) \\ &= (1-\delta_t)K_t^S + (1-\frac{\delta_t}{2})I_t \qquad (2.8) \end{aligned}$$

where K_t^S represents either capital stock or different accumulated energy R&D, I_t represents the newly invested capital or newly invested energy R&D and δ_t represents the rate of depreciation of capital or energy R&D at time t. Equation (2.7) also assumed that the average investments are made in mid-year.

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[2] Depreciation of residential assets as 1.5 percent, government assets as 2.5 percent, private non-residential assets as 4.25 percent.

[3] Depreciation of residential assets as 1.5 percent, government assets as 4 percent, private non-residential assets as 8.5 percent.

2.5.2 Calculation of Energy R&D

Gross fixed capital formation contributes to improvement and increment in quantities of machineries, equipments, and buildings. These are subjected to physical deterioration (wear and tear) as they age, leading to a decline in the efficiency. Energy R&D, on the other hand, contributes to new knowledge which contributes to improvement in energy products and processed, is not subjected to wear and tear. However, both capital and R&D could be surpassed by new capital and R&D as they become obsolete over time. The utilization of any past invested knowledge would decline over time.

Energy R&D could face similar depreciation rates like any other forms of R&D. The shares of obsolete energy R&D investments are not observed and hence, assumptions about the depreciation rates have to be made. Nadiri and Prucha (1996) and Bernstein and Mamuneas (2005) are some existing literature which have measured the depreciation rate of the R&D stock. Nadiri and Prucha (1996) observed that most research in the literature assumes a constant depreciation rate that varies between 10 and 15 percent as proposed by the work of Griliches. Hall and Mairesse (1995) have explored different depreciation rates and proposed that the depreciation rates have little influence on estimations.

The use of constant depreciation rate implies that regardless whether new energy R&D investments are made, a portion of the energy R&D stock becomes obsolete. Bitzer and Stephan (2007) argue that the creation of new knowledge that displaces the old and more (less) R&D results in higher (lower) depreciation rate.

The accumulated energy R&D is a creation and destruction process.

$$X_t = \sum_{j=0}^{\infty} R_{t-j} - \sum_{j=k}^{\infty} b_{t-j} R_{t-j} \tag{2.9}$$

where the first part of the equation ($\sum_{j=0}^{\infty} R_{t-j}$) represents the creation process and ($\sum_{j=k}^{\infty} b_{t-j} R_{t-j}$) represents the destruction process. The creation process is the accumulation of past energy R&D invested. b represents the displacement factor which captures the substitution rate of the newly invested energy R&D for the old energy R&D (where $0 < b < 1$). k represents the time lag for destruction process to take place ($k > 0$).

As it is assumed that ground-breaking innovations are rare, it is a plausible assumption that does not vary over time. Equation (2.9) can then be expressed as:

$$X_t = \sum_{j=0}^{\infty} R_{t-j} - b \sum_{j=k}^{\infty} R_{t-j} \tag{2.10}$$

Hall and Mairesse (1995) assumed the annual growth rate for R&D expenditures to be 2.5 percent. Bitzer and Stephan (2007) use the 2 years time lag found in Pakes and Schankerman (1984) and Ravenscraft and Scherer (1982) on the average implementation lag of new inventions. Hence, this study also assumes that the time lag (k) is 2 years in equation (2.10) for calculation of accumulated energy R&D. Bitzer (2005) assessed substitution rates as between 0.80 and 0.95 to have no significant differences in the results so we use a displacement rate of 0.85 in this chapter.

2.6 Econometric Methodology

2.6.1 Testing for Endogeneity

Endogeneity problem could arise from an omitted variable which has influence over two or more variables in the system. In analyzing the energy consumption-economic growth nexus, it is possible that higher output per labor is driven by an unobserved factor such as energy R&D, which is also correlated with capital stock and energy consumption. Likewise, the analysis of energy R&D-economic growth nexus may have influences from energy consumption. The applications of Ordinary Least Squares (OLS) estimations are biased and inconsistent due to the correlation of variables and the error term.

Table 2.2: Endogeneity Tests (Energy Consumption).

Tests	Independent Variables			
	Gdp	*Cap*	Fos^C	Ren^C
20 OECD				
Hausman Test	19.39***	98.03***	8.33**	28.03***
	(0.000)	(0.000)	(0.040)	(0.000)
Kleibergen-Paap F-Test	136.939***	165.264***	119.331***	118.436***
	(0.000)	(0.000)	(0.000)	(0.000)
Over-Identification Test	4.074	1.890	5.010	1.388
	(0.254)	(0.389)	(0.171)	(0.700)
With Oil Reserves				
Hausman Test	16.85***	36.29***	34.15***	16.97***
	(0.001)	(0.000)	(0.000)	(0.000)
Kleibergen-Paap F-Test	18.080***	21.658***	18.239***	36.069***
	(0.000)	(0.000)	(0.000)	(0.000)
Over-Identification Test	3.602	2.868	5.817	3.367
	(0.308)	(0.413)	(0.121)	(0.338)
Without Oil Reserves				
Hausman Test	14.10***	70.52***	28.91***	20.26***
	(0.003)	(0.000)	(0.000)	(0.000)
Kleibergen-Paap F-Test	93.200***	147.339***	128.818***	78.673***
	(0.000)	(0.000)	(0.000)	(0.000)
Over-Identification Test	3.154	4.900	5.569	1.823
	(0.368)	(0.179)	(0.135)	(0.610)

Notes: 1. *, **, *** represent the significance at the 10%, 5% and 1% levels, respectively. 2. Statistics are in chi-squares and probabilities are reported in parentheses.

Most existing literatures in the energy-growth nexus field have not addressed the issue of endogeneity which could stem from multiple unobserved sources. This chapter contributes to existing literature with the use of the Two-Stage-Least-Squares (2SLS) to segregate the movements of variables that are uncorrelated with the error terms (Stock and Watson, 2003) for the purpose of providing consistent estimates. With the use of instrumental variables, it reduces the misspecification error in the model. Before proceeding with any estimation, the variables are first tested for endogeneity using the Hausman tests. After which, the instruments chosen are tested for their validity and strength using

Table 2.3: Endogeneity Tests (Energy R&D).

Tests	Independent Variables			
	Gdp	Cap	Fos^R	Ren^R
20 OECD				
Hausman Test	41.32***	44.33***	136.5***	279.06***
	(0.009)	(0.000)	(0.000)	(0.000)
Kleibergen-Paap F-Test	14.478***	16.538***	77.283***	84.556***
	(0.000)	(0.000)	(0.000)	(0.000)
Over-Identification Test	1.356	4.210	3.959	3.098
	(0.716)	(0.122)	(0.266)	(0.377)
With Oil Reserves				
Hausman Test	16.95***	39.39***	76.47***	119.85***
	(0.000)	(0.000)	(0.000)	(0.000)
Kleibergen-Paap F-Test	9.497***	16.538***	47.647***	34.027***
	(0.000)	(0.000)	(0.000)	(0.000)
Over-Identification Test	0.472	4.962	3.498	2.113
	(0.790)	(0.175)	(0.321)	(0.549)
Without Oil Reserves				
Hausman Test	38.12***	23.05***	18.75***	125.53***
	(0.000)	(0.000)	(0.000)	(0.000)
Kleibergen-Paap F-Test	10.966**	10.819**	36.740***	70.270***
	(0.050)	(0.050)	(0.000)	(0.000)
Over-Identification Test	0.451	1.440	0.803	5.031
	(0.930)	(0.696)	(0.849)	(0.170)

Notes: 1. *, **, *** represent the significance at the 10%, 5% and 1% levels, respectively. 2. Statistics are in chi-squares and probabilities are reported in parentheses.

the Sargan test and F-test, respectively.

Instrumental variables (IVs) are used as part of the 2SLS estimation in the presence of endogeneity. One criterion for selecting the instruments is that the instruments should be powerful and the second criteria is that they should be uncorrelated with the error term, which means exogenous. Cameron and Trivedi (2009) proposed that lags of endogenous variables are exogenous by nature and offer consistent estimations. Therefore, we use the second and third lags of the endogenous explanatory variables as instruments. The significance of the excluded instruments (whether they are correlated with the endogenous regressors) can be observed through the first stage regressions, and tested by the F-statistics of Cragg-Donald (1993). The rule of thumb from Staiger and Stock (1997) proposed that the instrumental variables are weak when the first-stage F-statistics are less than ten. Kleibergen and Paap (2006) proposed the Wald *rk* F statistic in place of the Cragg-Donald statistics as the Cragg-Donald statistics are not valid in the presence of heteroscedasticity or serial correlation. The Kleibergen and Paap (2006) F-statistics are then compared against the critical values generated by Stock and Yogo (2005).

Tables 2.2 and 2.3 show the results for the Hausman endogeneity tests, F-tests for the strength of the variables and over-identification test for the validity of the instruments in equations assessing the linkage between (i) energy consumption and economic growth and (ii) accumulated energy R&D and economic growth, respectively. The Hausman tests show presence of endogeneity in all the equations, with the null hypothesis of no endogeneity rejected. The Kleibergen-Paap tests also reject the null hypothesis, which shows that the instruments are adequate to identify the equations. Last, the over-identification test, which is the Sargan-Hansen test, accepts the null hypothesis that the instruments are valid instruments.

2.6.2 Unit Root with Cross Dependence

In the presence of cross dependence across countries, the conventional panel unit root tests are biased (O'Connell, 1998; Maddala and Wu, 1999). The Pesaran (2007) cross-sectionally dependent unit root test, with the null hypothesis that output innovations are cross-sectionally independent, is used. Following Pesaran (2007), we first perform the individual ADF(ρ) regressions without any forms of cross section augmentations for lag lengths ρ =1, 2, 3, and 4, respectively[4]. After which, the regression residuals are collected and used to calculate the pair-wise cross section correlation coefficients ($\hat{\rho}_{ij}$). A simple average of these

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[4] Note: I am grateful to Mohammad Hashem Pesaran and Takashi Yamagata for their Gauss codes.

correlation coefficients ($\overline{\hat{\rho}}$) and the cross dependence (CD) statistic is calculated [5].

The results in Table 2.4 show that the null hypothesis that output innovations are cross-sectionally independent are often rejected, at the 1% significant levels, with the exception of renewable energy consumption per labor. Within the 20 OECD countries, the average cross-section error correlation coefficients for output per labor, capital stock per labor, fossil fuel consumption per labor, accumulated fossil fuel R&D per labor, and accumulated renewable energy R&D per labor is around 0.28, 0.13, 0.09, 0.09, 0.09, respectively. The result is robust across the choice of ρ.

Following Pesaran (2007), the derivations of the individual cross-sectionally augmented Augmented Dickey Fuller (CADF) statistics and their simple averages, known as the cross-sectionally augmented IPS (CIPS) test, are summarized as follows.

$X_{i,t}$ is an observation (either output, capital stock, fossil fuel consumption, renewable energy consumption, fossil fuel R&D, or renewable energy R&D) in country i at time t generated according to the simple dynamic linear heterogeneous panel data model in equation (2.11).

$$X_{it} = (1 - \phi_i)\mu_i + \phi_i X_{i,t-1} + \mu_{it} \tag{2.11}$$

where the error term (μ_{it}) has the single factor structure denoted as:

$$\mu_{it} = \gamma_i f_i + \varepsilon_{it} \tag{2.12}$$

where f_i and ε_{it} represent unobserved common effect and individual-specific error, respectively. Hence, equation (2.11) could be expressed as $\Delta X_{it} = \alpha_i + \beta_i X_{i,t-1} + \gamma_i f_i + \varepsilon_{it}$. The null hypothesis of unit root ($H_0 : \phi_i = 1$) can be

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[5] The calculations are: $\overline{\hat{\rho}} = (\frac{2}{N(N-1)}) \sum_{i=1}^{N-1} \sum_{j=i+1}^{N} \hat{\rho}_{ij}$, and $CD = [\frac{TN(N-1)}{2}]^{1/2}\overline{\hat{\rho}}$, respectively.

Table 2.4: Cross-Section Correlation of the Errors in the ADF(p) Regression.

Countries	Variable	Tests	$\rho = 1$	$\rho = 2$	$\rho = 3$	$\rho = 4$
20 OECD	Gdp	$\bar{\hat{\rho}}$	0.262	0.273	0.297	0.297
		CD	20.138***	20.920***	22.830***	22.781***
	Cap	$\bar{\hat{\rho}}$	0.159	0.140	0.121	0.110
		CD	12.231***	10.781***	9.313***	8.415***
	Fos^C	$\bar{\hat{\rho}}$	0.075	0.079	0.103	0.112
		CD	5.718***	6.065***	7.899***	8.571***
	Ren^C	$\bar{\hat{\rho}}$	0.015	0.010	0.008	-0.005
		CD	1.161	0.753	0.589	-0.354
	Fos^R	$\bar{\hat{\rho}}$	0.101	0.085	0.090	0.078
		CD	7.727***	6.545***	6.887***	5.998***
	Ren^R	$\bar{\hat{\rho}}$	0.096	0.094	0.082	0.083
		CD	7.399***	7.193***	6.273***	6.362***
With Oil Reserves	Gdp	$\bar{\hat{\rho}}$	0.324	0.340	0.370	0.366
		CD	8.277***	8.677***	9.434***	9.338***
	Cap	$\bar{\hat{\rho}}$	0.160	0.157	0.152	0.142
		CD	4.071***	4.015***	3.884***	3.621***
	Fos^C	$\bar{\hat{\rho}}$	0.144	0.152	0.188	0.179
		CD	3.664***	3.878***	4.803***	4.566***
	Ren^C	$\bar{\hat{\rho}}$	-0.030	-0.043	-0.025	-0.018
		CD	-0.764	-1.108	-0.638	-0.472
	Fos^R	$\bar{\hat{\rho}}$	0.075	0.081	0.085	0.050
		CD	1.905*	2.077**	2.157**	1.286
	Ren^R	$\bar{\hat{\rho}}$	0.117	0.116	0.107	0.133
		CD	2.974***	2.956***	2.732***	3.397***
Without Oil Reserves	Gdp	$\bar{\hat{\rho}}$	0.234	0.238	0.264	0.267
		CD	11.489***	11.708***	12.972***	13.114***
	Cap	$\bar{\hat{\rho}}$	0.192	0.165	0.136	0.139
		CD	9.438***	8.111***	6.674***	6.855***
	Fos^C	$\bar{\hat{\rho}}$	0.037	0.035	0.063	0.079
		CD	1.811*	1.713**	3.101***	3.897***
	Ren^C	$\bar{\hat{\rho}}$	0.056	0.059	0.062	0.045
		CD	2.770***	2.878***	3.042***	2.231***
	Fos^R	$\bar{\hat{\rho}}$	0.059	0.070	0.083	0.063
		CD	2.915***	3.464***	4.102***	3.090***
	Ren^R	$\bar{\hat{\rho}}$	0.096	0.104	0.094	0.092
		CD	4.729***	5.110***	4.611***	4.507***

Note: *, **, *** represent the significance at the 10%, 5% and 1% levels, respectively. The critical values of the CD test statistic follows a N(0,1) distributions, where the critical values at the 10%, 5% and 1% significant levels are 1.64, 1.96 and 2.57, respectively.

expressed as $H_0 : \beta_i = 0$, for all i.

Following Pesaran (2006), the common factor can be proxied by the cross-section mean of X_{it}, where $\bar{X}_t = N^{-1} \sum_{j=1}^{N} X_{jt}$ and the lagged values of X_{it} are sufficiently large. The unit root hypothesis can hence be tested on the t-ratio of the b_i of the OLS estimation in the CADF regression.

$$\Delta X_{it} = a_i + b_i X_{i,t-1} + c_i \bar{X}_{t-1} + d_i \Delta \bar{X}_t + \varepsilon_{it} \tag{2.13}$$

The t-ratio can be expressed as:

$$t_i(N,T) = \frac{\Delta X_i' \bar{M}_w X_{i,-1}}{\hat{\sigma}_i (X_{i-1}' \bar{M}_w X_{i,-1})^{1/2}} \tag{2.14}$$

where

$$\begin{aligned} \Delta X_i &= (\Delta X_{i1}, \Delta X_{i2}, ..., \Delta X_{iT})', \Delta X_{i,-1} = (X_{i0}, X_{i1}, .., X_{iT-1})' \\ \bar{M}_w &= I_T - \bar{W}(\bar{W}'\bar{W})^{-1}\bar{W}, \ \bar{W} = (\tau, \Delta\bar{X}, \bar{X}_{-1}) \\ \tau &= (1, 1, ..., 1)', \ \Delta\bar{X} = (\Delta\bar{X}_1, \Delta\bar{X}_2, ..., \Delta\bar{X}_T)', \ \bar{X}_{-1} = (\bar{X}_0, \bar{X}_1, ..., \bar{X}_{T-1})' \\ \hat{\sigma}_i^2 &= \frac{\Delta X_i' M_{i,w} \Delta X_i}{T-4}, \text{ where } M_{i,w} = I_T - G_i(G_i'G_i)^{-1}G_i', \text{ and } G_i = (\bar{W}, X_{i,-1}) \end{aligned}$$

The statistics denoted above can be extended to more general cases of the panel unit root. A cross-sectionally augmented version of the IPS test can be expressed as:

$$CIPS(N,T) = t - bar = N^{-1} \sum_{i=1}^{N} t_i(N,T) \tag{2.15}$$

where $t_i(N,T)$ represents the CADF statistic for country i given by the t-ratio of the coefficient of $X_{i,t-1}$ expressed in equation (2.13). Pesaran (2007) points out that the equation (2.15) is not analytically tractable but can be readily simulated.

Tables 2.5-2.10 report the results of the CIPS test for the individual 20 OECD countries for output per labor, capital stock per labor, fossil fuel con-

Table 2.5: CIPS Test Statistics for the Individual Countries (Output per labor).

Country	$\rho = 1$	$\rho = 2$	$\rho = 3$	$\rho = 4$
Australia	-3.439	-2.887	-1.989	-0.731
Austria	-2.111	-1.731	-2.356	-1.958
Belgium	-2.153	-2.296	-4.616**	-5.161***
Canada	-2.887	-1.572	-2.794	-2.511
Denmark	-4.324**	-3.242	-4.430**	-3.351
Finland	-0.639	-0.307	-0.597	-0.421
France	-2.496	-2.102	-3.344	-2.440
Ireland	-3.631*	-3.666*	-3.773*	-3.173
Italy	0.040	1.115	0.353	0.574
Japan	-1.290	-0.233	-0.520	0.539
Netherlands	-2.111	-1.522	-1.511	-1.148
New Zealand	-2.340	-1.674	-1.852	-0.650
Norway	-1.879	0.507	0.588	0.303
Portugal	-1.870	-1.123	-2.532	-1.586
Spain	-2.235	-0.493	-0.730	-0.601
Sweden	-1.304	-1.053	-3.139	-5.056***
Switzerland	-1.413	-0.338	-1.096	-1.227
Turkey	-2.577	-2.703	-3.246	-1.935
United Kingdom	-3.710*	-1.958	-2.568	-2.479
United States	-2.892	-3.114	-3.150	-3.284

Note: *, **, *** represent the significance at the 10%, 5% and 1% levels, respectively. The critical values for the 20 OECD countries at the 10%, 5% and 1% significance are -3.49, -3.87, and -4.68, respectively.

Table 2.6: CIPS Test Statistics for the Individual Countries (Capital Stock per Labor).

Country	$\rho = 1$	$\rho = 2$	$\rho = 3$	$\rho = 4$
Australia	-0.656	-0.475	-0.227	0.236
Austria	-1.353	-1.807	-1.986	-1.268
Belgium	-0.827	-0.205	-0.305	-1.359
Canada	-0.040	0.778	0.454	0.836
Denmark	-3.382	-2.334	-2.235	-1.769
Finland	-1.401	-1.326	-0.949	-1.734
France	-1.984	-2.006	-2.175	-3.160
Ireland	-1.768	-1.475	-2.263	-2.043
Italy	1.694	3.096	4.988	3.684
Japan	-2.740	-3.275	-3.462	-4.526**
Netherlands	-1.518	-1.043	-1.204	-0.987
New Zealand	-2.441	-2.229	-1.952	-2.464
Norway	-0.556	-0.279	-0.640	-1.027
Portugal	-1.890	-1.493	-0.693	-1.535
Spain	0.446	-0.134	0.708	0.131
Sweden	-0.370	-0.222	-0.696	-1.044
Switzerland	-0.697	-1.898	-2.241	-1.984
Turkey	-2.908	-3.032	-3.693*	-3.801*
United Kingdom	-3.212	-3.028	-3.168	-2.746
United States	-2.831	-3.107	-2.902	-3.169

Note: *, **, *** represent the significance at the 10%, 5% and 1% levels, respectively. The critical values for the 20 OECD countries at the 10%, 5% and 1% significance are -3.49, -3.87, and -4.68, respectively.

Table 2.7: CIPS Test Statistics for the Individual Countries (Fossil Fuel Consumption per Labor).

Country	$\rho = 1$	$\rho = 2$	$\rho = 3$	$\rho = 4$
Australia	-3.762*	-1.880	-2.674	-1.767
Austria	-2.369	-1.113	-1.957	-0.161
Belgium	-1.985	-1.347	-2.156	-1.395
Canada	-4.034**	-1.551	-1.458	-0.861
Denmark	-3.627*	-3.051	-3.082	-1.389
Finland	-2.586	-2.119	-3.708*	-1.378
France	-2.368	-1.961	-2.939	-0.750
Ireland	-3.010	-2.616	-2.829	-1.971
Italy	-3.564*	-2.539	-3.150	-1.632
Japan	-2.686	-1.759	-2.215	-3.518*
Netherlands	-5.969***	-3.386	-3.692*	-3.195
New Zealand	-1.192	-0.652	-1.288	-0.994
Norway	-4.403**	-3.904**	-3.849*	-2.390
Portugal	-2.108	-1.265	-3.238	-1.826
Spain	-2.970	-3.317	-1.441	-0.819
Sweden	-3.205	-2.325	-3.464	-2.258
Switzerland	-4.936***	-3.262	-2.370	-1.680
Turkey	-2.846	-2.301	-4.163**	-2.877
United Kingdom	-3.558*	-3.085	-1.937	-2.217
United States	-5.033***	-2.549	-4.543**	-6.111***

Note: *, **, *** represent the significance at the 10%, 5% and 1% levels, respectively. The critical values for the 20 OECD countries at the 10%, 5% and 1% significance are -3.49, -3.87, and -4.68, respectively.

Table 2.8: CIPS Test Statistics for the Individual Countries (Renewable Energy Consumption per Labor).

Country	$\rho = 1$	$\rho = 2$	$\rho = 3$	$\rho = 4$
Australia	1.795	-1.141	-2.034	-1.444
Austria	-1.715	-0.048	-1.959	-0.920
Belgium	-3.515*	-4.235**	-4.218**	-3.991**
Canada	-2.476	-0.458	-1.636	-0.914
Denmark	-2.355	-2.669	-2.461	-4.265**
Finland	-2.002	-1.551	-1.833	-1.369
France	-3.351	-1.492	-1.515	-1.585
Ireland	-1.145	0.630	0.540	0.979
Italy	-3.875*	-2.368	-3.448	-2.640
Japan	-3.068	-3.091	-2.777	-3.376
Netherlands	-1.521	-1.167	-2.174	-0.398
New Zealand	-3.450	-3.172	-4.221**	-3.656*
Norway	-2.369	-1.898	-2.237	-1.153
Portugal	-4.162**	-2.996	-2.647	-2.620
Spain	-3.672*	-3.655*	-3.145	-3.369
Sweden	-4.198**	-3.235	-3.040	-3.254
Switzerland	-3.487	-1.607	-2.268	-2.976
Turkey	-2.675	-2.347	-2.110	-2.642
United Kingdom	-2.461	-4.204**	-5.003***	-3.515*
United States	-2.701	-1.609	-3.165	-2.927

Note: *, **, *** represent the significance at the 10%, 5% and 1% levels, respectively. The critical values for the 20 OECD countries at the 10%, 5% and 1% significance are -3.49, -3.87, and -4.68, respectively.

Table 2.9: CIPS Test Statistics for the Individual Countries (Accumulated Fossil Fuel R&D per Labor).

Country	$\rho = 1$	$\rho = 2$	$\rho = 3$	$\rho = 4$
Australia	-0.591	-0.207	0.187	-0.280
Austria	-2.866	-1.474	-1.598	-1.425
Belgium	-2.246	-0.512	-0.051	-0.329
Canada	-2.157	-1.939	-0.982	1.772
Denmark	-3.466	-2.507	-0.995	-0.752
Finland	-3.016	-2.783	-6.190***	-6.190***
France	-2.284	-2.620	-3.995**	-6.190***
Ireland	-2.813	-0.554	-0.664	0.007
Italy	-3.053	-3.500*	-3.820*	-2.906
Japan	-3.400	-3.629*	-3.761*	-2.510
Netherlands	-6.190***	-3.485	-2.695	-3.004
New Zealand	-3.755*	-2.960	-2.439	-2.955
Norway	1.082	1.347	0.336	0.364
Portugal	-4.456**	-2.817	-2.283	-1.032
Spain	-2.611	-1.976	-1.478	0.179
Sweden	-6.190***	-4.421**	-4.083**	-2.710
Switzerland	-2.781	-1.904	-1.240	-1.306
Turkey	-2.610	-3.159	-5.411***	-6.190***
United Kingdom	-3.520*	-1.329	0.402	1.031
United States	-3.398	-2.389	-3.478	-3.304

Note: *, **, *** represent the significance at the 10%, 5% and 1% levels, respectively. The critical values for the 20 OECD countries at the 10%, 5% and 1% significance are -3.49, -3.87, and -4.68, respectively.

Table 2.10: CIPS Test Statistics for the Individual Countries (Accumulated Renewable Energy R&D per Labor).

Country	$\rho = 1$	$\rho = 2$	$\rho = 3$	$\rho = 4$
Australia	-0.844	1.936	0.428	-1.065
Austria	0.260	1.239	1.001	-0.087
Belgium	-3.433	-2.313	-3.014	-2.907
Canada	-3.010	-1.342	-0.736	-0.617
Denmark	-2.344	-1.106	-0.155	-0.688
Finland	-3.757*	-0.994	-2.793	-65.317***
France	-2.920	-6.137***	-3.908**	-24.852***
Ireland	-2.528	-2.711	-2.499	-1.338
Italy	-3.110	-4.657**	-4.705***	-3.776*
Japan	-4.372**	-4.133**	-3.939**	-3.780*
Netherlands	-4.881***	-2.394	-3.728*	-2.043
New Zealand	-3.450	-2.070	-0.613	0.964
Norway	-1.286	-1.285	-1.213	-0.771
Portugal	-3.619*	-2.513	-2.261	-1.178
Spain	-1.890	-1.385	-1.245	-0.230
Sweden	-2.756	-1.824	-2.693	-2.390
Switzerland	-4.452**	-2.722	-3.214	-2.185
Turkey	-4.293**	-3.503*	-3.120	-26.990***
United Kingdom	-2.859	-0.598	-2.047	-1.711
United States	-5.260***	-2.439	-2.850	-0.888

Note: *, **, *** represent the significance at the 10%, 5% and 1% levels, respectively. The critical values for the 20 OECD countries at the 10%, 5% and 1% significance are -3.49, -3.87, and -4.68, respectively.

Table 2.11: CIPS Test Statistics for the Country Groups.

Variables		Groups	$\rho = 1$	$\rho = 2$	$\rho = 3$	$\rho = 4$
20 OECD	Gdp	Levels	-2.263	-1.520	-2.165	-1.815
		Differences	-3.863***	-3.494***	-2.786**	-2.520
	Cap	Levels	-1.422	-1.275	-1.232	-1.486
		Differences	-4.920***	-3.639***	-3.342***	-2.765**
	Fos^C	Levels	-2.674*	-1.925	-2.085	-1.469
		Differences	-3.487***	-4.074***	-2.684*	-3.006***
	Ren^C	Levels	-2.800**	-2.116	-2.567	-2.302
		Differences	-3.484***	-3.844***	-2.635*	-2.711*
	Fos^R	Levels	-3.016***	-2.141	-2.212	-1.886
		Differences	-5.615***	-5.030***	-3.796***	-2.922***
	Ren^R	Levels	-3.040***	-2.059	-2.165	-2.197
		Differences	-3.412***	-4.193***	-2.669*	-2.676*
With Oil Reserves	Gdp	Levels	-2.758**	-1.383	-1.509	-1.125
		Differences	-4.516***	-4.313***	-4.158***	-3.428***
	Cap	Levels	-0.695	-0.694	-0.347	-0.389
		Differences	-3.475***	-2.885**	-2.819*	-2.132
	Fos^C	Levels	-3.669***	-2.032	-2.371	-1.406
		Differences	-3.688***	-4.984***	-3.561***	-3.905***
	Ren^C	Levels	-2.561	-2.034	-2.843*	-2.516
		Differences	-3.641***	-3.631***	-2.745*	-2.848*
	Fos^R	Levels	-2.069	-2.754*	-2.284	-2.170
		Differences	-4.835***	-2.914**	-3.609***	-3.375***
	Ren^R	Levels	-2.628	-2.940*	-2.646	-2.542
		Differences	-3.611***	-3.361***	-2.823*	-2.821*
Without Oil Reserves	Gdp	Levels	-1.844	-1.373	-2.228	-1.906
		Differences	-4.274***	-3.428***	-2.780**	-2.550
	Cap	Levels	-1.793	-1.768	-1.736	-2.008
		Differences	-4.071***	-3.722***	-3.288***	-2.566
	Fos^C	Levels	-2.872**	-2.156	-2.583	-1.701
		Differences	-3.632***	-2.623	-3.086***	-2.741*
	Ren^C	Levels	-3.130***	-2.185	-2.509	-2.487
		Differences	-3.406***	-3.951***	-2.663*	-2.589
	Fos^R	Levels	-0.239	0.385	0.405	0.666
		Differences	-5.574***	-5.449***	-4.008***	-3.100***
	Ren^R	Levels	-3.246***	-2.429	-2.476	-2.657
		Differences	-3.423***	-4.175***	-2.679*	-2.812**

Note: *, **, *** represent the significance at the 10%, 5% and 1% levels, respectively. The critical values for the 20 OECD countries at the 10%, 5% and 1% significance are -2.63, -2.72, and -2.88, respectively. The critical values for the 7 OECD countries with oil reserves at the 10%, 5% and 1% significance are approximately -2.73, -2.86, and -3.10, respectively. The critical values for the OECD countries without oil reserves at the 10%, 5% and 1% significance are approximately -2.66, -2.76, and -2.96, respectively.

sumption per labor, renewable energy consumption per labor, accumulated fossil fuel R&D per labor, and accumulated renewable energy R&D per labor, respectively. Table 2.5 shows that the null hypothesis of unit root is rejected for output per labor at least at the 10% of significance level for three out of four lags in Ireland and two out of four lags in both Belgium and Denmark. Table 2.6 shows that Turkey rejects the null hypothesis of unit for capital stock per labor in two out of four lags at 10% of significance level. Table 2.7 shows that Norway and the USA reject the null hypothesis of unit root in fossil fuel consumption per labor in three out of lags, whereas Netherlands show rejection in two out of four lags. The null hypothesis of unit root in renewable energy consumption per labor is rejected in all four lags in Belgium, three out of four lags in the UK, and two out of four in Spain and New Zealand in Table 2.8. The null hypothesis of unit root in accumulated fossil fuel R&D per labor is rejected in Sweden (three out of four lags), and Finland, France, Japan, and Turkey (two out of four lags) as shown in Table 2.9. The null hypothesis of unit root in accumulated renewable energy R&D per labor is also rejected in France, Italy, Japan, Turkey (three out of four) and Finland, Netherlands (two out of four) in Table 2.10. Therefore, all the variables show that they contain a unit root for most of the individual countries.

Table 2.11 reports the results of the panel CIPS test. The null hypothesis that the variables contain a unit root at their respective levels is not rejected for most of the variables at their respective levels, and the null hypothesis that the variables contain a unit root at their respective differences are rejected. In general, the panel results show that the variables contain unit roots in at least three out of all four lags for all the variables.

2.6.3 Unit Root with Structural Breaks

Some papers such as Katayama (2013) and Managi and Okimoto (2013) have found and included structural breaks in their analyses of the relationship between i) oil prices and the macroeconomy and ii) oil prices and the stock market. Accounting for structural breaks presents the true cointegrating relations in the energy-growth nexus and account for significant changes in the interactions within the economic system. Nonetheless, existing studies often do not account for structural change and consider the presence of economic regime shifts which could permanently change the dynamic linkages between energy consumption or energy R&D with economic growth. Majority of the studies apply the traditional method in testing for the null hypothesis of a unit root of stock prices. The traditional method becomes powerless once structural breaks are present in the true data-generating process of the variables. The oil market experiences low prices in the 1980s and high demand in the 2000s, and it is expected that there are structural changes within the economy. Managi and Okimoto (2013) further emphasize on the importance of including structural changes. They point out that the energy market before 2008 is different from the energy market after 2008, and this structural break could potentially originate from the 2008 economic shock or energy price hike.

For the estimation of the break dates, we follow the Carrion-i-Silvestre et al. (2005) (hereafter CBL) method by applying the Bai and Perron (1998) technique[6]. The CBL method has a few advantages. It allows for up to five structural breaks at unspecified dates and allows for heterogeneity in the countries. The number and dates of structural breaks could differ between countries in the panel. Both changes in the levels and slopes could be possible. Bootstrapped critical values are also computed to allow for any form of cross-sectional dependence. The selection of optimal break dates is based on Liu et al. (1997) modified Schwartz Information.

The Carrion-i-Silvestre et al. (2005) panel data stationary test has the null hypothesis (H_0) of a regime-wise stationarity for all countries, versus the alternative hypothesis (H_1) of non-stationarity for some countries. The Carrion-

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[6] Note: I am grateful to Josep Lluís Carrion-i-Silvestre, Tomás del Barrio Castro and Enrique López-Bazo for their Gauss codes.

i-Silvestre et al. (2005) stationary test which allows for multiple structural breaks is written as below:

$$X_{i,t} = \alpha_i + \sum_{k=1}^{m_i} \theta_{i,k} DU_{i,k,t} + \beta_i t + \sum_{k=1}^{m_i} \gamma_{i,k} DT^{*}_{i,k,t} + \varepsilon_{i,t} \tag{2.16}$$

where $X_{i,t}$ represents the variables (output per labor, capital stock per labor, fossil fuel consumption per labor, renewable energy consumption per labor, accumulated fossil fuel R&D per labor or accumulated renewable energy R&D per labor) in country i at time t. $DU_{i,k,t}$ and $DT^{*}_{i,k,t}$ are the dummy variables. $DU_{i,k,t} = 1$ for $t > T^{i}_{b,k}$ and 0 elsewhere; $DT_{i,k,t} = t - T^{i}_{b,k}$ for $t > T^{i}_{b,k}$ and 0 elsewhere, where $T^{i}_{b,k}$ represents the kth date of the break for country i.

Besides unit-specific means and shift in slopes, equation (2.16) also allows for unit specific intercepts and time trends. The CBL test of panel stationarity follows that of Hadri (2000), which is the average of the univariate stationary test of Kwiatkowski et al. (KPSS) (1992). The average of KPSS test statistic is expressed as:

$$LM(\hat{\lambda}) = N^{-1} \sum_{i=1}^{N} (\hat{\Psi}_i^{-2} T^{-2} \sum_{i=1}^{T} \hat{S}^2_{i,t}) \tag{2.17}$$

where $\hat{S}^2_{i,t} = \sum_{j=1}^{t} \varepsilon_{i,j}$ represents the partial sum process which is obtained using the estimated OLS residuals from equation (2.16). $\hat{\Psi}^2_i$ represents the consistent estimation of the long-run variance of $\varepsilon_{i,t}$.

The CBL test is dependent on the location of the breaks ($\lambda_i = (\lambda_{i,1,\ldots,}\lambda_{t,m_i})'$) relative to the whole period T. The locations of the breaks (λ_i) are estimated using the procedure of Bai and Perron (1998), which is based on the minimization of the sum of squared residuals. m_i represents the breaks for each country i (where $m_i \leq m^{\max}$). m_i is selected using the modified Schwarz information criterion of Liu et al. (1997).

The test statistic for the null hypothesis of a stationary panel with multiple shifts is expressed as:

Table 2.12: GDP per Labor Stationarity Panel Data Tests with Structural Breaks.

Country Groups	Bartlett Test	Prob.	Bootstrap Crit. Values 10%	5%	1%
20 OECD Countries					
No breaks (homogeneous)	3.873***	0.000	0.849	4.612	5.785
No breaks (heterogeneous)	4.283*	0.000	2.860	9.297	12.200
Breaks (homogeneous)	5.642***	0.000	3.880	4.401	5.412
Breaks (heterogeneous)	5.136*	0.000	2.51	8.900	12.177
With Oil Reserves					
No breaks (homogeneous)	2.832	0.002	3.194	3.892	4.778
No breaks (heterogeneous)	7.216**	0.000	5.803	7.108	10.115
Breaks (homogeneous)	2.996	0.001	3.151	3.650	4.952
Breaks (heterogeneous)	7.617**	0.000	5.947	7.451	10.189
Without Oil Reserves					
No breaks (homogeneous)	2.519	0.006	3.750	4.295	5.354
No breaks (heterogeneous)	4.470*	0.000	1.758	8.322	11.162
Breaks (homogeneous)	1.904*	0.028	0.940	5.375	6.753
Breaks (heterogeneous)	3.628*	0.000	2.587	9.520	13.106

Note: *, **, *** represent the significance at the 10%, 5% and 1% levels, respectively.

Table 2.13: Stationarity Panel Data Tests with Structural Breaks (Capital Stock per Labor).

Country Groups	Bartlett		Bootstrap Crit. Val.		
	Test	Prob.	10%	5%	1%
20 OECD Countries					
No breaks (homogeneous)	5.106**	0.000	3.905	4.417	5.885
No breaks (heterogeneous)	5.313*	0.000	2.849	9.130	11.670
Breaks (homogeneous)	7.683***	0.000	5.002	5.402	6.490
Breaks (heterogeneous)	12.676**	0.000	9.672	11.015	13.401
With Oil Reserves					
No breaks (homogeneous)	0.362	0.359	3.221	3.763	4.879
No breaks (heterogeneous)	7.478**	0.000	5.730	7.239	10.398
Breaks (homogeneous)	0.450	0.326	3.160	3.646	4.577
Breaks (heterogeneous)	8.854**	0.000	5.867	7.333	10.182
Without Oil Reserves					
No breaks (homogeneous)	1.072	0.142	3.577	4.211	5.260
No breaks (heterogeneous)	1.982*	0.024	1.882	8.408	11.597
Breaks (homogeneous)	1.060	0.144	3.519	4.093	5.335
Breaks (heterogeneous)	1.933*	0.027	1.843	7.948	10.621

Note: *, **, *** represent the significance at the 10%, 5% and 1% levels, respectively.

Table 2.14: Stationarity Panel Data Tests with Structural Breaks (Fossil Fuel Consumption per Labor).

Country Groups	Bartlett		Bootstrap Crit. Val.		
	Test	Prob.	10%	5%	1%
20 OECD Countries					
No breaks (homogeneous)	1.874*	0.030	0.836	4.421	5.529
No breaks (heterogeneous)	3.584*	0.000	2.595	9.007	11.727
Breaks (homogeneous)	10.380***	0.000	5.873	6.518	7.670
Breaks (heterogeneous)	16.976***	0.000	10.066	11.559	15.144
With Oil Reserves					
No breaks (homogeneous)	3.734**	0.000	3.089	3.708	4.876
No breaks (heterogeneous)	4.453*	0.000	2.729	7.309	10.615
Breaks (homogeneous)	-0.135	0.554	3.036	3.751	4.968
Breaks (heterogeneous)	9.084**	0.000	5.407	6.898	9.989
Without Oil Reserves					
No breaks (homogeneous)	0.689	0.245	3.675	4.324	5.407
No breaks (heterogeneous)	2.852*	0.002	1.782	8.417	11.735
Breaks (homogeneous)	0.732	0.232	3.610	4.214	5.330
Breaks (heterogeneous)	2.750*	0.003	1.697	7.836	10.757

Note: *, **, *** represent the significance at the 10%, 5% and 1% levels, respectively.

Table 2.15: Stationarity Panel Data Tests with Structural Breaks (Renewable Energy Consumption per Labor).

Country Groups	Bartlett		Bootstrap Crit. Val.		
	Test	Prob.	10%	5%	1%
20 OECD Countries					
No breaks (homogeneous)	2.510	0.006	3.823	4.299	5.493
No breaks (heterogeneous)	4.566*	0.000	2.761	8.977	11.592
Breaks (homogeneous)	22.327***	0.000	6.700	7.185	8.364
Breaks (heterogeneous)	16.136***	0.000	11.162	12.549	14.928
With Oil Reserves					
No breaks (homogeneous)	-0.410	0.659	3.182	3.844	4.878
No breaks (heterogeneous)	2.196*	0.014	0.782	7.192	10.628
Breaks (homogeneous)	-0.491	0.688	3.104	3.619	4.950
Breaks (heterogeneous)	2.421*	0.008	1.882	7.119	10.736
Without Oil Reserves					
No breaks (homogeneous)	-0.506	0.694	3.479	3.994	5.046
No breaks (heterogeneous)	0.538*	0.295	1.809	7.935	10.811
Breaks (homogeneous)	0.134	0.447	4.363	4.931	6.048
Breaks (heterogeneous)	2.192*	0.014	2.171	8.323	10.854

Note: *, **, *** represent the significance at the 10%, 5% and 1% levels, respectively.

Table 2.16: Stationarity Panel Data Tests with Structural Breaks (Fossil Fuel R&D per Labor).

Country Groups	Bartlett		Bootstrap Crit. Val.		
	Test	Prob.	10%	5%	1%
20 OECD Countries					
No breaks (homogeneous)	-3.674	1.000	5.261	6.276	8.588
No breaks (heterogeneous)	921.813***	0.000	9.337	11.046	14.763
Breaks (homogeneous)	4.442*	0.000	1.683	5.500	6.685
Breaks (heterogeneous)	5.004*	0.000	3.330	10.086	12.673
With Oil Reserves					
No breaks (homogeneous)	0.717	0.237	3.221	3.836	4.832
No breaks (heterogeneous)	9.666***	0.000	5.568	6.819	9.646
Breaks (homogeneous)	-0.783	0.590	3.197	3.686	5.065
Breaks (heterogeneous)	2.324*	0.010	0.885	7.303	10.141
Without Oil Reserves					
No breaks (homogeneous)	0.226	0.411	3.673	4.237	5.425
No breaks (heterogeneous)	2.484*	0.006	1.830	8.227	10.726
Breaks (homogeneous)	2.312	0.010	3.923	4.495	5.973
Breaks (heterogeneous)	3.502*	0.000	1.990	8.768	12.062

Note: *, **, *** represent the significance at the 10%, 5% and 1% levels, respectively.

Table 2.17: Stationarity Panel Data Tests with Structural Breaks (Renewable Energy R&D per Labor).

Country Groups	Bartlett		Bootstrap Crit. Val.		
	Test	Prob.	10%	5%	1%
20 OECD Countries					
No breaks (homogeneous)	0.847	0.199	3.987	4.602	5.791
No breaks (heterogeneous)	1.468	0.071	2.791	8.937	11.962
Breaks (homogeneous)	1.760	0.039	4.424	5.007	6.143
Breaks (heterogeneous)	3.558*	0.000	3.120	9.893	12.841
With Oil Reserves					
No breaks (homogeneous)	0.717	0.237	3.113	3.645	5.018
No breaks (heterogeneous)	9.666**	0.000	5.663	7.041	9.720
Breaks (homogeneous)	0.801	0.212	3.200	3.740	5.052
Breaks (heterogeneous)	13.496***	0.000	5.579	6.819	10.411
Without Oil Reserves					
No breaks (homogeneous)	0.226	0.411	3.615	4.274	5.312
No breaks (heterogeneous)	2.484*	0.006	1.910	6.990	11.927
Breaks (homogeneous)	0.313	0.377	0.639	4.316	5.178
Breaks (heterogeneous)	2.717*	0.003	1.847	8.216	11.428

Note: *, **, *** represent the significance at the 10%, 5% and 1% levels, respectively.

$$Z(\hat{\lambda}) = \frac{\sqrt{N}(LM(\hat{\lambda}) - \bar{\xi})}{\bar{\zeta}} \rightarrow N(0,1) \tag{2.18}$$

where $\bar{\xi}_i$ and $\bar{\zeta}_i^2$ represents the mean and variance of the individual country i of $LM_i(\hat{\lambda}_i)$.

Tables 2.12 - 2.17 report both the Hadri (2000) panel KSS test and the CBL panel KPSS test, with and without structural breaks, respectively. The tests are also reported for both homogeneous and heterogeneous long-run variance. For the CBL panel KPSS test, we set a maximum of three structural breaks. Tables 2.12 - 2.17 show that for the CBL panel KPSS test, output per labor, capital stock per labor, fossil fuel consumption per labor, renewable energy consumption per labor, accumulated fossil fuel R&D per labor, and accumulated renewable energy R&D per labor are rejecting the null hypothesis of joint stationarity at least at the 10% significance level for the heterogeneous panel estimation. The CIPS tests and CBL tests conclude presence of unit root in the variables. As OECD countries are often developed and have a number of their industrial processes which depend heavily on energy, it is expected that these countries are more likely to exhibit unit roots in their energy consumption and energy R&D, as the shocks influencing the levels of energy consumption and energy R&D are often greater and hence the departure from the equilibrium path will be more persistent. This is similar to the reasoning of Hsu et al. (2008) and Mishra et al. (2009) which found unit roots in countries which are larger energy consumers.

2.6.4 Cointegration Tests

Before estimating for long-run elasticities using the FMOLS and DOLS regressions, tests on whether the variables are cointegrated should be conducted. The Kao residual cointegration test is first conducted, with the null hypothesis of no cointegration.

Table 2.18 shows that the null hypothesis of no cointegration is rejected for

Table 2.18: Kao Residual Cointegration Test Results.

	t-statistic	Prob.
Energy Consumption		
20 OECD	-3.994***	(0.000)
With Oil Reserves	-1.836**	(0.033)
Without Oil Reserves	-3.926***	(0.000)
Energy R&D		
20 OECD	-4.176***	(0.000)
With Oil Reserves	-2.275**	(0.011)
Without Oil Reserves	-3.629***	(0.000)

Notes: 1. *, **, *** represent the significance at the 10%, 5% and 1% levels, respectively. 2. Lags lengths are selected based on the Akaike Information Criterion.

all the regressions. However, in the presence of heterogeneity in the individual countries and structural breaks in the sample, the Kao residual cointegration test might not be reliable. Further investigation with the cointegration test by Pedroni (1999, 2004) is conducted.

Pedroni (1999) cointegration accounts for heterogeneity in the individual countries within the panel. In the most general form, the panel cointegration test by Pedroni (1999, 2004) can be expressed as:

$$Gdp_{it} = \alpha_{it} + \delta_i t + \Psi_{1i} Cap_{it} + \Psi_{2i} Fos_{it} + \Psi_{3i} Ren_{it} + \varepsilon_{it} \tag{2.19}$$

where α_{it} and δ_i allow for country-specific fixed effects and deterministic trends in country i at time t. In the examination of the linkages between energy consumption and economic growth, Gdp_{it}, Cap_{it}, Fos_{it}, and Ren_{it} represents the GDP per labor, capital stock per labor, fossil fuel consumption per labor, and renewable energy consumption per labor, respectively. On the other hand, in the examination of the linkages between energy R&D and economic growth, the variables represent GDP per labor, capital stock per labor, accumulated fossil fuel R&D per labor, and accumulated renewable energy R&D per labor, respectively. ε_{it} represents the deviations from long-run equilibrium.

The Pedroni (2004) test accounts for structural breaks through correcting for time effects with dummy variables. Pedroni (2004) test is chosen over the Westerlund (2006) test as the time observations are less than 100. In regressions with small sample, Joyeux and Ripple (2011) point out that the Pedroni test is more reliable than the Westerlund test.

Table 2.19: Pedroni Test Results.

	Within Dimension		Between Dimension	
	Panel ADF-statistic	Prob.	Group ADF-statistic	Prob.
Energy Consumption				
20 OECD	-4.760***	0.000	-5.855***	0.000
With Oil Reserves	-1.860**	0.031	-1.319*	0.093
Without Oil Reserves	-5.478***	0.000	-6.401***	0.000
Energy R&D				
20 OECD	-2.495***	0.006	-3.817***	0.000
With Oil Reserves	-1.304*	0.096	-1.351*	0.088
Without Oil Reserves	-2.679***	0.004	-3.743***	0.000

Notes: 1. *, **, *** represent the significance at the 10%, 5% and 1% levels, respectively. 2. Cointegration tests are performed under assumption that there is a constant and trend. Lags lengths are selected based on the Akaike Information Criterion.

The null hypothesis of no cointegration, where $\rho_i = 1$, is tested via the unit root test on the residuals ($\varepsilon_{it} = \rho_i \varepsilon_{it-1} + w_{it}$). There are a total of seven different statistics to assess the panel data cointegration. Three of them are based on the between dimension and the other four are based on the within dimension (also known as pooling). Pedroni (2004) finds that in the presence of small time observations, the group ADF test and the panel ADF test have better power properties. The group *rho* test performs rather poorly. Table 2.19 hence, only reports these two ADF results. The null hypotheses of no presence of cointegration are rejected in both energy consumption-income and energy R&D-income equations.

As the method by Pedroni (1999) could not provide the long-run relationships amongst the variables, Pedroni (2000) suggested the use of the Fully Modified Ordinary Least Squares (FMOLS) estimator. FMOLS estimation produces unbiased estimation of the long-run elasticities, consistent standard errors and t-statistics in the presence of endogenous regressors.

Besides the FMOLS, Dynamic Ordinary Least Squares (DOLS) is also crucial to proceed to determine whether a long-run relationship exists for estimating the cointegration vector. DOLS uses the past and future values of the differenced regressors as additional regressors and the DOLS regression and the estimated coefficient can be written as:

$$y_{it} = \alpha_i + X'_{it}\beta + \sum_{k=-K_i}^{K_i} c_{ij}\Delta X_{i,t-k} + v_{it}, \tag{2.20}$$

$$\widehat{\beta}_{DOLS} = \sum_{i=1}^{N} \left(\sum_{t=1}^{T} z_{it} z'_{it} \right)^{-1} \left(\sum_{t=1}^{T} z_{it} \widehat{y}_{it} \right), \tag{2.21}$$

where y_{it}, in this chapter, is Gdp_{it} and X_{it} is either (1) accumulated capital stock per labor, fossil fuel consumption per labor and renewable energy consumption per labor, or (2) accumulated capital stock per labor, accumulated fossil fuel R&D per labor and accumulated renewable energy R&D per labor, of country i at time t, c_{ij} is the lead or lag of the first differenced explanatory variables and K_i is the different lag truncations used when the error terms are heterogeneous across the countries, z_{it} is a vector of regressors of $\left[X_{it} - \overline{X}, \Delta X_{i,t-q_i}, ..., \Delta X_{i,t+q_i}\right]$ and $\widehat{y}_{it} = y_{it} - \overline{y}_i$. A bar over a letter denotes a mean.

2.7 Results and Interpretation

Tables 2.20 and 2.21 show the FMOLS and DOLS estimations of the long run elasticity of capital and energy consumption to economic growth. Although fossil fuel consumption usually assumes the larger role in promoting higher GDP as compared to renewable energy consumption, the importance of renewable energy consumption should not be undermined. In the FMOLS estimation and DOLS estimation in Tables 2.20 and 2.21, GDP per labor increases by 0.059 and

Table 2.20: Long Run Elasticity Estimates from Panel FMOLS (Energy Consumption).

	Variables	Coefficient	T-Statistics	Diagnostic Tests
20 OECD				
Without	*Cap*	1.138***	54.773	LM Test: 5.115 (0.276)
Time Dummies	Fos^C	0.322***	13.564	White Test: 11.191 (0.263)
	Ren^C	0.083***	2.512	RESET Test: 3.387 (0.357)
With	*Cap*	0.571***	7.101	Cusum Test: 11.556 (0.278)
Time Dummies	Fos^C	0.143***	4.224	Jarque-Bera Test: 9.603 (0.202)
	Ren^C	0.059***	3.227	
With Oil Reserves				
Without	*Cap*	1.246***	55.371	LM Test: 7.645 (0.105)
Time Dummies	Fos^C	0.389***	17.155	White Test: 11.434 (0.247)
	Ren^C	0.013***	0.137	RESET Test: 0.693 (0.874)
With	*Cap*	0.391***	5.427	Cusum Test: 2.637 (0.831)
Time Dummies	Fos^C	0.096***	1.641	Jarque-Bera Test: 1.323 (0.802)
	Ren^C	0.017***	1.862	
Without Oil Reserves				
Without	*Cap*	1.077***	27.306	LM Test: 5.332 (0.255)
Time Dummies	Fos^C	0.380***	11.664	White Test: 4.834 (0.849)
	Ren^C	0.138***	5.632	RESET Test: 6.390 (0.124)
With	*Cap*	1.062***	31.857	Cusum Test: 43.701 (0.104)
Time Dummies	Fos^C	0.126***	3.266	Jarque-Bera Test: 3.255 (0.581)
	Ren^C	0.101***	5.764	

Notes: 1. *, **, *** represent the significance at the 10%, 5% and 1% levels, respectively. 2. Diagnostic tests statistics are reported in chi-squares. Probabilities are reported in parentheses.

0.068, respectively, at 1% significance level in the presence of higher renewable energy consumption. Consistent across both the FMOLS and DOLS estimation, the elasticity of real output with respect to renewable energy consumption is larger in the countries without oil reserves (0.101 for FMOLS estimation and 0.066 for DOLS estimation) as compared to the countries with oil reserves (0.017 for both FMOLS and DOLS estimations). Countries without oil reserves are more to susceptible oil price and oil supply shocks, the use of renewable energy consumption could provide them with energy security for continued economic growth no disruptions to their daily production processes.

Table 2.21: Long Run Elasticity Estimates from Panel DOLS (Energy Consumption).

	Variables	Coefficient	T-Statistics	Diagnostic Tests
20 OECD				
Without	Cap	1.200***	65.564	LM Test: 9.369 (0.053)
Time Dummies	Fos^C	0.294***	10.695	White Test: 27.989 0.518)
	Ren^C	0.132***	3.612	RESET Test: 1.896 (0.609)
With	Cap	0.475***	8.307	Cusum Test: 11.454 (0.282)
Time Dummies	Fos^C	0.058***	2.409	Jarque-Bera Test: 5.982 (0.369)
	Ren^C	0.068***	0.024	
With Oil Reserves				
Without	Cap	1.292***	67.410	LM Test: 5.992 (0.200)
Time Dummies	Fos^C	0.567***	44.790	White Test: 27.871 (0.471)
	Ren^C	0.111***	0.023	RESET Test: 5.619 (0.188)
With	Cap	0.181***	6.332	Cusum Test: 27.750 (0.235)
Time Dummies	Fos^C	0.040***	6.545	Jarque-Bera Test: 0.048 (0.992)
	Ren^C	0.017***	0.601	
Without Oil Reserves				
Without	Cap	0.632***	7.465	LM Test: 8.336 (0.080)
Time Dummies	Fos^C	0.504***	11.900	White Test: 28.003 (0.518)
	Ren^C	0.144***	4.371	RESET Test: 5.496 (0.390)
With	Cap	0.450***	8.078	Cusum Test: 13.755 (0.197)
Time Dummies	Fos^C	0.196***	2.312	Jarque-Bera Test: 1.845 (0.735)
	Ren^C	0.066***	2.124	

Notes: 1. *, **, *** represent the significance at the 10%, 5% and 1% levels, respectively. 2. Diagnostic tests statistics are reported in chi-squares. Probabilities are reported in parentheses.

The FMOLS and DOLS estimations of the long run elasticity of capital and energy R&D to economic growth are shown in Tables 2.22 and 2.23. Energy R&D, similar to energy consumption, is shown to be important for economic growth. Energy R&D affects the supply of energy whereas energy consumption affects the demand of energy, which in turn affects the output in the economy. As countries still rely more on fossil fuels, fossil fuel R&D is much more important for economic growth. The impact of fossil fuel R&D appears to even outweigh those of fossil fuel consumption in Tables 2.20 and 2.21 as it reduces manufacturing costs with improvements in the efficiency of fossil fuel usage. Renewable energy R&D, however, is shown to cause positive and significant effects (0.014 and 0.01 in FMOLS and DOLS estimations, respectively) on economic growth within the countries without oil reserves. This is in line with the results of Tables 2.20 and 2.21 which show that renewable energy consumption is more important in countries without oil reserves.

To select a model that is most parsimonious, we have to ensure that it passes several diagnostic tests. They include: (i) LaGrange multiplier test for serial correlation, (ii) white test for heteroscedasticity, (iiii) Ramsey RESET test for model misspecification, (iv) CUSUM test for constancy, and (v) Jarque-Bera test for normality. The estimations in Tables 2.20-2.23 show that they passed the diagnostic tests at least at the 10% significance level.

2.8 Robustness Checks

This chapter conducts a robustness check to assess whether the important variables behave consistently to determine the structural stability of the specifications. The calculations of the capital stock and accumulated energy R&D are changed as part of the robustness check, with the results of the FMOLS estimations reported in Tables 2.25 and 2.24.

Tables 2.25 and 2.24 show that the signs and magnitudes of the estimated

Table 2.22: Long Run Elasticity Estimates from Panel FMOLS (Energy R&D).

	Variables	Coefficient	T-Statistics	Diagnostic Tests
20 OECD				
Without Time Dummies	Cap	1.185***	88.018	LM Test: 5.776 (0.216)
	Fos^R	0.356***	0.206	White Test: 12.298 (0.197)
	Ren^R	-0.083***	-2.576	RESET Test: 4.398 (0.250)
With Time Dummies	Cap	0.640***	13.973	Cusum Test: 14.451 (0.186)
	Fos^R	0.254***	0.263	Jarque-Bera Test: 3.873 (0.524)
	Ren^R	-0.001***	-1.450	
With Oil Reserves				
Without Time Dummies	Cap	1.150***	94.614	LM Test: 7.626 (0.106)
	Fos^R	0.148***	2.176	White Test: 6.211 (0.719)
	Ren^R	-0.071***	-0.641	RESET Test: 4.161 (0.269)
With Time Dummies	Cap	0.615***	12.148	Cusum Test: 22.344 (0.189)
	Fos^R	0.256***	0.151	Jarque-Bera Test: 1.992 (0.718)
	Ren^R	-0.035***	-2.594	
Without Oil Reserves				
Without Time Dummies	Cap	1.185***	77.762	LM Test: 6.885 (0.142)
	Fos^R	0.237***	1.211	White Test: 11.517 (0.242)
	Ren^R	-0.109***	-6.505	RESET Test: 6.894 (0.525)
With Time Dummies	Cap	0.655***	16.964	Cusum Test: 8.172 (0.436)
	Fos^R	0.225***	0.106	Jarque-Bera Test: 3.528 (0.555)
	Ren^R	0.014***	0.081	

Notes: 1. *, **, *** represent the significance at the 10%, 5% and 1% levels, respectively. 2. Diagnostic tests statistics are reported in chi-squares. Probabilities are reported in parentheses.

regression coefficients are remain rather consistent, we conclude that the estimated regression coefficients are reflecting the true causal effects of respective variables examined. Column (1) of Table 2.24 shows the results when displacement rate of energy R&D is 85.0%. As the displacement rate is changed to 93.8% in column (2), results remain fairly similar. Column (1) in Table 2.25 shows the results when growth rate of gross fixed capital before 1960 is assumed to be 4%, and column (2) assumes each individual countries have their own constant growth rates, where the growth rate of gross fixed capital before 1960 is similar to the average growth rate of the respective countries from 1960 to 2010.

Table 2.23: Long Run Elasticity Estimates from Panel DOLS (Energy R&D).

	Variables	Coefficient	T-Statistics	Diagnostic Tests
20 OECD				
Without	Cap	1.188***	134.509	LM Test: 4.820 (0.306)
Time Dummies	Fos^R	0.293***	0.672	White Test: 28.757 (0.478)
	Ren^R	-0.152***	-4.301	RESET Test: 3.186 (0.401)
With	Cap	0.621***	24.497	Cusum Test: 17.628 (0.118)
Time Dummies	Fos^R	0.303***	2.302	Jarque-Bera Test: 6.093 (0.362)
	Ren^R	-0.012	-0.832	
With Oil Reserves				
Without	Cap	1.189***	132.991	LM Test: 8.855 (0.065)
Time Dummies	Fos^R	0.354***	3.153	White Test: 28.005 (0.464)
	Ren^R	-0.117***	-1.871	RESET Test: 3.708 (0.339)
With	Cap	0.572***	17.760	Cusum Test: 27.504 (0.103)
Time Dummies	Fos^R	0.488***	4.177	Jarque-Bera Test: 0.075 (0.988)
	Ren^R	-0.064***	-0.269	
Without Oil Reserves				
Without	Cap	1.185***	142.465	LM Test: 5.842 (0.211)
Time Dummies	Fos^R	0.343***	0.260	White Test: 28.003 (0.5178)
	Ren^R	-0.140***	-5.869	RESET Test: 5.721 (0.182)
With	Cap	0.563***	25.906	Cusum Test: 27.408 (0.104)
Time Dummies	Fos^R	0.190***	0.815	Jarque-Bera Test: 9.00 (0.223)
	Ren^R	0.001***	0.247	

Notes: 1. *, **, *** represent the significance at the 10%, 5% and 1% levels, respectively. 2. Diagnostic tests statistics are reported in chi-squares. Probabilities are reported in parentheses.

2.9 Concluding Remarks

Energy consumption and energy R&D in general influence economic growth in varying degree. Existing literature has emphasized on the dynamic linkages between energy consumption and economic growth but overlooked the dynamic linkages between energy R&D and economic growth. This study largely seeks to fill this missing link. We examine the causal relationship between (1) capital stock, fossil fuel consumption, renewable energy consumption and real output, and (2) capital stock, fossil fuel R&D, renewable energy R&D and real output for 20 OECD countries from 1980 to 2010 by explicitly taking into account the role of fossil fuel and renewable energy.

Table 2.24: Robustness Tests (Energy R&D).

Countries		(1)		(2)	
		$b = 85.0\%$		$b = 93.8\%$	
		Coefficient	T-Statistics	Coefficient	T-Statistics
20 OECD					
With	Cap	1.185***	88.018	1.198***	101.864
Time Dummies	Fos^R	0.004***	0.334	0.153***	2.076
	Ren^R	-0.083***	-2.576	-0.117***	-2.230
Without	Cap	0.640***	13.973	0.638***	14.661
Time Dummies	Fos^R	0.029***	1.707	0.021***	1.185
	Ren^R	-0.001***	-1.450	-0.009***	-1.572
With Oil Reserves					
With	Cap	1.150***	94.614	1.162***	109.365
Time Dummies	Fos^R	0.023***	0.353	0.167***	1.653
	Ren^R	-0.071***	-0.641	-0.118***	-0.221
Without	Cap	0.615***	12.148	0.614***	12.339
Time Dummies	Fos^R	0.010***	1.191	0.031***	1.508
	Ren^R	-0.035***	-2.594	-0.035***	-2.212
With Oil Reserves					
With	Cap	1.185***	77.762	1.214***	85.775
Time Dummies	Fos^R	0.050***	0.191	0.157***	1.799
	Ren^R	-0.109***	-6.505	-0.032***	-4.678**
Without	Cap	0.655***	16.964	0.626***	16.966
Time Dummies	Fos^R	0.137***	0.429	0.153***	2.835
	Ren^R	0.014***	0.081	0.004***	0.763

Notes: 1. *, **, *** represent the significance at the 10%, 5% and 1% levels, respectively.
2. b represents the displacement factor.

New empirical insights into the long-run relationship among these two sets of variables are provided using the fully-modified ordinary least squares (FMOLS) and dynamic ordinary least squares (DOLS). The contribution of energy R&D to economic growth is affirmed in both the FMOLS and DOLS estimations, showing that output is dependent not only on energy consumption but also energy R&D. In fact, output could be more responsive towards changes in fossil fuel R&D than fossil fuel consumption. Countries should also look at initiatives, such as subsidies or tax reliefs which promote energy R&D, besides targeting energy consumption.

Table 2.25: Robustness Tests (Capital Stock).

Countries		(1)		(2)	
		$g = 4\%$		$g =$ Different %	
		Coefficient	T-Statistics	Coefficient	T-Statistics
20 OECD					
With	Cap	1.138***	54.773	2.110***	46.218
Time Dummies	Fos^C	0.322***	13.564	0.258***	10.792
	Ren^C	0.083***	2.512	0.115***	7.841
Without	Cap	0.571***	7.101	0.437***	8.388
Time Dummies	Fos^C	0.143***	4.224	0.125***	3.008
	Ren^C	0.059***	3.227	0.061***	3.884
With Oil Reserves					
With	Cap	1.246***	55.371	2.229***	60.054
Time Dummies	Fos^C	0.389***	17.155	0.328***	14.379
	Ren^C	0.013***	0.137	0.044***	4.330
Without	Cap	0.391***	5.427	0.344***	6.170
Time Dummies	Fos^C	0.096***	1.641	0.084***	1.209
	Ren^C	0.017***	1.862	0.023***	2.567
With Oil Reserves					
With	Cap	1.077***	27.306	1.840***	37.914
Time Dummies	Fos^C	0.380***	11.664	0.284***	7.918
	Ren^C	0.138***	5.632	0.191***	11.824
Without	Cap	1.062***	31.857	0.942***	6.572
Time Dummies	Fos^C	0.126***	3.266	0.106***	2.777
	Ren^C	0.101***	5.764	0.110***	6.836

Notes: 1. *, **, *** represent the significance at the 10%, 5% and 1% levels, respectively. 2. g represents the growth rates.

While capital stock and fossil fuels are key factors in driving the economic growth, we find, in both the FMOLS and the DOLS estimation, that renewable energy consumption and R&D do have a crucial role in promoting economic growth. The effects of renewable energy consumption on economic growth are sizable and significant regardless of oil endowment within countries whereas the effects of renewable energy R&D on economic growth are significant amongst countries without oil reserves. Interestingly, we also find that countries without oil reserves, as compared to countries with oil reserves, tend to have their real output to be responding more positively to renewable energy consumption. This shows that when countries lack important energy endowment and face energy security issues which could threaten their sustainable economic growth, renewable energy is definitely a viable option.

Chapter 3

Energy Consumption and Energy R&D in OECD: Perspectives from Oil Prices and Economic Growth [1]

3.1 Introduction

Given the significance of renewable energy on economic growth, it is crucial to also examine what brings about higher usage of renewable energy or cleaner forms of energy and improvements in renewable energy-related technologies. In this chapter, Nerlove Partial Adjustment Model (NPAM) is used to study the responses of various forms of energy consumption and energy R&D (including renewable energy consumption and R&D) to changes in oil prices and real output, using data from 20 OECD countries for the period 1980-2010. The purpose of this study is to assess the reliance of countries on oil and the potential to substitute away from oil to other energy sources. Similar studies which seek

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[1] Note: An earlier version of this chapter was presented in the 13th International Convention of the East Asian Economic Association (EAEA) and the 8th annual conference of the Asia-Pacific Economic Association (APEA).

to determine the effects of oil consumption to changes in oil prices or changes in income usually use either the NPAM method (e.g. Cooper, 2003) or the error-correction model (e.g. Wadud et al, 2009). Prior to the estimations of energy consumption or energy R&D to changes in oil prices and real output, this study conducts a Two-Stage-Least-Squares (2SLS) regression first to prevent the potential presence of endogeneity in the estimations.

As one of the most important sources of energy, crude oil continues to occupy a key position in the heart of many economies. To macroeconomists, oil price changes are significant source of economic fluctuations that affect many economies simultaneously. Oil price shocks have indeed occurred several times since World War II. For instance, the 1973-1974 oil price shock triggered by the Yom Kippur war and the 1979-1980 oil price shock as a result of Iranian revolution are the primary explanation of the stagflation of the 1970s. Interestingly, since the late 1990s, the global economy has experienced similar magnitude of oil shocks, but its impacts on output and inflation are relatively stable to many industrialized economies. To energy economists, oil price shocks should provide incentive to many economies, especially those without oil reserves, to use oil more efficiently either through more cautious oil consumption or the development of new technology that uses alternative sources of energy. While oil price shocks encourage more efficient use of oil and promote substitution away from oil to other alternative energy resources, economic growth during economic boom stimulates oil consumption. In light of this contradiction and its crucial policy relevance, this study is motivated to investigate how various types of energy consumption (including renewable energy) respond to oil price changes and income changes.

As oil holds a prominent position as the principal energy source, accounting for 36.3 percent of OECD primary energy consumption in 2010, much interest has been devoted to investigate the responses of oil consumption towards changes in oil prices and real output. Most recent studies include Ramanathan

(1999), Cooper (2003), Ramanathan and Subramanian (2003), Narayan and Wong (2009) and Wadud et al. (2009). Cooper (2003) and Narayan and Wong (2009) find relatively inelastic oil consumption to changes in oil prices. Goodwin et al. (2004) show that elasticity of oil consumption to changes in oil prices ranges from 0.25 in the short-run to 0.64 in the long-run. As for the responsiveness of oil consumption to changes in real output, Narayan and Wong (2009) document that oil consumption is more responsive, in terms of both magnitude and statistical significance in Australia. Narayan and Smyth (2007), however, document that the same coefficient is statistically insignificant in the Middle East. In the contrary, Wadud et al. (2009) show no meaningful relationship in the long-run between oil consumption, oil prices and real output before introducing the structural break during the oil shock.

A new strand of recent literature has moved on to examine the elasticity of oil consumption using disaggregated data such as various gasoline products (see Huntington, 2010; Iwayemi et al, 2010). Own price elasticity of natural gas is also quite well-studied (see Cornillie and Fankhauser, 2004; Erdogdu, 2010). As the existing studies tend to focus only on the own price elasticities of oil consumption and gas consumption, findings from these studies though useful could not be used to address the issue of how other forms of energy can be used as substitutes to oil. This study attempts to fill such a gap. This study is interested in finding out not only how countries change their energy consumption and energy R&D behavior during periods of soaring oil prices and income growth but also the dynamic linkage between energy consumption and energy R&D. While past studies did not seem to clearly distinguish the difference between energy consumption and energy R&D, they are indeed distinct and should be treated differently as energy consumption reflects the economy's demand for energy while energy R&D reflects the economy's supply of energy. Potential influence from one to the other could also arise. As a result, to differentiate the two, this study examines distinctly two different sets of relationships: (1)

the impact of energy R&D, economic growth, oil and gas prices on energy consumption, and (2) the impact of energy consumption, economic growth, oil and gas prices on energy R&D.

This study adds to the current literature in two dimensions. First, we examine not only the own price and income elasticities of oil consumption but also the responsiveness of other forms of energy consumption and energy R&D to changes in oil prices and real output where energy consumption portrays energy demand, energy R&D portrays energy supply. Third, we also clearly distinguish the responses of energy consumption and energy R&D to changes in oil prices and real output in two different groups of countries, with oil reserves and without oil reserves. As before, the notion of energy security breaks up the panel of countries into two groups. Using group-country panel regressions, we analyze whether differences in oil endowments could potentially influence the willingness of countries to switch from one form of energy to another. Existing studies such as Wadud et al. (2009), Eltony and Al-Mutairi (1995), Cheung and Thomson (2004), and Narayan and Wong (2009) looked at individual countries instead of groups of countries. The countries examined are the US, Kuwait, China, and Australia.

The main finding in this chapter is that higher oil prices could increase renewable energy consumption R&D. However, as compared to changes in oil prices, growth in real output per labor plays a key role in promoting the usage of cleaner forms of energy. While negative income elasticity is found in coal consumption, positive income elasticities are found in oil, gas and renewable energy consumption. This finding suggests the importance of economic growth in promoting the usage of cleaner forms of energy from coal consumption to oil, gas, and renewable energy consumption.

The remaining of the paper is organized as follows. Section 3.2 outlines the empirical framework that is used in the estimation of elasticities of energy consumption and energy R&D to changes in oil price and income in the 20

OECD countries. Section 3.3 describes the data and methodology used in this paper. Tests for endogeneity and selection of structural breaks are also discussed in this section. Section 3.4 discusses the empirical findings of the elasticities of energy consumption and energy R&D to changes in oil price and income. Section 3.5 concludes.

3.2 Empirical Model

We use a system of GMM estimator derived from Nerlove Partial Adjustment Model (NPAM) to estimate the short-run and long-run elasticities of (i) various energy consumption to changes in oil prices and income and (ii) various energy R&D to changes in oil prices and income of the 20 OECD countries. This study provides an overall analysis within the OECD countries as well as analysis on both groups of countries with and without oil reserves. We first introduce a basic model where GDP per labor and oil prices are the two independent variables.

In the basic model, to investigate the relationship between the oil consumption, oil prices and income per labor, it is assumed that demand is a function of price and income. The classical demand theory postulates that price will have a negative effect and income will have a positive effect on demand. As oil is one of the most important sources of energy, fluctuations in oil prices could potentially influence the usage of oil and other forms of energy. Therefore, this study seeks to investigate the effect of oil prices on not only oil consumption but also on the consumption and newly invested R&D of other forms of energy such as coal, gas, and renewable energy. Based on this theoretical foundation, long run oil consumption, $O^{C}_{i,t}$ within a particular country i can be represented by the following log-linear demand function:

$$O^{C*}_{i,t} = \alpha_0 + \alpha_1 Gdp_{i,t} + \alpha_2 Oil\_P_{i,t} + e_{i,t} \tag{3.1}$$

where all the variables are expressed in natural logarithm form. $O^{C*}_{i,t}$ is the desired demand for oil per labor for country i at time t, $Oil\_P_{i,t}$ is the real price of oil for country i at time t, Gdp_{it} is the real output per labor for country i at time t and e_{it} is a random error term. Oil price is the only energy price included as it is the most sought after fossil fuel and the most widespread source of energy. Most of the industrialization activities, heating facilities, powering of fuel vehicles, and manufacturing of chemical products depend heavily on oil. Most of the activities could do without other energies such as gas, coal, fossil fuels and renewable energy but cannot do without oil. A change in oil prices could have material impact on the demand of other forms of energy but the opposite influence could be rather negligible. As the standard practice to assess economic performance is to use productivity, which is derived from the amount of real GDP produced by per labor instead of per capita, the paper uses per labor data instead of per capita data. The growth study of Mankiw et al. (1992) also uses GDP per labor instead of GDP per capita as GDP per labor allows us to identify total labor productivity in the economy. Since energy R&D is one part of this study, the rate of technological progress also depends largely on the labor instead of the general population, per labor data and not per capita data is used. α_0, α_1 and α_2 are the parameters. α_1 is the long-run price elasticity of demand for oil and $\alpha_1 < 0$. α_2 is the long-run elasticity of oil consumption per labor to changes in real output per labor.

Suppose that due to technological rigidity the country can only gradually adjust its oil consumption based on the following process:

$$O_{i,t}^{C} - O_{i,t-1}^{C} = \lambda_0 \left(O_{i,t}^{C*} - O_{i,t-1}^{C} \right) \tag{3.2}$$

where O_{it}^{C} is the short-run demand for oil at time t and O_{it-1}^{C} is the short-run demand for oil at time $t-1$. λ_0 is the coefficient of adjustment and $0 < \lambda_0 \leq 1$. Larger λ_0 implies faster speed of adjustment. By substituting Eq. (3.2) into Eq. (3.1), the following equation can be obtained with some algebraic manipulations,:

$$\begin{aligned} O^C_{i,t} &= O^C_{i,t-1} + \lambda_0 \left((\alpha_0 + \alpha_1 Gdp_{i,t} + \alpha_2 Oil\_P_{i,t} + e_{i,t}) - O^C_{i,t-1} \right) \qquad (3.3) \\ &= \alpha_0\lambda_0 + (1-\lambda_0) O^C_{i,t-1} + \alpha_1\lambda_0 Gdp_{i,t} + \alpha_2\lambda_0 Oil\_P_{i,t} + \varepsilon_{i,t} \end{aligned}$$

where $\varepsilon_{it} = (1-\lambda_0)\, e_{it}$. Accordingly, $\alpha_1 (1-\lambda_0)$ and $\alpha_2 (1-\lambda_0)$ are the short-run elasticity of oil consumption to changes in oil prices and to changes in income, respectively. It should be noted that with the exception of oil prices and income, Eq. (3.3) does not include other variables except lagged dependent variable, O^C_{it-1} (Wooldridge, 2009). Two advantages are associated with this type of regression. First, the lagged dependent variable becomes a good proxy when data on other variables are not readily available. Second, it makes the regression interpretations far easier such that holding histories the same, how an increase in the prices of oil or income would go towards changes in oil consumption. The regressions of other types of energy consumption are similarly estimated by replacing $O^C_{i,t}$ by $Y^C_{i,t}$ and $O^C_{i,t-1}$ by $Y^C_{i,t-1}$ where $Y^C_{i,t}$ and $Y^C_{i,t-1}$, depending on the variable of interest, are the short-run fossil fuel consumption, renewable energy consumption, gas consumption and coal consumption in time t and $t-1$, respectively. As a result, a general form that is used to estimate how other types of energy consumption respond to changes in oil prices and income for the basic model can be written as:

$$Y^C_{it} = \alpha_0\lambda_0 + (1-\lambda_0) Y^C_{it-1} + \alpha_1\lambda_0 OP_{i,t} + \alpha_2\lambda_0 Gdp_{it} + v_{it} \qquad (3.4)$$

Regression 3.4 could also be used to analyze how different types of energy R&D respond to changes in oil prices and income.

3.3 Data Description and Methodological Issues

3.3.1 Data Description

Similar to Chapter 2, Chapter 3 also categorizes the 20 OECD countries to those with and without oil reserves based on BP Statistical Review of World Energy (refer to the list of countries in Section 2.5). The countries are grouped by their presence of oil endowment as it influences their respective energy market structures. Countries without oil and gas reserves could be more subjected to volatility in imported energy prices and energy supply. The lower energy security could result in their energy consumption or R&D being more endogenous to external shocks than countries with oil and gas reserves.

Statistics on GDP, energy consumption, official exchange rate, real exchange rate index, fossil fuels over total energy consumed and GDP deflator are obtained from World Development Indicators (WDI). Data on oil consumption, coal consumption, nuclear energy consumption and gas consumption are retrieved from BP statistics. Data on newly invested renewable energy and fossil fuel R&D are retrieved from International Energy Agency (IEA). Data on renewable energy consumption are calculated by subtracting fossil fuel consumption and nuclear energy consumption from total energy consumption.

Table 4.2 summarizes the descriptions of the variables used.

3.3.1.1 Calculation of National Energy Prices

Real national oil prices are used as the oil prices at national levels are subjected to price controls, taxes, exchange rates fluctuations. The real national oil prices are calculated by first converting the world's oil prices (retrieved from BP) in dollars to the currencies of the respective countries. The world oil prices denominated in the respective countries' currencies are then deflated (Cunado and Perez de Garcia, 2003) using the GDP deflator of the respective countries.

Table 3.1: Descriptive Statistics.

Variables	Mean	Std.Dev.	Obs.
Coal consumption (mtoe)	40.6	108.7	620
Fossil fuel consumption (mtoe)	162.8	381.8	620
Fossil fuel R&D (billions 2000 US$)	414.4	2230.6	595
Gas consumption (mtoe)	45.5	115.5	620
Gas price (current US$ per thousand cubic feet)	3.1	1.8	31
Nuclear energy consumption (mtoe)	17.6	36.9	620
Oil consumption (mtoe)	84.3	177.1	620
Oil price (current US$ per barrel)	32.8	21.4	31
Real GDP per labor (thousands 2000 US$)	31.8	13.0	620
Renewable energy consumption (mtoe)	16.1	27.9	620
Renewable energy R&D (billions 2000 US$)	174.4	890.9	593

3.3.2 Tests for Endogeneity

As endogeneity problem could arise as a result of omitted variables, instrumental variables (IVs) are used to reduce misspecification error in the model. Following Cameron and Trivedi (2009), lags of first-difference endogenous variables can be used as these variables are exogenous by nature and hence offer consistent estimations. The instruments chosen are tested for their validity and strength using the over-identification Sargan test and F-test, respectively. After which, the over-identification test is conducted to assess whether the instruments are valid instruments. From the Hausman test results in Table 3.2, endogeneity is shown in the basic and extended models. The F-test results show that the instruments have appropriate strength and the over-identification tests show that the specified models are appropriate.

3.4 Results and Interpretation

Tables 3.3 shows the responsiveness of different energy consumption and energy R&D to changes in GDP and oil prices in the short-run and the long-run. The short-run elasticities could have less bias as compared to the long-run elasticities. In the long-run, there could be a shift in industry's energy composition.

Table 3.2: Endogeneity Tests (Basic Model).

Tests	Hausman Test		F-Test		Over-Identification Test	
	Stat.	Prob.	Stat.	Prob.	Stat.	Prob.
Fos^C						
20 OECD	25.55***	(0.000)	451.96***	(0.000)	0.618	(0.432)
With Oil Reserve	12.24***	(0.002)	780.13***	(0.000)	0.277	(0.599)
Without Oil Reserve	14.88***	(0.001)	259.61***	(0.000)	1.989	(0.159)
Ren^C						
20 OECD	18.24***	(0.000)	356.13***	(0.000)	0.417	(0.519)
With Oil Reserve	18.83***	(0.000)	461.81***	(0.000)	2.509	(0.113)
Without Oil Reserve	15.50***	(0.000)	301.03***	(0.000)	0.066	(0.797)
Oil^C						
20 OECD	79.84***	(0.000)	182.44***	(0.000)	0.467	(0.495)
With Oil Reserve	53.44***	(0.000)	602.66***	(0.000)	2.021	(0.155)
Without Oil Reserve	57.50***	(0.000)	144.25***	(0.000)	0.077	(0.781)
Gas^C						
20 OECD	16.25***	(0.001)	114.71***	(0.000)	0.301	(0.583)
With Oil Reserve	8.09**	(0.018)	101.74***	(0.000)	1.254	(0.263)
Without Oil Reserve	21.95***	(0.000)	92.54***	(0.000)	0.076	(0.782)
$Coal^C$						
20 OECD	15.05***	(0.001)	389.17***	(0.000)	1.078	(0.299)
With Oil Reserve	8.50**	(0.037)	782.46***	(0.000)	0.529	(0.467)
Without Oil Reserve	7.55**	(0.023)	229.45***	(0.000)	0.722	(0.395)
Fos^R						
20 OECD	21.51***	(0.000)	38.66***	(0.000)	0.151	(0.698)
With Oil Reserve	11.72***	(0.003)	39.94***	(0.000)	0.359	(0.549)
Without Oil Reserve	9.32***	(0.010)	41.01***	(0.000)	0.301	(0.583)
Ren^R						
20 OECD	20.11***	(0.000)	31.78***	(0.000)	0.076	(0.782)
With Oil Reserve	11.47***	(0.009)	26.64***	(0.000)	0.094	(0.759)
Without Oil Reserve	13.63***	(0.001)	30.34***	(0.000)	1.020	(0.312)

Notes: Statistics are in chi-squares and probabilities are reported in parentheses.

An example is Japan's shift to non-oil consumption (nuclear energy) after the 1973 and 1981 oil price shock.

3.4.1 Regressions on Energy Consumption (Basic Model I)

Table 3.3 summarizes the results of the responsiveness of fossil fuel consumption, renewable energy consumption, oil consumption, gas consumption and coal consumption towards changes in GDP and oil prices. The overall long run elasticities of the respective energy consumption to the respective variables are also provided in the tables.

Based on the results, we can observe that economic growth plays a large role to increase gas, oil and renewable energy consumption and reduce coal consumption. In general, economic growth promotes cleaner forms of energy. Coal, which has the highest level of carbon emission amongst the types of energy examined, is reduced by -1.699 in the long run with a 0.01 increment in GDP per labor. As countries gained in wealth, they become more environmentally cautious and place importance on intangible things such as a green and eco-friendly environment.

From the estimates, energy consumption is more responsive towards income changes than oil price changes for the 20 OECD countries in terms of magnitude and significance. Oil consumption, and other forms of energy consumption, is rather inelastic to changes in oil prices as compared to economic growth. Renewable energy consumption and coal consumption do not change significantly with respect to changes in oil prices, indicating that they might not be substitutes for oil or have less correlation with oil. However, gas consumption reduces significantly by -0.026 to higher oil prices, suggesting that it could be closely related to oil consumption. Oil consumption is significantly reducing with respect to higher oil prices (-0.023).

Table 3.3: Energy Consumption (First-Difference GMM Results in Basic Model I).

Variables	20 OECD Countries		With Oil Reserves		Without Oil Reserves	
	Short Run Coeff.	Long Run Coeff.	Short Run Coeff.	Long Run Coeff.	Short Run Coeff.	Long Run Coeff.
Fossil Fuel Consumption						
Fos^C_{t-1}	0.858***		0.941***		0.839***	
Gdp	0.082***	0.574	0.009	0.152	0.109***	0.677
Oil_P	-0.017***	-0.118	-0.017***	-0.291	-0.018***	-0.111
$Constant$	-2.464***		-0.663*		-2.992***	
Renewable Energy Consumption						
Ren^C_{t-1}	0.874***		0.828***		0.933***	
Gdp	0.058*	0.455	0.158**	0.915	-0.010	-0.150
Oil_P	-0.008	-0.059	0.009	0.051	0.004	0.066
$Constant$	-2.309***		-4.158***		-0.854	
Oil Consumption						
Oil^C_{t-1}	0.877***		0.908***		0.869***	
Gdp	0.066***	0.531	0.012	-0.028	0.094***	0.715
Oil_P	-0.023***	-0.189	-0.028***	-0.305	-0.021***	-0.161
$Constant$	-2.084***		-1.070***		-2.489***	
Gas Consumption						
Gas^C_{t-1}	0.845***		0.851***		0.868***	
Gdp	0.191***	1.229	0.060	0.402	0.143***	-0.028
Oil_P	-0.026***	-0.170	-0.025*	-0.165	-0.028***	-0.210
$Constant$	-3.882***		-2.386***		-3.071***	
Coal Consumption						
$Coal^C_{t-1}$	0.936***		0.936***		0.930***	
Gdp	-0.110***	-1.699	-0.104**	-1.628	-0.139***	-1.981
Oil_P	0.008	0.121	-0.005	-0.085	0.009	0.123
$Constant$	0.144		0.250		0.327	

Note: Fos^C_{t-1}, Ren^C_{t-1}, Oil^C_{t-1}, Gas^C_{t-1}, and $Coal^C_{t-1}$ represent fossil fuel consumption per labor, renewable energy consumption per labor, oil consumption per labor, gas consumption per labor, and coal consumption per labor at time $t-1$, respectively. Gdp is GDP per labor and Oil_P is oil price.

3.4.2 Regressions on Energy R&D (Basic Model II)

Table 3.4 shows the responsiveness of fossil fuel R&D and renewable energy R&D towards changes in GDP per labor and oil prices. The overall long run elasticities of the respective energy R&D of the respective variables are also provided in the tables.

The results show that economic growth could help to promote cleaner forms of energy R&D significantly. Newly invested renewable energy R&D is increased by 1.292 as compared to newly invested fossil fuel R&D increment of 0.196.

Table 3.4: Fossil Fuel R&D Invested (First-Difference GMM Results in Basic Model II).

Variables	20 OECD Countries		With Oil Reserves		Without Oil Reserves	
	Short Run	Long Run	Short Run	Long Run	Short Run	Long Run
	Coeff.	Coeff.	Coeff.	Coeff.	Coeff.	Coeff.
Fossil Fuel R&D						
Fos^R_{t-1}	0.389***		0.620***		0.319***	
Gdp	0.196	0.321	0.941	2.475	0.963**	1.415
Oil_P	0.588***	0.963	1.129***	2.970	0.459***	0.674
$Constant$	-5.282		-17.867***		-12.050***	
Renewable Energy R&D						
Ren^R_{t-1}	0.477***		0.674***		0.379***	
Gdp	1.292***	2.471	1.961***	6.016	1.839***	2.961
Oil_P	0.525***	1.004	0.799***	2.450	0.338**	0.544
$Constant$	-16.003***		-26.070***		-19.645***	

Notes: 1. Fos^R_{t-1} and Fos^R_{t-1} represent newly invested fossil fuel R&D per labor and newly invested fossil fuel R&D per labor at time $t-1$, respectively. Gdp is GDP per labor and Oil_P is oil price.

3.5 Concluding Remarks

This study estimates both the short-run and the long-run elasticities of various per labor energy consumption and energy R&D to changes in oil prices and income of the OECD countries over the period of 1980 to 2010 using the Nerlove partial adjustment model. As countries with different oil endowments may respond differently to changes in oil prices and income, this study runs panel regressions that include all countries and countries with and without oil reserves.

There are a few findings which are particularly worth noting for the regressions. First, the results of this study show that the group-country panel regressions have a negative and significant income elasticity of coal consumption but positive and significant income elasticities for oil, gas and renewable energy consumption. Second, in contrast to Narayan and Wong (2009) who find no significant statistical impact of oil prices on oil consumption, the results of this study show that when oil prices are higher, countries reduce their oil consumption. Higher oil prices could also increase renewable energy R&D.

This chapter focuses on whether income and oil prices could play a role in affecting energy. Some other factors including climatic policies and technological advancement could have impact on the energy consumption. Likewise, climatic policies and energy demand could influence the newly invested energy R&D. The next chapter takes a step further to analyze whether these factors have influence over energy consumption or R&D.

Chapter 4

Dynamic Linkages between Energy Consumption and Energy R&D [1]

4.1 Introduction

Countries are looking at renewable energy or alternative forms of energy to substitute for oil to confront climate change and cushion themselves from higher oil prices (Awerbuch and Sauter, 2006) such as the energy crises in 1970s. It is demonstrated that economic growth is the main driver of cleaner forms of energy consumption and renewable energy R&D, with oil prices playing a supporting role in the shift in OECD as a whole in Chapter 3. To date, countries remain more heavily dependent on fossil fuels, especially oil, and this chapter seeks to investigate whether there are other factors which could promote cleaner forms of energy.

In Chapter 3, the analysis focuses on whether GDP or oil price could have influence over energy consumption or energy R&D but there could be other important causal factors such as climatic policies, technological changes and

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[1] Note: The key content of this chapter will also be published in *Energy Policy* (forthcoming).

other energy prices omitted from the regressions. This chapter also uses the Nerlove Partial Adjustment Model (NPAM) but with additional variables such as time dummies, energy R&D or consumption, and gas prices included. Since 1992, many climatic policies have been introduced and shaped the way people view environmental issues, therefore time dummies are introduced in the regressions to account for the effects of these climatic policies on energy consumption and energy R&D in this chapter. Accumulated energy R&D (energy consumption) are included in estimating for energy consumption (newly invested energy R&D) as potential bi-lateral causality exists between them. Policies which target higher energy R&D could raise energy efficiency which promotes energy usage and policies which raise higher productions and energy demand cause industries to invest in more efficient energy technologies. Natural gas is included in this chapter as it is perceived to be growing in importance in electricity generation. Though oil and gas are jointly discovered, Ramberg and Parsons (2012) suggested that the prices of these variables are not cointegrated.

There are several findings in this chapter. First, negative income elasticity for coal consumption but positive income elasticity for oil and gas consumption are also shown, reaffirming the importance of economic growth in encouraging the usage of cleaner energy from coal to oil and gas. Second, energy consumption and energy R&D are found to have a bilateral causational relationship. Renewable energy R&D could promote renewable energy consumption, especially in countries without oil reserves, and decrease fossil fuel consumption. Fossil fuel R&D could promote more fossil fuel consumption, especially in countries with oil reserves. On the other hand, fossil fuel consumption could cause higher fossil fuel R&D. Third, climatic mitigation policies are able to promote the usage of cleaner energies.

The rest of this chapter is organized as follows. Section 4.2 discusses the relationship between oil and gas prices. Section 4.3 introduces the potential bilateral linkages between energy consumption and energy R&D. Section 4.4

introduces the extended models and the calculation of the respective short- and long-run elasticities. Section 4.5 describes the data and other methodological issues on endogeneity and structural breaks. Section 4.6 presents the results and the interpretations. Section 4.7 concludes.

4.2 Oil Prices versus Gas Prices

Oil is one of the most important sources of energy and fluctuations in oil prices influence the domestic energy consumption. Higher oil prices are often the result of OPEC reduction in production. Therefore, this study seeks to investigate whether there is significant influence from oil prices to oil consumption, alternative energy consumption and energy R&D investments, and whether the presence of such influence, if there is, occurs immediately or with a lag.

On the other hand, natural gas is perceived as the most important energy source for the future, overtaking the position of oil. Natural gas is mainly used for residential and commercial heating and natural gas usage has been increasing worldwide. As natural gas powered applications become more advanced, the trend of increasing natural gas usage is undeniable. Energy R&D investments (in terms of both fossil fuels and renewable energy) and other types of energy consumption (such as renewable energy and coal) could also be conditioned upon natural gas prices. Countries would also behave similarly to oil price hikes. With increasing interest to improve their operations, performance, productivity and efficiency, countries also raise their budget for energy R&D. Besides attempting to lower costs through higher level of efficiency, countries may choose to use less energy and materials or turn to alternative energy.

Contrary to the belief that oil and gas prices are often viewed as cointegrated, Ramberg and Parsons (2012) suggested that the relationship between the two variables is not stable through time. Gas sales contracts worldwide are often based on oil prices, and it is widely expected that a decline in oil production send both oil and gas prices soaring high. The study of Ramberg and Parsons (2012) have found that the two variables "decoupled" throughout the 1980s and early 1990s in the presence of excess supply of deliverable gas, which cause natural gas prices to be consistently lower relative to crude oil prices. From late 1990s to early 2000s, natural gas prices went above the expected level based on historical relationship. Therefore, both oil and gas prices which are main energy sources, are included in the extended models.

4.3 Dynamic Linkages between Energy Consumption and Energy R&D

This study focuses separately on both energy consumption and energy R&D, which have been overlooked in previous studies. Energy consumption, or more commonly known as energy demand, affects the economy's demand for energy while energy R&D affects the economy's supply of energy. They are distinct. This study also accounts for earlier invested energy R&D apart from exploring the effects of newly invested energy R&D as accumulated energy R&D is the one that truly reflects the total energy innovations. Besides soaring energy prices and diminishing fuel supplies in the world which could have led to changes in the energy market, there could be bi-lateral causality relationship existing between energy consumption and R&D. Therefore, the analysis of energy consumption should account for energy R&D, and vice versa.

Among many other options, renewable energy is seen as a potential candidate to overcome sustainability challenges faced in the global energy market. Energy market structures tend to vary from country to country and this information is useful for policy makers to decide which are the sectors for them to target to encourage the transition towards renewable energy-based economies and to reduce the overall carbon emissions.

Higher energy consumption leads to depletion of energy sources and companies have to invest in energy R&D to improve their energy efficiency. Both fossil fuel R&D and renewable energy R&D have to be increased. New energy technologies have been constantly developed to meet the ever-growing energy demand in the world economy. This study suggests that if renewable energy consumption positively causes accumulated renewable energy R&D, accumulated renewable energy R&D are hence demand driven. To have higher investments in renewable energy technologies would require a general higher environmental awareness with preference in energy consumption from renewable energy sources and renewable energy-related products. If fossil fuel consumption not only promotes fossil fuel R&D but also renewable energy R&D, such spillover effects could cause countries to increase their clean energy technologies in the long run. Even with little incentives from government to raise renewable energy R&D, the private sectors will try to have renewable energy innovations to meet the high energy demand.

On the other hand, energy R&D improves energy efficiency and promotes efficient energy conversion. The new technologies make production more efficient and reduce the energy consumption if the amount of energy required remains at a constant level. Theoretically, given all else remain constant, this reduces the overall energy consumed. Given the more efficient energy technologies, there could be changes to the energy market as countries turn to usage of the more efficient energy. Assuming in the short-run, the first effect is dominant; in the long-run, the second effect sets in. In the case of renewable energy, once countries attain a certain level of renewable energy technologies and have a pool of renewable energy-related products, more industry players and population will be encouraged to shift their energy consumption to renewable energy sources.

If accumulated renewable energy R&D (accumulated fossil fuel energy R&D) has positive (negative) causations on renewable energy consumption, the country should implement policies such as renewable energy technologies subsidies (removal of fossil fuel technologies subsidies) which increase (reduce) their renewable energy consumption. This will not hamper the overall economic productivity and is able to drive environmentally friendly innovation and technological advancement with a reduction in the wages and employment in the fossil fuel sector but an increment in the wages and employment in the renewable energy sector. Similarly, to reduce fossil fuels usage, if the country experiences a causal relationship running from accumulated fossil fuel R&D to fossil fuel consumption, barriers to increase investments in fossil technologies such as taxes on fossil fuel R&D could reduce the energy consumption from fossil fuel sources. Nonetheless, if oil, gas, and coal consumption is not affected by energy R&D, countries would have to resort to other means that could directly reduce the fossil fuel consumption.

4.4 Empirical Model

Similar to Chapter 3, we use a system of GMM estimator derived from Nerlove Partial Adjustment Model (NPAM) to estimate the short-run and long-run elasticities. We first introduce the Extended model I where i) gas prices, accumulated fossil fuel R&D per labor and accumulated renewable energy R&D per labor GDP per labor or ii) gas prices, fossil fuel consumption per labor and renewable energy consumption per labor are added to the basic equations with GDP per labor and oil prices which analyze the various energy consumption or various energy R&D. Then the Extended Model II which includes the dynamic adjustment of various energy consumption or various energy R&D to oil price and energy consumption or energy R&D is introduced.

4.4.1 Extended Model

In the basic model, some important causal factors such as natural gas prices, various energy consumption and energy R&D could be left out, causing unreliable estimates. Natural gas, mainly used for residential and commercial heating, is perceived to overtake oil as the main source of energy in the future. Ramberg and Parsons (2012) found that oil and gas prices do not maintain a cointegrated relationship and with the surge in the usage of natural gas, gas prices should be included in the model. Energy consumption (accumulated energy R&D) should also be included in the regressions to estimate newly invested energy R&D (energy consumption) as there could be potential bi-lateral causality existing. To encourage the transition towards renewable energy-based economies, it is critical to understand such causality relationships for more specific policy targeting. If renewable energy R&D is demand-driven, greater environmental awareness which brings about higher renewable energy consumption could be critical to increase renewable energy technologies. If accumulated fossil fuel R&D promotes fossil fuel consumption, fossil fuel R&D taxes could reduce fossil fuel consumption. Nonetheless, if the respective energy consumption are unaffected by accumulated energy R&D, countries would have to resort to other means that could reduce fossil fuel consumption or increase renewable energy consumption.

The variables introduced in this extended model are: gas prices ($Gas\_P_{i,t}$), accumulated fossil fuel R&D ($Acc\_Fos^R_{i,t}$) and accumulated renewable energy R&D ($Acc\_Ren^R_{i,t}$). Equation (3.3) could then be expressed as:

$$\begin{aligned} Y^C_{si,t} &= \beta_0\lambda_1 + (1-\lambda_1)Y^C_{si,t-1} + \beta_1\lambda_1 Gdp_{i,t} + \beta_2\lambda_1 Oil\_P_{i,t} \\ &\quad + \beta_3\lambda_1 Gas\_P_{i,t} + \beta_4\lambda_1 Acc\_Fos^R_{i,t} + \beta_5\lambda_1 Acc\_Ren^R_{i,t} + \varepsilon_{i,t} \end{aligned} \tag{4.1}$$

Using similar methodology as equation (3.3), this study investigates what are the factors that cause energy consumption such as gas, coal, renewable energy and overall fossil fuels on oil price and income per labor to change. The regression model takes the following form where $Y^C_{si,t}$ and $Y^C_{si,t-1}$ are the short-run gas, coal, renewable energy or fossil fuel consumption per labor at time t and $t-1$, respectively. Similarly, λ_1 is the coefficient of adjustment and $0 < \lambda_1 \leq 1$.

Besides the elasticity of the respective energy consumption to changes in income, this study is interested in the effects of oil price on different energy consumption. As a result, $\beta_2\lambda_1$ can be interpreted as the short-run cross price elasticity of demand. It should be noted that with the exception of oil price and income, equation (4.2) does not include prices of other energy as data on prices of most other energy are not readily available. In order to account for these omitted variables, lagged dependent variable is used as a proxy variable (Wooldridge, 2009). An advantage of this type of regression is that it makes interpretation far easier such that holding histories the same, how would an increase in price of oil or income might go towards changes in consumption of other energy.

The regressions to estimate the effects of oil price and income on fossil fuel R&D and renewable energy R&D are very similar to that of equation (4.2) except now $Y^R_{si,t}$ and $Y^R_{si,t-1}$ are the short-run fossil fuel or renewable energy R&D at time t and $t-1$, respectively. Also, instead of regressing on accumulated fossil fuel R&D and accumulated renewable energy R&D, these regressions have fossil fuel consumption ($Fos^C_{i,t}$) and renewable energy consumption ($Ren^C_{i,t}$) as independent variables.

$$\begin{aligned} Y^R_{si,t} &= q_0\lambda_1 + (1-\lambda_1)Y^R_{si,t-1} + q_1\lambda_1 Gdp_{i,t} + q_2\lambda_1 Oil\_P_{i,t} \\ &\quad + q_3\lambda_1 Gas\_P_{i,t} + q_4\lambda_1 Fos^C_{i,t} + q_5\lambda_1 Ren^C_{i,t} + \varepsilon_{i,t} \end{aligned} \tag{4.2}$$

The short-run and long-run elasticities can be derived for the country group i for equation (4.1) and equation (4.2) with the formula described in Table 4.1.

Equations (4.1) and (4.2) are estimated using a Arellano-Bond modified GMM estimator (first-differenced GMM) where lagged first-difference of the

Table 4.1: Derivation of Elasticity.

Variables in equation (4.1)			Variables in equation (4.2)		
Elasticity	Short Run	Long Run	Elasticity	Short Run	Long Run
Gdp	$\beta_1\lambda_1$	β_1	Gdp	$q_1\lambda_1$	q_1
Oil_P	$\beta_2\lambda_1$	β_2	Oil_P	$q_2\lambda_1$	q_2
Gas_P	$\beta_3\lambda_1$	β_3	Gas_P	$q_3\lambda_1$	q_3
Acc_Fos^R	$\beta_4\lambda_1$	β_4	$Fos^C_{i,t}$	$q_4\lambda_1$	q_4
Acc_Ren^R	$\beta_5\lambda_1$	β_5	$Ren^C_{i,t}$	$q_5\lambda_1$	q_5

Note: Gdp, Oil_P, Gas_P, Acc_Fos^R, Fos^C, Acc_Ren^R, and Ren^C represent GDP per labor, oil price, gas price, accumulated fossil fuel R&D per labor, fossil fuel consumption, accumulated renewable energy R&D per labor, and renewable energy consumption per labor, respectively.

variable is used as an instrument. GMM estimator provides consistent estimates in the presence of lagged dependent variables which could cause unobserved panel-level effects.

4.5 Data Description and Methodological Issues

Similar to Chapter 3, statistics on GDP, energy consumption, official exchange rate, real exchange rate index, fossil fuels over total energy consumed and GDP deflator are obtained from World Development Indicators (WDI). Data on oil consumption, coal consumption, nuclear energy consumption and gas consumption are retrieved from BP statistics. Data on newly invested renewable energy and fossil fuel R&D are retrieved from International Energy Agency (IEA). Data on renewable energy consumption are calculated by subtracting fossil fuel consumption and nuclear energy consumption from total energy consumption. This chapter introduces accumulated energy R&D and gas prices.

Table 4.2 summarizes the descriptions of the variables used.

Table 4.2: Descriptive Statistics.

Variables	Mean	Std.Dev.	Obs.
Coal consumption (mtoe)	40.6	108.7	620
Fossil fuel consumption (mtoe)	162.8	381.8	620
Fossil fuel R&D (billions 2000 US$)	414.4	2230.6	595
Gas consumption (mtoe)	45.5	115.5	620
Gas price (current US$ per thousand cubic feet)	3.1	1.8	31
Nuclear energy consumption (mtoe)	17.6	36.9	620
Oil consumption (mtoe)	84.3	177.1	620
Oil price (current US$ per barrel)	32.8	21.4	31
Real GDP per labor (thousands 2000 US$)	31.8	13.0	620
Renewable energy consumption (mtoe)	16.1	27.9	620
Renewable energy R&D (billions 2000 US$)	174.4	890.9	593

4.5.1 Calculation of National Energy Prices

Real national gas prices are also calculated using similar methodology as real oil prices using world gas prices (retrieved from BP) as shown in Chapter 3. The calculation of accumulated energy R&D follows the Chapter 2.

4.5.2 Tests for Endogeneity

The regressions are first tested for endogeneity using the Hausman test, and results in Table 4.3 shows that endogeneity is present in the extended model. After that, the instruments (lags of first-differences) are assessed and shown to have appropriate strength through the F-test results. Finally, the over-identification test results indicate that the specified models are appropriate.

4.5.3 Tests for Structural Breaks

In the event that presences of structural breaks are ignored, it leads to misleading conclusions with inaccurate parameter estimations. Model specification has to account for structural breaks when any shifts in regimes are detected.

Three structural breaks are selected: 1992, 1998, and 2003. In 1992, countries joined an international treaty, the United Nations Framework Convention

Table 4.3: Endogeneity Tests (Extended Model I).

Tests	Hausman Test		F-Test		Over-Identification Test	
	Stat.	Prob.	Stat.	Prob.	Stat.	Prob.
Fos^C						
20 OECD	27.26***	(0.000)	257.49***	(0.000)	0.775	(0.855)
With Oil Reserve	32.73***	(0.000)	307.95***	(0.000)	1.008	(0.799)
Without Oil Reserve	15.94**	(0.026)	198.78***	(0.000)	1.017	(0.797)
Ren^C						
20 OECD	37.13***	(0.000)	265.24***	(0.000)	4.463	(0.216)
With Oil Reserve	18.47***	(0.010)	122.19***	(0.000)	5.491	(0.139)
Without Oil Reserve	28.59***	(0.000)	219.88***	(0.000)	4.210	(0.240)
Oil^C						
20 OECD	47.95***	(0.000)	137.63***	(0.000)	4.810	(0.186)
With Oil Reserve	48.18***	(0.000)	410.57***	(0.000)	1.317	(0.725)
Without Oil Reserve	46.24***	(0.000)	139.50***	(0.000)	1.905	(0.593)
Gas^C						
20 OECD	112.67***	(0.000)	105.91***	(0.000)	1.759	(0.780)
With Oil Reserve	51.13***	(0.000)	32.49***	(0.000)	1.628	(0.443)
Without Oil Reserve	93.14***	(0.000)	81.21***	(0.000)	1.610	(0.807)
$Coal^C$						
20 OECD	79.73***	(0.000)	215.87***	(0.000)	5.081	(0.406)
With Oil Reserve	28.86***	(0.000)	487.72***	(0.000)	7.786	(0.169)
Without Oil Reserve	58.59***	(0.000)	153.05***	(0.000)	6.175	(0.290)
Fos^R						
20 OECD	17.97**	(0.012)	35.96***	(0.000)	1.503	(0.682)
With Oil Reserve	31.98***	(0.000)	24.73***	(0.000)	3.590	(0.309)
Without Oil Reserve	27.69***	(0.000)	36.45***	(0.000)	5.190	(0.158)
Ren^R						
20 OECD	15.21**	(0.033)	24.64***	(0.000)	0.333	(0.954)
With Oil Reserve	48.14***	(0.000)	19.79***	(0.000)	1.624	(0.654)
Without Oil Reserve	15.36**	(0.032)	26.56***	(0.000)	0.773	(0.856)

Notes: 1. *, **, *** represent the significance at the 10%, 5% and 1% levels, respectively. 2. Statistics are in chi-squares and probabilities are reported in parentheses.

on Climate Change. It was also the start of the Energy Policy Act (EPAct) which set goals, created mandates, and amended utility laws to increase clean energy use and improve overall energy efficiency in one of the leading country — United States. In 1997, the European Commission's White Paper on renewable energy sources set the goal of doubling the share of RES in the EU energy sector from 6 to 12 % by 2010. Since 2003, a rise in prices caused by continued global increases in petroleum demand coupled with production stagnation, the falling value of the US dollar, and a myriad of other secondary causes.

The validity of assuming constant model parameters is then checked using the F-tests of Chow (1960) which examine the fitted residuals from the data.

4.6 Results and Interpretation

Tables 4.4 to 4.10 show the responsiveness of different energy consumption and energy R&D to various factors. Chow test results are first reported to determine the significance of any structural breaks. After which, a set of diagnostic tests are conducted and passed. They include: (i) LaGrange multiplier test for serial correlation, (ii) white test for heteroscedasticity, (iiii) Ramsey RESET test for model misspecification, (iv) CUSUM test for constancy, and (v) Jarque-Bera test for normality.

4.6.1 Regressions on Energy Consumption (Extended Model I)

Table 4.4 - 4.8 present the short-run and the long-run estimated coefficients of various types of energy consumption to changes in income, oil prices, gas prices, accumulated fossil fuel R&D and accumulated renewable energy R&D: fossil fuel consumption in Table 4.4, renewable energy consumption in Table 4.5, oil consumption in Table 4.6, gas consumption in Table 4.7 and coal consumption in Table 4.8. The results for the basic model and the extended model are

reported. The results for the extended model can be used as a robustness check of the key variables (oil prices and income per labor) on the various types of energy consumption.

Table 4.4 reports the results of fossil fuel consumption. The effect of change in oil prices on fossil fuel consumption is consistent for all the three panel regressions: 20 OECD countries and countries with and without oil reserves. The coefficient of oil prices is negative and significant at 1% suggesting negative elasticity of fossil fuel consumption to change in oil prices. In general, the effect of change in oil prices on fossil fuel consumption is significance and robust as the coefficient continues to report consistent signs and levels of significance after adding in more independent variables in the extended model for all-country panel (20 OECD countries) and countries with oil reserves. The effect of oil prices on fossil fuel consumption becomes insignificant in the extended model for countries without oil reserves although the sign remains negative. Economic growth is found to positively affect fossil fuel consumption for all-country panel regression and countries without oil reserves suggesting the importance of economic growth in driving fossil fuel consumption. It is also interesting to note that fossil fuel consumption is positively related to its own accumulated R&D and negatively related to accumulated renewable energy R&D.

While economic growth seems to promote the consumption of renewable energy in the 20 OECD countries and countries with oil reserves as reported in the basic model of Table 4.5, this finding is not robust as the significance disappears in the extended model. The consumption of renewable energy is driven mainly by its own lag. This finding suggests that the basic model has a tendency to overestimate the importance of economic growth in promoting the usage of renewable energy.

Turning to Tables 4.6 - 4.8, we note that similar to Chapter 3, while economic growth promotes consumption of oil and gas, the OECD countries decrease their coal consumption in the midst of higher economic growth. The regression results from the extended model show that for every 10 percent increase in GDP per labor, while coal consumption reduced by 0.96 percent (Table 4.8), oil consumption and gas consumption are found to increased by 0.84 percent (Table 4.6) and 2.22 percent (Table 4.7), respectively. This finding suggests that economic growth is the main factor that promotes the usage of cleaner energy, from coal to oil and gas. Gas which has less carbon emission than oil is preferred over oil as a key source of energy during periods of high economic growth. This suggests that policies targeting on economic growth could, at the same time, reduce carbon emissions as a by-product. When we compare the estimations of oil consumption and coal consumption, we find that oil is an effective substitute for gas but the reverse is not true. Higher gas prices promote oil consumption, 0.026 for all-country panel regression, 0.037 for countries with oil reserves and 0.030 for countries without oil reserves, in Table 4.6. Such a relationship is not observed in gas consumption is reported in Table 4.7. Most of the transportation modes remain highly dependent on gasoline where gas is usually not used as a substitute for oil. However, electricity generation could depend on both gas and oil, and therefore higher gas prices promote the switch from gas to oil usage. Last, there have been many climate mitigation policies since 1992 which the aim of reducing fossil fuel consumption which have higher carbon emission. These policies could be effective after some time lag and several policies could have reinforced one another, causing a shift towards cleaner forms of energy. We use three different time dummies to account for such potential changes. It is noted from the estimation that coal consumption is reduced by -0.069 (see Table 4.8) and oil consumption is reduced by -0.017 (see Table 4.6) from 2003 onwards. Introducing time dummies allows us to draw some conclusions for the change in climate mitigation policies, a variable which is otherwise hard to quantify.

Putting all these findings together, we see that even though economic growth cannot promote the OECD countries to use more renewable energy but it can at least drive them to substitute away from coal to other cleaner types of energy such as oil and gas. When fossil fuel R&D and renewable energy R&D are added into the estimations of the extended model, the findings from these estimations suggest that R&D in fossil fuel and renewable energy could potentially changes the usage of these two types of energy. For instance, higher R&D in fossil fuel actually promotes the usage of fossil fuel (Table 4.4) and reduces the usage of renewable energy (Table 4.5) in the 20 OECD countries. More R&D in renewable energy, on the other hand, reduces fossil fuel consumption (Table 4.4) suggesting that countries with and without oil reserves can effectively reduce their reliance on fossil fuel through the promotion of R&D in renewable energy. However, accumulated renewable energy R&D is not able to increase renewable energy consumption significantly. One of the reasons why renewable energy has not taken off is that it requires large cumulative investment and the accumulated renewable energy R&D is still relatively low as compared to accumulated fossil fuel R&D.

Table 4.4: Fossil Fuel Consumption (First-Difference GMM Results in Extended Model I).

Variables	20 OECD Countries			With Oil Reserves			Without Oil Reserves		
	Short Run		Long Run	Short Run		Long Run	Short Run		Long Run
	Coeff.	Prob.	Coeff.	Coeff.	Prob.	Coeff.	Coeff.	Prob.	Coeff.
Fos^C_{t-1}	0.835***	(0.000)		0.922***	(0.000)		0.811***	(0.000)	
Gdp	0.103***	(0.000)	0.624	0.005	(0.873)	0.064	0.136***	(0.000)	0.720
Oil_P	-0.016*	(0.084)	-0.097	-0.044**	(0.015)	-0.564	-0.008	(0.425)	-0.042
Gas_P	-0.000	(0.999)	0.000	0.027	(0.162)	0.346	-0.007	(0.581)	-0.037
Acc_Fos^R	0.009**	(0.011)	0.055	0.012**	(0.024)	0.154	0.007	(0.103)	0.037
Acc_Ren^R	-0.009***	(0.006)	-0.055	-0.013**	(0.012)	-0.167	-0.006*	(0.085)	-0.032
$dum92\_97$	-0.004	(0.496)		-0.010	(0.356)		0.000	(0.936)	
$dum98\_02$	-0.008	(0.239)		-0.016	(0.175)		-0.001	(0.855)	
$dum03$	-0.014	(0.105)		0.020	(0.199)		-0.024**	(0.017)	
$Constant$	-2.960***	(0.000)		-0.787*	(0.097)		-3.643***	(0.000)	
Diagnostic Tests									
Chow Test	3.82	(0.281)		3.77	(0.287)		6.04	(0.109)	
LM Test	0.040	(0.694)		0.109	(0.183)		0.038	(0.703)	
White Test	3.857	(0.870)		3.324	(0.950)		5.324	(0.805)	
RESET Test	1.334	(0.721)		2.620	(0.454)		1.223	(0.748)	
Cusum Test	4.076	(0.715)		7.986	(0.447)		3.748	(0.741)	
Jarque Bera Test	7.674	(0.278)		5.620	(0.392)		3.965	(0.516)	

Notes: 1. *, **, *** represent the significance at the 10%, 5% and 1% levels, respectively. 2. Fos^C_{t-1}, Gdp, Oil_P, Gas_P, Acc_Fos^R, and Acc_Ren^R represent fossil fuel consumption per labor at time $t-1$, GDP per labor, oil prices, gas prices, accumulated fossil fuel R&D per labor, accumulated renewable energy R&D per labor at time t. $dum92\_97$, $dum98\_02$ and $dum03$ represent the periods 1992-1997, 1998-2002 and 2003 onwards respectively. 3. Diagnostic tests statistics are reported in chi-squares. Probabilities are reported in parentheses.

Table 4.5: Renewable Energy Consumption (First-Difference GMM Results in Extended Model I).

Variables	20 OECD Countries			With Oil Reserves			Without Oil Reserves		
	Short Run		Long Run	Short Run		Long Run	Short Run		Long Run
	Coeff.	Prob.	Coeff.	Coeff.	Prob.	Coeff.	Coeff.	Prob.	Coeff.
Ren^C_{t-1}	0.862***	(0.000)		0.818***	(0.000)		0.931***	(0.000)	
Gdp	0.058	(0.244)	0.420	0.018	(0.890)	0.099	0.008	(0.841)	0.116
Oil_P	-0.023	(0.432)	-0.167	-0.070	(0.311)	-0.385	0.017	(0.522)	0.246
Gas_P	0.002	(0.961)	0.014	0.103	(0.153)	0.566	-0.022	(0.409)	-0.319
Acc_Fos^R	-0.021**	(0.037)	-0.152	0.002	(0.899)	0.011	-0.012	(0.164)	-0.174
Acc_Ren^R	0.015	(0.108)	0.109	-0.001	(0.977)	-0.005	0.010	(0.187)	0.145
$dum92\_97$	-0.018	(0.342)		0.017	(0.689)		-0.011	(0.475)	
$dum98\_02$	-0.005	(0.815)		0.040	(0.374)		-0.011	(0.540)	
$dum03$	0.038	(0.157)		0.081	(0.174)		-0.004	(0.880)	
$Constant$	-2.354***	(0.000)		-2.813*	(0.092)		-1.057**	(0.032)	
Diagnostic Tests									
Chow Test	3.42	(0.332)		2.52	(0.472)		0.62	(0.891)	
LM Test	0.124	(0.124)		0.006	(0.962)		-0.010	(0.818)	
White Test	14.148	(0.117)		10.009	(0.124)		14.569	(0.149)	
RESET Test	1.776	(0.620)		3.382	(0.337)		1.981	(0.577)	
Cusum Test	-0.000	(1.000)		10.296	(0.330)		6.038	(0.570)	
Jarque Bera Test	13.368	(0.108)		8.655	(0.236)		5.413	(0.406)	

Notes: 1. *, **, *** represent the significance at the 10%, 5% and 1% levels, respectively. 2. Ren^C_{t-1}, Gdp, Oil_P, Gas_P, Acc_Fos^R, and Acc_Ren^R represent renewable energy consumption per labor at time $t-1$, GDP per labor, oil prices, gas prices, accumulated fossil fuel R&D per labor, accumulated renewable energy R&D per labor at time t. $dum92\_97$, $dum98\_02$ and $dum03$ represent the periods 1992-1997, 1998-2002 and 2003 onwards respectively. 3. Diagnostic tests statistics are reported in chi-squares. Probabilities are reported in parentheses.

Table 4.6: Oil Consumption (First-Difference GMM Results in Extended Model I).

Variables	20 OECD Countries			With Oil Reserves			Without Oil Reserves		
	Short Run		Long Run	Short Run		Long Run	Short Run		Long Run
	Coeff.	Prob.	Coeff.	Coeff.	Prob.	Coeff.	Coeff.	Prob.	Coeff.
Oil^C_{t-1}	0.828***	(0.000)		0.890***	(0.000)		0.808***	(0.000)	
Gdp	0.084***	(0.000)	0.488	0.008	(0.692)	0.073	0.140***	(0.000)	0.729
Oil_P	-0.029***	(0.001)	-0.169	-0.051***	(0.000)	-0.464	-0.032***	(0.004)	-0.167
Gas_P	0.026***	(0.004)	0.151	0.037***	(0.007)	0.336	0.030**	(0.012)	0.156
Acc_Fos^R	0.002	(0.517)	0.012	0.009**	(0.020)	0.082	-0.002	(0.638)	-0.010
Acc_Ren^R	-0.004	(0.178)	-0.023	-0.004	(0.276)	-0.036	-0.007*	(0.062)	-0.036
$dum92\_97$	0.016***	(0.002)		0.012	(0.124)		0.016**	(0.019)	
$dum98\_02$	0.002	(0.757)		-0.017**	(0.044)		0.003	(0.747)	
$dum03$	-0.017**	(0.030)		-0.014	(0.245)		-0.010	(0.316)	
$Constant$	-2.991***	(0.000)		-1.141**	(0.011)		-3.786***	(0.000)	
Diagnostic Tests									
Chow Test	17.82***	(0.001)		14.50***	(0.002)		7.66*	(0.054)	
LM Test	-0.166	(0.202)		-0.131	(0.171)		-0.227	(0.151)	
White Test	11.829	(0.159)		3.220	(0.864)		7.058	(0.423)	
RESET Test	0.969	(0.809)		4.290	(0.235)		4.792	(0.191)	
Cusum Test	2.970	(0.804)		13.448	(0.214)		14.980	(0.172)	
Jarque Bera Test	7.137	(0.304)		3.963	(0.516)		9.767	(0.196)	

Notes: 1. *, **, *** represent the significance at the 10%, 5% and 1% levels, respectively. 2. Oil^C_{t-1}, Gdp, Oil_P, Gas_P, Acc_Fos^R, and Acc_Ren^R represent oil consumption per labor at time $t-1$, GDP per labor, oil prices, gas prices, accumulated fossil fuel R&D per labor, accumulated renewable energy R&D per labor at time t. $dum92\_97$, $dum98\_02$ and $dum03$ represent the periods 1992-1997, 1998-2002 and 2003 onwards respectively. 3. Diagnostic tests statistics are reported in chi-squares. Probabilities are reported in parentheses.

Table 4.7: Gas Consumption (First-Difference GMM Results in Extended Model I).

Variables	20 OECD Countries			With Oil Reserves			Without Oil Reserves		
	Short Run		Long Run	Short Run		Long Run	Short Run		Long Run
	Coeff.	Prob.	Coeff.	Coeff.	Prob.	Coeff.	Coeff.	Prob.	Coeff.
Gas^C_{t-1}	0.792***	(0.000)		0.842***	(0.000)		0.809***	(0.000)	
Gdp	0.222***	(0.000)	1.067	0.058	(0.381)	0.367	0.160***	(0.000)	0.838
Oil_P	-0.009	(0.657)	-0.043	-0.061	(0.128)	-0.386	-0.016	(0.451)	-0.084
Gas_P	0.008	(0.721)	0.038	0.037	(0.369)	0.234	0.026	(0.268)	0.136
Acc_Fos^R	-0.007	(0.295)	-0.034	0.000	(0.993)	0.000	-0.019**	(0.014)	-0.099
Acc_Ren^R	-0.003	(0.681)	-0.014	-0.007	(0.563)	-0.044	0.001	(0.844)	0.005
$dum92\_97$	0.003	(0.786)		0.007	(0.768)		-0.008	(0.544)	
$dum98\_02$	0.039***	(0.004)		-0.008	(0.772)		0.051***	(0.001)	
$dum03$	0.037**	(0.038)		0.069*	(0.059)		0.052***	(0.007)	
$Constant$	-5.082***	(0.000)		-2.400***	(0.004)		-4.248***	(0.000)	
Diagnostic Tests									
Chow Test	14.60***	(0.002)		3.81	(0.282)		25.95***	(0.000)	
LM Test	-0.050	(0.291)		-0.034	(0.463)		-0.037	(0.459)	
White Test	12.079	(0.148)		11.197	(0.191)		8.313	(0.306)	
RESET Test	0.962	(0.811)		4.389	(0.226)		0.340	(0.941)	
Cusum Test	3.060	(0.796)		13.668	(0.207)		9.139	(0.385)	
Jarque Bera Test	1.374	(0.795)		1.096	(0.833)		1.096	(0.833)	

Notes: 1. *, **, *** represent the significance at the 10%, 5% and 1% levels, respectively. 2. Gas^C_{t-1}, Gdp, Oil_P, Gas_P, Acc_Fos^R, and Acc_Ren^R represent gas consumption per labor at time $t-1$, GDP per labor, oil prices, gas prices, accumulated fossil fuel R&D per labor, accumulated renewable energy R&D per labor at time t. $dum92\_97$, $dum98\_02$ and $dum03$ represent the periods 1992-1997, 1998-2002 and 2003 onwards respectively. 3. Diagnostic tests statistics are reported in chi-squares. Probabilities are reported in parentheses.

Table 4.8: Coal Consumption (First-Difference GMM Results in Extended Model I).

Variables	20 OECD Countries			With Oil Reserves			Without Oil Reserves		
	Short Run		Long Run	Short Run		Long Run	Short Run		Long Run
	Coeff.	Prob.	Coeff.	Coeff.	Prob.	Coeff.	Coeff.	Prob.	Coeff.
$Coal_{t-1}^{C}$	0.931***	(0.000)		0.939***	(0.000)		0.925***	(0.000)	
Gdp	-0.096**	(0.029)	-1.391	-0.061	(0.374)	-1.000	-0.167***	(0.003)	-2.227
Oil_P	0.002	(0.954)	0.029	-0.014	(0.729)	-0.230	0.013	(0.721)	0.173
Gas_P	0.026	(0.390)	0.377	0.041	(0.321)	0.672	0.018	(0.660)	0.240
Acc_Fos^{R}	-0.003	(0.743)	-0.043	0.024**	(0.018)	0.393	-0.017	(0.159)	-0.227
Acc_Ren^{R}	0.006	(0.513)	0.087	-0.024***	(0.006)	-0.393	0.021*	(0.051)	0.280
$dum92\_97$	-0.023	(0.200)		0.004	(0.869)		-0.030	(0.201)	
$dum98\_02$	-0.008	(0.696)		-0.009	(0.743)		-0.001	(0.985)	
$dum03$	-0.069***	(0.007)		-0.022	(0.524)		-0.080**	(0.019)	
$Constant$	-0.145	(0.765)		-0.328	(0.665)		0.394	(0.501)	
Diagnostic Tests									
Chow Test	8.34**	(0.039)		0.65	(0.886)		6.90*	(0.075)	
LM Test	0.049	(0.731)		0.033	(0.822)		-0.145	(0.340)	
White Test	13.004	(0.162)		13.028	(0.111)		0.639	(0.999)	
RESET Test	1.583	(0.664)		3.883	(0.277)		3.809	(0.261)	
Cusum Test	5.017	(0.643)		12.119	(0.257)		3.898	(0.254)	
Jarque Bera Test	3.548	(0.554)		8.981	(0.224)		3.938	(0.519)	

Notes: 1. *, **, *** represent the significance at the 10%, 5% and 1% levels, respectively. 2. $Coal_{t-1}^{C}$, Gdp, Oil_P, Gas_P, Acc_Fos^{R}, and Acc_Ren^{R} represent coal consumption per labor at time $t-1$, GDP per labor, oil prices, gas prices, accumulated fossil fuel R&D per labor, accumulated renewable energy R&D per labor at time t. $dum92\_97$, $dum98\_02$ and $dum03$ represent the periods 1992-1997, 1998-2002 and 2003 onwards respectively. 3. Diagnostic tests statistics are reported in chi-squares. Probabilities are reported in parentheses.

4.6.2 Regressions on Energy R&D (Extended Model II)

Tables 4.9 and 4.10 show the responsiveness of newly invested fossil fuel R&D and renewable energy R&D to changes in gas prices, fossil fuel consumption and renewable energy consumption besides changes in income and oil prices.

A few interesting findings are reported. First, compared to renewable energy consumption as shown in Table 4.5, renewable energy R&D is more responsive to changes in economic growth. This is true for the regressions of all the 20 OECD countries and the OECD countries with and without oil reserves. If energy consumption is meant for current needs, then energy R&D can be interpreted as investment required to meeting the future demand for energy. This implies that energy technological advancement usually occurs during periods of high economic growth for renewable energy. As countries progress, they become more environmentally cautious and tend to shift towards renewable energy. While the estimations of fossil fuel R&D are less consistent between the countries with and without oil reserves, the estimations of renewable energy R&D show that economic growth is the key factor to promote renewable energy-related technologies.

Second, while renewable energy R&D is promoted through economic growth, fossil fuel R&D is driven mainly by its own demand as positive and significant coefficient of fossil fuel consumption is reported, 3.107 for all the 20 OECD countries and 2.875 for OECD countries with oil reserves. Positive coefficient is also found in the regression of OECD countries without oil reserves but not significant. Last, climatic policies which involve targeting lower carbon emissions appear to have an effect on energy R&D.

Putting these results together suggest that economic growth has both direct and indirect effects on fossil fuel consumption. The direct effect suggests that higher economic growth leads to higher fossil fuel consumption as we report positive and significant coefficient of economic growth for the regression of all the 20 OECD countries (0.103) and OECD countries without oil reserves

(0.136) in Table 4.4. The indirect effect of higher economic growth on fossil fuel consumption works through renewable energy R&D. Higher economic growth promotes renewable energy R&D and renewable energy R&D in turn reduces fossil fuel consumption as renewable energy R&D has negative and significant effect on fossil fuel consumption as reported in Table 4.4, -0.009 on all the 20 OECD countries, -0.013 on countries with oil reserves and -0.006 on countries without oil reserves.

Table 4.9: Fossil Fuel R&D Invested (First-Difference GMM Results in Extended Model I).

Variables	20 OECD Countries			With Oil Reserves			Without Oil Reserves		
	Short Run		Long Run	Short Run		Long Run	Short Run		Long Run
	Coeff.	Prob.	Coeff.	Coeff.	Prob.	Coeff.	Coeff.	Prob.	Coeff.
Fos^R_{t-1}	0.333***	(0.000)		0.576***	(0.000)		0.290***	(0.000)	
Gdp	-1.130	(0.128)	-1.694	-2.061**	(0.043)	-4.861	0.921	(0.286)	1.297
Oil_P	-0.216	(0.556)	-0.324	-0.150	(0.812)	-0.354	-0.252	(0.574)	-0.355
Gas_P	0.602	(0.114)	0.903	1.416**	(0.022)	3.340	0.553	(0.235)	0.779
Fos^C	3.107***	(0.000)	4.658	2.875***	(0.006)	6.781	1.052	(0.197)	1.482
Ren^C	-0.510*	(0.095)	-0.765	0.013	(0.964)	0.031	-0.261	(0.446)	-0.368
$dum92\_97$	-0.582***	(0.009)		0.394	(0.296)		-0.780***	0.003)	
$dum98\_02$	-0.524**	(0.035)		0.183	(0.652)		-0.637**	(0.037)	
$dum03$	0.818**	(0.011)		2.114***	(0.000)		-0.069	(0.860)	
$Constant$	42.653**	(0.015)		50.242**	(0.014)		0.645	(0.974)	
Diagnostic Tests									
Chow Test	16.56***	(0.001)		15.15***	(0.002)		9.51**	(0.023)	
LM Test	-0.119	(0.536)		0.038	(0.451)		-0.026	(0.935)	
White Test	4.658	(0.588)		4.580	(0.711)		6.738	(0.565)	
RESET Test	4.433	(0.220)		6.078	(0.109)		1.022	(0.796)	
Cusum Test	13.478	(0.213)		18.419	(0.105)		3.128	(0.791)	
Jarque Bera Test	3.778	(0.533)		1.171(	(0.823)		10.376	(0.177)	

Notes: 1. *, **, *** represent the significance at the 10%, 5% and 1% levels, respectively. 2. Fos^R_{t-1}, Gdp, Oil_P, Gas_P, Fos^C, and Ren^C represent newly invested fossil fuel R&D per labor at time $t-1$, GDP per labor, oil prices, gas prices, fossil fuel consumption per labor, renewable energy consumption per labor at time t. $dum92\_97$, $dum98\_02$ and $dum03$ represent the periods 1992-1997, 1998-2002 and 2003 onwards respectively. 3. Diagnostic tests statistics are reported in chi-squares. Probabilities are reported in parentheses.

Table 4.10: Renewable Energy R&D Invested (First-Difference GMM Results in Extended Model I).

Variables	20 OECD Countries			With Oil Reserves			Without Oil Reserves		
	Short Run		Long Run	Short Run		Long Run	Short Run		Long Run
	Coeff.	Prob.	Coeff.	Coeff.	Prob.	Coeff.	Coeff.	Prob.	Coeff.
Ren^R_{t-1}	0.451***	(0.000)		0.642***	(0.000)		0.354***	(0.000)	
Gdp	1.873**	(0.024)	3.412	1.734*	(0.083)	4.844	2.017**	(0.023)	3.122
Oil_P	-0.108	(0.758)	-0.197	-0.271	(0.658)	-0.757	-0.101	(0.806)	-0.156
Gas_P	0.507	(0.185)	0.923	0.954	(0.134)	2.665	0.319	(0.473)	0.494
Fos^C	-0.452	(0.531)	-0.823	-0.863	(0.344)	-2.411	0.281	(0.729)	0.435
Ren^C	-0.538	(0.128)	-0.980	-0.408	(0.261)	-1.140	-0.116	(0.758)	-0.180
$dum92\_97$	-0.511**	(0.020)		0.087	(0.818)		-0.846***	(0.001)	
$dum98\_02$	-0.275	(0.281)		-0.104	(0.797)		-0.319	(0.282)	
$dum03$	0.404	(0.225)		1.317**	(0.018)		-0.085	(0.822)	
$Constant$	-32.916*	(0.071)		-36.879*	(0.043)		-17.624	(0.373)	
Diagnostic Tests									
Chow Test	7.96**	(0.047)		5.71	(0.127)		11.04**	(0.012)	
LM Test	0.072	(0.442)		0.072	(0.247)		0.195	(0.417)	
White Test	3.327	(0.853)		3.796	(0.803)		5.686	(0.682)	
RESET Test	9.399	(0.125)		0.554	(0.668)		1.069	(0.785)	
Cusum Test	-3.618	(0.247)		0.564	(0.665)		3.270	(0.779)	
Jarque Bera Test	3.303	(0.577)		7.262	(0.298)		3.427	(0.564)	

Notes: 1. *, **, *** represent the significance at the 10%, 5% and 1% levels, respectively. 2. Ren^R_{t-1}, Gdp, Oil_P, Gas_P, Fos^C, and Ren^C represent newly invested renewable energy R&D per labor at time $t-1$, GDP per labor, oil prices, gas prices, fossil fuel consumption per labor, renewable energy consumption per labor at time t. $dum92\_97$, $dum98\_02$ and $dum03$ represent the periods 1992-1997, 1998-2002 and 2003 onwards respectively. 3. Diagnostic tests statistics are reported in chi-squares. Probabilities are reported in parentheses.

4.7 Concluding Remarks

Chapter 4 also seeks to estimate both the short-run and the long run elasticities of various energy consumption and energy R&D to changes in oil prices and income of the OECD countries over the period of 1980 to 2010 using the Nerlove partial adjustment model. As compared to Chapter 3, other variables including gas price to account for cross-price elasticity and fossil fuel R&D and renewable R&D to account for technological innovations are added into the extended models. Time dummies are also added to detect potential structural changes.

There are a few interesting findings which are particularly worth noting. First, the time dummies suggest that climatic mitigation policies, in general, are able to stimulate the use of cleaner energies after some time lag. Second, significant and dynamic linkages are found between energy consumption and energy R&D. Fossil fuel consumption promotes fossil fuel R&D and fossil fuel R&D in turn drives its own consumption. Renewable energy R&D also has a role in reducing fossil fuel consumption. These effects often occur instantaneously.

All these findings put together draw important policy implications. The effects of policies that aim at increasing environmental awareness are slow to take effect as compared to policies that focus directly on reducing fossil fuel R&D and promoting renewable energy R&D. The dynamic linkages between energy consumption and energy R&D established in this study suggest that fossil fuel consumption which usually leads to higher carbon emission can be reduced through lower fossil fuel R&D and higher renewable energy R&D. As a result, taxes on fossil fuel consumption and subsidies directed from fossil fuel R&D towards renewable energy R&D deem useful to facilitate the shift towards renewable energy-based economies.

Chapter 5

Conclusions

5.1 Findings

Academia has tackled the energy-economic growth nexus and affirmed the dynamic linkages between the two. The oil crises in 1970s and growing environmental concerns have changed the energy landscape in recent years. A great deal of attention has shifted to renewable energy, promoting it as the candidate to attain energy security and climate change mitigation. The relationship between energy and economic growth is hence, reshaped.

The central question now is whether renewable energy could be a good substitute that replaces the role of fossil fuels in economic growth. Clearly, this thesis is not the first to examine the implications of renewable energy consumption on economic growth. However, literature on such issues remains scarce and some of the earlier works on this issue comes from Apergis and Payne (2010 and 2011). This question becomes increasingly important as countries are still more dependent on traditional fossil fuels. In this thesis, the main objective is to investigate the direction of the causality between renewable energy consumption and income, which is an important issue in the field of energy economics.

Energy R&D is central to promote energy productivity but existing literature has overlooked the importance of energy R&D on economic growth.

Energy consumption influences the demand of the energy market but energy R&D influences the supply of the energy market. Fossil fuel R&D has been the incumbent energy technology but the introduction of renewable energy R&D will undeniably change the energy market. To better account for the total energy technologies in the economy, this thesis calculates the accumulated energy R&D which includes both past and newly invested energy R&D and derives the total existing energy R&D through a creation and destruction process.

Besides attempting to answer the question on whether renewable energy consumption and R&D affects economic growth, this thesis also seeks to answer other related questions. How countries respond in terms of their energy consumption and energy R&D when there are changes in economic growth and oil prices? What is the causality relationship between energy consumption and energy R&D? The main empirical findings in this thesis as summarized below.

First, analyses of Chapter 2 show that renewable energy consumption and R&D play an important role in driving economic growth, especially amongst the countries without oil reserves. The panel analyses show that output of countries with oil and gas reserves (without oil reserves) respond more significantly to fossil fuel R&D (renewable energy R&D) than countries without oil and gas reserves (with oil reserves). However, output per labor remains more dependent on changes in capital stock and fossil fuels rather than renewable energy.

Second, results of Chapter 3 show that though higher oil prices could promote renewable energy R&D, economic growth plays a larger role as compared to oil prices to shift countries to shift to cleaner forms of energy. Economic growth reduces coal consumption and increase oil, gas and renewable energy consumption.

Third, Chapter 4 finds that potential bilateral causality relationship between energy consumption and energy R&D. To reduce fossil fuel consumption and facilitate the shift towards renewable energy-based economies, countries could also implement policies such as subsidies for renewable energy R&D and removal of subsidies for fossil fuel-related R&D to reduce overall fossil fuel consumption.

Overall, renewable energy and sustainable development are integrated issues. Renewable energy can be one of the production inputs and this thesis overrules the controversy that renewable energy could hamper economic growth. Both renewable energy consumption and R&D are drivers of economic growth. As the energy market structure of different country groups vary, countries should have different policy targets to increase their levels of renewable energy or promote usage of cleaner forms of energy.

5.2 Future Research

The results of this thesis show that energy R&D could be important for economic growth and provide the recommendations that countries could look into energy R&D apart from energy consumption. However, it does not provide the full picture for the world as the focus is solely on 20 OECD countries. Hence, this raises additional questions which could be explored. 1) Would the dynamics between energy and economic growth in OECD countries differ from non-OECD countries? 2) What would the optimal level of the respective energy R&D in countries be?

As this thesis extends to the role of energy R&D which is currently lacking in existing literature, more work could be done on the role of energy R&D in the energy market. Energy efficiency is expected to improve as countries increase their energy R&D. Higher oil prices are also expected to reduce countries' energy consumption. Amidst pressing climatic change issues, countries are exploring ways to reduce their respective energy intensity (energy-GDP ratio). It would be interesting to discuss the role of energy R&D and oil prices in influencing the energy intensity. As countries shift away from fossil fuels towards renewable energy amidst pressing climatic change issues, a comparison of fossil fuel R&D or renewable energy R&D (internal factors) against changes in oil prices (external factor) in influencing energy intensity could assist countries to attain part of their sustainable development plan.

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