ESSAYS ON ENERGY, CO2 EMISSIONS AND INCOME CONVERGENCE

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ABSTRACT

THREE ESSAYS ON THE ENERGY ECONOMICS

Onater İsberk, Esra

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This thesis presents three articles on energy, CO2 economics, and income convergence. The first essay derives a carbon emission convergence equation by using the Solovian growth theory and tests the empirical equation by using data of Annex I countries. Hence, the study checks the extent of the success of the carbon emission reduction policies implemented within the framework in terms of CO2 emission convergence. System GMM estimations strongly suggest the existence of unconditional and conditional convergence of carbon emissions among Annex I countries. The second essay develops an energy intensity convergence equation by extending the Solovian income convergence equation, which is tested for OECD countries. System GMM estimations strongly suggest the existence of unconditional and conditional convergence of energy intensity among the OECD countries. The environmental Kuznets curve hypothesis argues that carbon emissions are higher at the beginning of countries' development processes, but, after exceeding a certain development threshold, carbon emissions then decrease. The third essay of this thesis examines the environmental Kuznets curve hypothesis for OECD countries. The ARDL approach employed confirms the existence of the environmental Kuznets curve hypothesis for Denmark, South Korea, France, and Israel.

Keywords: Carbon Emissions; Energy Intensity; Environmental Kuznets Curve Hypothesis; Income Convergence; Energy intensity Convergence; Carbon Emission convergence, Panel Data Models; Time Series Analysis

ÖZET

ENERJİ EKONOMİSİ ALANINDA ÜÇ MAKALE
Onater İsberk, Esra
Ekonomi Doktora Programı

Tez Yöneticisi: İbrahim Hakan Yetkiner

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Bu tez, enerji, CO2 ekonomisi ve gelir yakınsama konularında üç makale sunmaktadır. İlk makale, Solovyen büyüme teorisini kullanarak bir karbon emisyonu yakınsama denklemini türetir ve Annex I ülkelerinin verilerini kullanarak ampirik denklemi test eder. Bu nedenle, çalışma, uygulanan karbon emisyonu azaltma politikaları çerçevesinde bu politikaların karbon emisyonu yakınsaması açısından başarısını ölçmektedir. Sistem GMM tahminleri, Annex I ülkeleri arasında koşulsuz ve koşullu karbon emisyonlarının yakınlaşmasının varlığını kuvvetle ortaya koymaktadır. İkinci çalışma, Solovyen gelir yakınsama denklemini genişleterek bir enerji yoğunluğu yakınsama denklemi geliştirir. OECD ülkeleri için test edilen bu denklem sonucunda Sistem GMM tahminleri, OECD ülkeleri arasında enerji yoğunluğunun koşulsuz ve koşullu yakınsamasının varlığını kuvvetle ortaya koymaktadır. Çevresel Kuznets eğrisi hipotezi, ülkelerin kalkınma süreçlerinin başlangıcında karbon emisyonlarının daha yüksek olduğunu, ancak belli bir kalkınma eşiğini aştıktan sonra karbon emisyonlarının azalacağını savunur. Bu tezin üçüncü çalışması, OECD ülkeleri için çevresel Kuznets eğrisi hipotezini incelemektedir. ARDL yaklaşımı, Danimarka, Güney Kore, Fransa ve İsrail için çevresel Kuznets eğrisi hipotezinin varlığını ortaya koymaktadır

Anahtar Kelimeler: Karbon Emisyonları; Enerji Yoğunluğu; Çevresel Kuznets Eğrisi hipotezi; Gelir Yakınsaması; Enerji Yoğunluğu Yakınsaması; Karbon Emisyonları Yakınsaması; Yakınsama; Panel Veri Modelleri; Zaman Serisi Analizi

This thesis is dedicated to my family; Taylan İsberk and Kumsal İsberk

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CHAPTER 1 : INTRODUCTION

According to the Intergovernmental Panel on Climate Change (IPCC, 2007), carbon dioxide comprises the largest proportion of anthropogenic greenhouse gases and has evidently impacted global climate change. Global energy consumption increased by 265% between 1965 and 2017, with carbon emissions showing an increasing trend (BP Statistical Review of World Energy, 2018). Hence, climate change is now one of the most severe problems the world faces. Whilst it is an article of faith that increasing global energy consumption leads to accelerated carbon emissions, reducing anthropogenic emissions is critical in order to prevent global warming. This belief has developed a considerable following and public awareness. Consequently, this awareness of the role increased carbon emissions play in global warming has given rise to discussions over reducing greenhouse gases (Cline, 1992; Ezcurra, 2007; IPCC, 1995; Lanne and Liski; 2004; Lee and Chang, 2008; Solow, 1991). The quest for effective and efficient solutions to prevent global warming has caused many countries to note their carbon emission levels and debate which country should mitigate its carbon emissions. Moreover, the amount of carbon emissions each country should eliminate has also been subject to debate.[1] In line with this objective, many countries came together to sign international agreements (e.g., UNFCCC, IPCC, Kyoto Protocol) aimed at controlling and decreasing carbon emissions where economic objectives were not the priority.

The United Nations Framework Convention on Climate Change (UNFCCC) was adopted in 1992. Going into force in 1994, this agreement was intended to form the basis of the global response to climate change. Altogether, 197 countries ratified this treatee. The ultimate target of the convention, and of the treatee it produced, was "to stabilize greenhouse gas concentrations at a level that would prevent dangerous anthropogenic interference with the climate system" (UNFCCC, 1992). Also emphasized was that this objective should be met in a time frame that would allow the world's ecosystems to adjust naturally, without endangering food production or undermining sustainable economic development. All parties of this treatee agreed to meet certain obligations, with the Convention setting stricter requirements for the developed countries listed in Annex I. According to the Kyoto Protocol, during the period 2008-2012, 43 Annex I countries, including transitional industrialized economies, pledged to reduce their total greenhouse gas

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[1] For further information about discussions on egalitarian rule of equal per capita emissions please see Brooks and Sethi, 1997; Arora and Cason, 1999; List, 1999; Strazicich and List; 2003, Aldy (2006), Patterson et al. (2014), and Bulte et al., 2007.

emissions by 5.2% from their 1990 levels. Developing countries such as China and India have higher emissions but were not obligated to reduce their emission levels, resulting in the U.S failure to ratify the protocol until these major developing countries also committed to reducing their emission levels.[2] In 2007, the Bali Roadmap set a deadline for all parties to negotiate a post-2012 plan since no regulated targets for developed countries existed for the mitigation of carbon emissions after 2012. However, parties opposed to the distribution of obligations set forth during the Copenhagen Conference in 2009 produced the non-binding Copenhagen Accord. The Durban Climate Change Conference in 2011 was the last attempt to agree on the commitments in carbon emission reduction prior to the expiration of the first commitment period of the Kyoto Protocol, and yet only major EU developed countries were willing to agree to this Protocol. The outcome of this conference was that both developed and developing countries agreed to co-operate in a universal agreement that would be legally binding for all parties no longer than 2015. In 2012, the Doha Amendment to the Kyoto Protocol was adopted, with Annex I parties agreeing to a second commitment period of 2013-2020. During this second commitment period, these parties committed to mitigate greenhouse gas emissions by at least 18% below their 1990 levels throughout this period. As a further step, an action by the United Nations Framework Convention on Climate Change resulted in the Paris Agreement, which was adopted in 2015 in Paris. This agreement was designed to provide new cornerstone to address climate change and was intended to replace the Kyoto Protocol in 2020. In order for the Paris Agreement to go into force, the 55 countries that produce at least 55% of global greenhouse gases had to ratify or accept the agreement, and this was achieved in 2016 with 152 parties ratifying it (UNFCCC, 2016). The primary objectives of this agreement are to ensure that increases in average global temperatures remain well below 2 degrees Celsius, i.e., at pre-industrial levels, to set a limit to the 1.5 degrees Celsius threshold, and achieve net zero emissions in the second half of the 21st century.[3]

To achieve the objectives of this agreement, the amount of carbon emissions should meet a precise target so as to attain emission-level sustainability. Achieving such levels in emissions in developed economies would provide an inspiration to developing countries and perhaps influence them to make concession with respect to their own carbon emission levels. As is apparent,

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[2] See Appendix A for further details on important dates related to Annex I countries.

[3] The future success of this agreement will depend on the United States changing its position as Republican President Trump has threatened to withdraw the United States from it.

“common cause, stylized responsibilities” in taking action with respect to global warming should be an essential part of all nations’ international policy making. The dynamic nature of environmental degradation, especially per capita carbon emissions, needed to be well understood in order to generate reliable and applicable international policies and bridge the differences between developed and developing countries so as to enhance international cooperation.

1.1. Organization of Dissertation

Brundtland (1987) defines sustainable development as “development that meets the needs of the present without compromising the ability of future generations to meet their own needs.” While this definition has become increasingly prevalent, the definition of sustainable development has changed over time to consist of three main branches: economic, environmental, and social (Dobson, 1991; Elkington, 1998; Fleurbaey et al., 2014; Flint and Danner, 2001; Murdiyarso, 2010; Okereke, 2011; Pope et al., 2004; Sneddon et al., 2006). Accordingly, the main focus of this thesis is the dynamic patterns of two of these three branches of sustainable development, the economic and the environment branches. However, it is impossible to understand economic activity-driven global warming without first understanding the role of energy in economic growth.

With respect to basic physical principals, the laws of thermodynamics and conservation of matter imply that energy is essential to achieve production (Stern, 2011). Functioning economic systems are bound by perpetual constraints. The mass-balance principle suggests that an equal or a greater amount of input must be used to produce a certain amount of goods. According to second law of thermodynamics, in order to physically achieve work, a minimum quantity of energy must be expended. Hence, all production processes require energy, and, reciprocally, energy is an essential factor in production.

The conventional growth models beginning with the Solow growth model (1956) do not include energy as factor of production. However, a remarkable inference of Solow’s growth model forms the basis for this thesis. The convergence notion is one of the most important cornerstones in the growth literature and is the basic inference of Solow’s Neoclassical Growth Model (1956). After six decades, the model maintains its importance and continues to attract great interest from both theoretical and empirical approaches. Empirical convergence studies began in the late 1980s with Abramowitz’s labor productivity study (1986). In a short time, studies inspired by Solow’s neoclassical growth model has become popular (Barro & Sala-I Martin, 1992; Mankiw, Romer & Weil, 1992) and has have broader ramifications.[4]

In broad terms, the assumption of diminishing marginal returns predicts Solow's (1956) per-capita income convergence. This assumption forces an economy to converge to equilibrium independently whether current per-capita capital is higher or lower than the equilibrium capital level (Islam, 2003). Consequently, lower per-capita income countries are expected to experience higher income levels due to their higher marginal productivity of capital. Following this "catch-up" process, a country will then reach a steady state where per-capita income and consumption grow at a constant rate at which technological progress can then be determined exogenously (Patterson et al., 2014). Cross-country differences, however, lead to a conditional convergence that depends on similar nations having idiosyncratic characteristics. Hence, when considering perpetual differences in economies, "conditional convergence" may predict convergence across economies (Mankiw, Romer, & Weil, 1992). The conclusion that could be drawn from the Solow model is that, regardless of per-capita income levels, economies with lower incomes would tend to catch up with high-income economies. The Solow model could also inspire the derivation of a convergence equation in the environmental literature. Therefore, the second and third chapters of this thesis focus on theoretical derivations and empirical examinations of convergence behaviors of carbon emissions and energy intensity, respectively. Inspired by the income convergence equation, the second chapter develops a distinctive approach by augmenting the textbook model with the Jevons paradox.

In 1856, William Stanley Jevons asserted that an increase in the efficiency of a technology causes overall energy consumption to increase. This belief contrasts with another belief that technological change is one of the primary drivers of consumption and production in economic growth theory. After a century, Jevons' analysis was revisited by Brookes (1979) and Khazzoom (1980), who individually reached the same conclusion, that, paradoxically, improvements in energy efficiency tend to increase overall demand for energy. In 1992, Saunders combine these two studies in the "Khazzoom-Brookes Postulate" and proved the postulate's existence under neo-classical growth

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[4] Neoclassical growth models assume diminishing returns, which provides a base for the convergence notion. On the other hand, endogenous growth models cannot reach a convergence conclusion because of the absence of the diminishing returns assumption. Barro (1997) also asserts that endogenous growth models ironically promote the explanatory power of the neoclassical growth model. See Islam (1995) for a broad review of income convergence.

theory. Moreover, their study proves that improvements in energy efficiency lead to increases in energy consumption under the Cobb-Douglas production function assumption. Since then, this phenomenon has prevailed in the energy economics literature and has continued to be discussed by Greening et al. (2000), Alcott (2005), Saunders (2013), Freire-Gonzales and Puig-Ventosa (2015), Sorrell (2009), among others.

Jevons' paradox has emerged in two forms.[5] First, in accordance with the fundamental price theory, a decrease in the price of using energy leads to a rise in demand, a phenomenon called the direct rebound effect. In the second form, savings from efficient energy are channeled to meet another demand, a phenomenon called indirect rebound effect. In order to avoid this paradox, new sources of demand would be restricted and the resulting savings would not circulate back into the economy. Yet, given global current economic conditions, this could be only a myth. Politicians and leading companies in the global economy are strongly opposed to the idea of reducing circulating money in the market in parallel with decreasing demand.

As noted above, gains in energy efficiency is a crucial part of developing a strategy to address global warming. The logic behind this belief is that improved energy efficiency leads to lower energy consumption and, accordingly, a decline in greenhouse gas emissions (IPCC, 2007). Moreover, energy efficiency improvements emerging from technological progress promotes economic growth through reduced resource consumption (Freire-Gonzales and Puig-Ventosa, 2015). However, when the rebound effect occurs, energy efficiency does not necessarily reduce greenhouse gas emissions; hence, environmental preservation policies become less effective or even have misleading results.[6] The conclusion of improvements in efficiency accelerate environmental degradation (Alcott, 2005), ultimately showing that current or modern efficiency policies still have a missing role to play in preserving the environment. As Saunders (1992) states, policies supporting preservation may even lead to worsening environmental degradation.

Considering this serious notion that has been neglected in the literature, this study formulates energy consumption per capita as a function of income per capita and rate of technological change and derives a carbon emission convergence equation. In the empirical part, a dynamic panel data

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[5] Thomas and Azevedo (2013) provide a body of direct and indirect rebound effect studies in the literature.
[6] Saunders (2013) also argues that studies that have ignored the rebound effect have misleading energy consumption forecasts.

approach was adopted and the System Generalized method of Moments (GMM) proposed by Arellano and Bover (1995) and Blundell and Bond (1998) was applied to a five-year span of panel data of 41 Annex I countries between 1960 and 2014.

The motivation behind examining Annex I countries is that those economies that have adopted the United Nations Framework Convention of Climate Change in 1992 can provide concrete results, thereby giving the opportunity to measure the success of countries that have attempted to address global warming. Within the related literature, the current study has also been the first study to examine the Annex I countries.

As a first step, the carbon emission convergence equation was estimated in absolute form (i.e., absolute convergence). Next, the conditional convergence version was estimated by using population growth rate (in annual percentages), gross savings (in percentage of GDP), GDP per capita (at a constant 2010 US$). Third, the conditional convergence equation was extended by including several control variables in order. These control variables included GDP per capita (at a constant 2010 US$), energy use (in kg of oil equivalent) per capita, net energy imports (in percentage of energy use), fossil fuel energy consumption (in percentage of total consumption), alternative and nuclear energy consumption (in percentage of total energy use), an openness variable expressed as total trade in percentage of GDP, net inflows of foreign direct investment (in percentage of GDP), and value added agricultural growth rate (in annual percentage).

Estimation results of the System GMM revealed strong evidence of carbon emission convergence across Annex I countries between 1960 and 2014. The lagged dependent variable, carbon emissions per capita, was positive and statistically significant in all estimation models, a finding congruent with theoretical expectations. In addition, the control variables entered one by one into the model, GDP per capita, energy consumption per capita, fossil fuel consumption, renewable and alternative energy consumption, and agricultural growth rate, were found to be statistically significant and to have the expected signs. In total, these findings significantly strength the validity of carbon emissions convergence. Moreover, the estimated implied speed of convergence was higher in the conditional convergence than that in the absolute convergence, thus supporting the contribution of the control variables in carbon emission convergence. In all, Chapter 2 discusses the carbon emission convergence across Annex I countries over the last five decades.

Given that carbon emissions are a sub-branch of sustainable development studies, while judging the success of environmental protection policies, the other side of the coin from the amount of carbon emissions is energy intensity. In this sense, Chapter 3 provides theoretical and empirical examinations of the convergence tendency of energy intensity across 34 OECD countries over the period 1980-2014. However, examining energy intensity convergence differs from conventional convergence studies. Firstly, for most countries, the average growth rate of energy intensity is negative, meaning that energy efficiency is increasing. Second, the direction of change is from right to left. Both of these stylized facts contradict the stylized facts regarding income convergence; the average growth rate is positive, and the convergence is from west to east. However, energy intensity is simply energy per unit of output, and so using income convergence as a starting point in the derivation of the energy-intensity convergence equation is meaningful, given that income dynamics must have a significant role to play in energy-intensity dynamics. Hence, in a quest to measure improvements in energy intensity, the heuristic move adopted in this study was twofold. First, the energy use function whose derivation is given in Chapter 2 was employed rather than assuming it was a factor of production, and, second, the energy-intensity convergence equation is a function of time, a major novelty of the derived equation.

In the empirical part, as described earlier, a dynamic panel data approach was adopted, and the System GMM was applied to a five-year span of panel data of 34 OECD countries for 1980-2014. The estimation procedure of conditional convergence applies various control variables that affect energy-intensity convergence, such as gross savings (in percentage of GDP), population growth rate (in annual percentages), openness variable as total trade in percentage of GDP, net inflows of foreign direct investment (in percentage of GDP), and a value-added agricultural growth rate (in annual percentages). Estimations supported the theoretical expectation of energy-intensity convergence. In particular, the lagged dependent variable, energy intensity, was positive and statistically significant in all regression equations. Adding control variables to the convergence equation one by one, the conditional energy-intensity convergence results were in line with theoretical expectations, except for the human capital index, which was found to be statistically insignificant. Furthermore, the implied speed of convergence was found to be higher in the conditional convergence equations than in the absolute convergence equation, implying that each of the control variables contributes to energy-intensity convergence. Foremost, the time trend was found to be statistically significant in the absolute and conditional convergence equations, suggesting that energy intensity convergence is subject to time trend but negatively; that is, as time progresses, energy intensity decreases.

As described in Chapters 2 and 3, three motivations lay behind employing the System GMM, First, the System GMM is a highly suggested estimator for empirically examining theoretical convergence equations where a dynamic dependent variable and additional control variables in linear equations improve the estimator's fit (Bond, Hoeffler, & Temple, 2001; Roodman, 2009b). Secondly, the System GMM deals with fixed effects and potential endogeneity of dependent and control variables, thereby in return providing unbiased estimations within a dynamic panel data framework (Bond, Hoeffler, & Temple, 2001; Hoeffler, 2002). Lastly, the System GMM is designed for panel data sets that have small time dimensions and relatively large cross-sections. Moreover, the fact that the first differences of instruments are assumed to be uncorrelated with fixed effects makes System GMM more efficient; in addition, more instruments can be added into the regressions (Roodman, 2009a).

Apart from the aforementioned advantages, four key diagnostics are vital in validating the consistency of the System GMM, as shown in Chapter 2 and 3. Firstly, as a rule of thumb, the number of instruments should be smaller than or equal to the number of groups in a regression in order to avoid finite sample bias by overfitting number of instruments (Roodman, 2009b). Secondly, a negative first-order autocorrelation (AR1) may exist, but the error term should be confirmed to not contain second-order autocorrelation (AR2). The Arellano-Bond (1991) test is used to identify first and second order autocorrelation in first-differenced residuals, and so it was employed to verify whether the residuals met that requirement. Thirdly, the validity of instrument set must be confirmed using the Hansen (1982) J test for detecting over-identifying restrictions, as these should not be correlated with the error term. Lastly, for the consistency of the system GMM estimations, the additional moment restrictions proposed by Blundell and Bond (1998) had to be validated with the Difference-in-Hansen test. In Chapters 2 and 3, all GMM estimates are presented and are shown to be consistent and robust in terms of the validity of the instruments used in the equations. In all, as shown in Chapters 2 and 3, the validity of all four diagnostics mentioned above demonstrates that the system GMM was the most appropriate estimator to employ in these analyses.

The third essay comprising Chapter 4 of this dissertation discusses the impact of economic development on the environment in the context of the Environmental Kuznets Curve (EKC) hypothesis. The EKC hypothesis suggests that carbon emissions have an inverted U-shaped pattern with respect to economic development process. This nonlinear relationship can be explained as follows: The relatively lower levels of waste accumulation generated in the early stages of an economy's development process begin to increase with the industrialization process, accompanied by higher levels of carbon-based energy consumption. As a result of this significant rise, environmental degradation has a positive relationship with per capita income. However, as a country's economy approaches its post-industrialization period, the higher level of economic growth results in the service sector and technological development having a higher share of the country's GDP, resulting in reduced emission levels by the production sector. Although the literature provides a large spectrum of studies in the field of renewable energy usage and nuclear energy, which are treated separately in examining EKC, this study comprises the first empirical research to combine nuclear and renewable energy as "noncarbohydrate" energy. The empirical analysis employs the autoregressive distributed lag (hereafter, ARDL) bounds test developed by Pesaran and Shin (1999) and Pesaran, Shin, and Smith (2001). This general dynamic model uses the lagged values of dependent and independent variables to directly estimate short-run elasticities and long-run elasticities indirectly. ARDL has several advantages over other cointegration methodologies. First, the model solves the order of integration problem and variables can be either integrated of order zero, I(0), or in order one, I(1). Second, ARDL allows different variables to have different optimal lag lengths. Third, the model runs with a single reduced-form equation, and, lastly, the model provides efficient estimates even when some variables are endogenous in small samples. The bounds' *F*-test for cointegration estimates for 27 OECD countries over the period 1960-2010 show that Canada, Chile, Denmark, France, Greece, Israel, Italy, Korea Republic, New Zealand, and Sweden have a long-run relationship with per capita carbon emissions, primary energy consumption, GDP per capita, and alternative and nuclear energy, i.e., noncarbohydrates. Moreover, the EKC hypothesis holds for Denmark, France, Israel, and Korea Republic, and a monotonic increase in the relationship between carbon emissions and GDP per capita was found for Canada, Greece, Italy, and New Zealand.

CHAPTER 2 : CONVERGENCE IN CARBON EMISSIONS ACROSS ANNEX I COUNTRIES: THEORY AND EVIDENCE

Countries have been trying to control global warming by developing policies, both individually and in collaboration with each other. However, an important aspect of greenhouse gas emissions due to carbon-based energy use has sometimes been ignored: the Jevons Paradox or the rebound effect. In 1856, contrary to the general belief, W. Stanley Jevons claimed that efficiency gains in technology lead to increased overall energy consumption, that is, economic growth theory considers technological change to be a primary driver of production and thus energy usage. After a century, Jevons' interpretations were re-examined first by Brookes (1979) and then by Khazzoom (1980), both of whom concluded that improvements in energy efficiency paradoxically increase overall energy demand. Saunders (1992) pairs these two studies and calls this hypothesis the Khazzoom-Brookes Postulate and proved the validity of the postulate under neo-classical growth theory. One of the main conclusions of this study was that, under the Cobb-Douglas production function assumption, energy-efficiency improvements increase energy consumption. This phenomenon has become prevalent in the energy economics literature and has continued to be discussed (Alcott, 2005; Freire-Gonzales & Puig-Ventosa, 2015; Greening et al., 2000; Saunders, 2013; Sorrell, 2009; among others).

This paper augments the neoclassical income convergence equation with the Jevons paradox in order to obtain the carbon convergence equation for ANNEX I countries. Since the Jevons paradox claims that "energy efficiency gains increase energy consumption" and since "carbon-based energy consumption leads to higher greenhouse gas emissions," this study integrates these two observations in order to provide more accurate policy proposals. To this end, the study imposed the Jevons paradox on the Solovian convergence theory and so introduced a new perspective on energy use and carbon emission convergence into the literature. Moreover, following the tradition of Islam (1995), this study empirically estimated the carbon convergence equation using a dynamic panel data approach, i.e., the System Generalized Method of Moments (GMM) proposed by Arellano and Bover (1995) and Blundell and Bond (1998), using a five-year span of panel data from 41 Annex I countries for the 1960-2014 period. This study's contribution to the literature is twofold: First, to our knowledge, this study is the first to theoretically solve the convergence equation employing the Jevons paradox hypothesis for carbon emissions and to provide an implied convergence rate, thereby filling a significant gap in the related literature. Secondly, this study is also the first to employ empirical analysis to examine Annex I countries. Hence, the theoretical analysis and empirical findings from this study can now provide the basis for policy implications, as they should provide insights enabling policymakers to develop increased cooperation between developed and developing economies.

The aim of this paper is to introduce a new perspective to the carbon emissions convergence literature. Accordingly, the next section thoroughly investigates the related literature, the third section derives the carbon emissions convergence by augmenting the neoclassical Solow growth model with the Jevons paradox hypothesis. The fourth section empirically tests if such a convergence existed among the Annex I countries between 1960 and 2014. The last section summarizes conclusions and suggest avenues for further research.

2.1. Literature Review

Convergence of carbon emission studies began to dominate the environmental economics literature after the relationship between economic development and carbon emissions was recognized. This body of literature has become highly popular in both the empirical and policy areas, although a consensus has not yet been reached (Jobert et al., 2010; Payne, 2010). The literature contains mixed results with respect to global levels and particular regions or countries because empirical results are extremely sensitive to the methodology applied and the type of data used.

The principles of carbon emission convergence are based on the assumption of the so-called environmental Kuznets curve hypothesis.[7] Since carbon emissions are a byproduct of fossil fuel consumption, carbon contamination can be reduced through abatement policies, and the inverted U-shaped relationship between income and carbon emissions can be built into the model of the environmental Kuznets curve hypothesis. Domestic and international policies, increasing returns to scale in abatement applications, or exogenous technological change can provide a basis for this relationship. In the long run, exogenous technological change-driven income growth reaches a threshold that forces carbon emissions to decline, a state that then apparently triggers absolute (unconditional) convergence of carbon emissions over the long run. In the short run, however,

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[7] The environmental Kuznets curve is another popular subject of this body of literature. Chapter 4 provides more detailed information about the environmental Kuznets curve hypothesis.

individual countries converge to their individual balanced income and carbon emissions paths. Economies with lower incomes therefore have positive carbon emissions growth rates whereas economies with higher incomes exhibit negative carbon emissions growth rates (Bulte et al., 2007). Income differences between countries determines whether these economies converge or diverge: Smaller differences between income levels lead emissions to converge whereas larger differences lead emissions to diverge.

Different convergence measures have emerged over time; among them, β-convergence, σ-convergence, and stochastic convergence are the most commonly implemented ones in examining per capita carbon emissions. σ-convergence measures the distribution properties of carbon emissions across regions, groups, or countries over time by examining the standard deviation of per capita carbon emissions. If the standard deviation of per capita carbon emissions decreases over time among a group of countries, the absence of convergence that has been accepted since an external shock occurred generates permanent difference in individual countries. Stochastic convergence examines the time series properties of dataset. Basically, shocks to mean carbon emissions are temporary, and thus the series of carbon emissions are stationary. However, the presence of a unit root in per capita carbon emissions indicates that the effect of a shock is permanent, and so the economy is not converging over time. β-convergence of per capita carbon emission measures the ability of an economy having relatively low initial levels of per capita emissions to grow faster than developed economies and so create a catch-up effect with respect to economies that are relatively higher polluters. In order to reveal conspicuous results and to check for robustness, most studies prefer to apply more than one of these methodologies and often come up with contradictory results. However, β-convergence still has widespread acceptance among researchers because it is a necessary but not a sufficient condition for σ-convergence and provides evidence for structural components of growth models. However, evidence is lacking for σ-convergence (Islam, 1995).

Even though the literature include studies that have examined different pollutants such as sulfur dioxide and nitrogen oxides (Bulte et al., 2007; Lee and List, 2004; List, 1999; Ordas Criado et al., 2011) Strazicich and List (2003) was the first study to examine β-convergence for carbon emissions. Panel unit root tests for stochastic convergence and cross-sectional regression analyses for conditional convergence identified evidence of absolute and conditional convergence for 21 OECD countries over the time period 1960-1997. In this study, countries were assumed to be independent and cross-section dependency was ignored and it is found that only gasoline prices contributes to carbon emissions convergence. Considering cross-sectional dependency and a common factor, Westerlund and Basher (2008) provide strong evidence of carbon emissions convergence for 16 developed countries for the 1901-2002 period and for 28 developed and developing countries between 1870 and 2002. In Bai and Ng (2004), Phillips and Sul (2003), and Moon and Perron (2004), panel unit root tests were used to determine if the panel or individuals displayed unit root.

Romero-Avila (2008) also examined stochastic convergence for 23 OECD countries over the time period 1960-2002 employing different panel unit root tests. According to the study, ignoring structural breaks and cross-section dependency leads to divergence, but, if both of these are not ignored, then convergence occurs. This reveals the importance of structural breaks and cross-sectional dependencies, since dynamic behavior of per capita carbon emission series are highly sensitive to such possibilities. In this sense, the results of Chang and Lee (2008) and of Lee and Chang (2008; 2009) support those of Romero-Avila (2008). Chang and Lee (2008) identified convergence behavior of relative per capita carbon emissions for 21 OECD countries over 1960-2000 using Lagrange multiplier tests with endogenous structural breaks. A significant result is that structural breaks occur around energy crisis times in 1970s and in the early 1990s. Additionally, Lagrange multiplier tests with no structural breaks show a divergence tendency for carbon emissions per capita. Lee and Chang (2008) used the same dataset (21 OECD countries, 1960-2000) to examine relative per capita carbon emissions with a different unit root test: the SUR-ADF test results revealed that 14 out of 21 OECD countries exhibited divergence and only seven out of 21 converge to an average. Also, allowing for structural breaks and cross-sectional dependencies, Lee and Chang (2009) report evidence of convergence of relative carbon emissions per capita for 21 OECD countries between 1950 and 2002. In contrast, Barassi et al. (2008) indicate that per capita carbon emissions did not converge among 21 OECD countries between 1950 and 2002, according to stationarity and unit root tests and allowing for cross-sectional dependency.

Aldy (2006) is one of the most remarkable studies in the σ-convergence literature. Numerous percentiles in emissions distributions are estimated and statistically tested to determine whether dispersion of a particular interpercentile range differs over time. Cross-sectional distribution techniques were conducted for 23 OECD countries and a global sample covering 88 countries between 1960 and 2000. The results reveal that the global sample shows evidence of divergence while the per capita carbon emissions of the OECD sample converges. The study also projects that divergence will continue over the next 50 years but that, after 10 decades, carbon emissions per capita could converge.

Nguyen Van (2005) also provides a comprehensive analyses of σ-convergence using Epanechnikov kernels and β-convergence using cross-sectional and panel data analyses. For a global sample of 100 countries including 26 industrial economies between 1966 and 1996, cross-sectional regression analysis was employed and provided evidence of convergence whereas panel data regressions provided no evidence of convergence. The results of this nonparametric approach were uncertain. Countries exhibiting high initial emissions tend to decrease emissions over time, whereas countries exhibiting relatively low initial emissions continue to be relatively low-emission countries. For industrial countries, the nonparametric approach provided evidence of convergence.

Jobert et al. (2010) examined per capita carbon emissions convergence for 22 European countries over the time period 1971-2006 using the Bayesian shrinkage estimation method. The findings supported absolute and conditional per capita carbon emissions convergence even though the speed of convergence was shown to differ among countries.

McKibbin and Stegman (2005) included emissions intensity of energy supply in their convergence analysis. Distributional analyses are conducted for 26 OECD countries over the time period 1900-1999 and for a global sample of 97 countries between 1950 and 1999, and results identified little evidence of convergence among the global sample whereas the OECD sample exhibited convergence in per capita emissions.

Examining a global sample of 128 countries between 1960 and 2003 for club convergence, Panopoulou and Pantelidis (2009) divided per capita emissions into a common factor and idiosyncratic components. In their analysis, the global sample showed a divergence tendency, with 91 countries converging more slowly than 37 countries. Ezcurra (2007) also examined 87 countries between 1960 and 1999. Employing nonparametric analysis with Gaussian adaptive kernels, Ezcurra (2007) showed that convergence occurs in industrial economics and in intensely-polluting economies. Li and Lin (2013) divided a global sample of 110 countries into groups among income levels for the period of 1971-2008. Subsamples by income showed convergence in per capita carbon emissions while the global sample showed little evidence of convergence.

It should be underlined that the studies above lacked theoretical modelling, and their findings were therefore based on employing empirical methodologies. Few studies in the literature provides comprehensive theoretical modelling and empirical evidence. The findings Brock and Taylor (2010) report are similar to those of this study, but their main purpose was to provide derivations for the existence of EKC. Brock and Taylor (2010) proposed a Green Solow model and derived the convergence equation in per capita carbon emissions. The model predictions hold when either emissions diminish and the EKC pattern exists and growth is unsustainable and the EKC pattern does not exist. The predictions of this model hold when emissions diminish and demonstrate the EKC pattern and when growth is unsustainable without any EKC pattern. β-convergence was examined for five different panels for the time period 1960 and 1998, and 173 countries showed evidence of absolute convergence. Lack of data availability forces authors to reduce which conditional convergence occurred. Further differences in datasets—i.e., eliminating OPEC countries, the fact that there were less than 1 million populated countries in 1960, and having no ratings on Penn World tables—did not significantly impact results: conditional convergence still held in these cases.

Ordas Criado, Valente and Stengos (2011) also examined the dynamic relationship between pollution growth, emission levels, and output growth rates that generate pollution. Based on the neoclassical growth model with endogenous pollution abatement, pollution is assumed as a byproduct of the production process, which is also a byproduct of energy consumption. The Ramsey-Cass-Koopmans growth model with endogenous emissions reduction reveals that pollution growth rates have a negative relationship with emission levels but have a positive relationship with output growth. This dynamic relationship was interpreted as β-convergence and per capita sulfur dioxide and nitrogen oxide levels were tested for 25 European countries over the period 1980-2005. Semiparametric and nonparametric methods and linear regression estimates identified the convergence behavior.

In the theoretical literature examining economic growth and pollution dynamics, Keeler et al. (1971), Bovenberg and Smulders (1996), and Van der Ploeg and Withagen (1991) present a positive relationship between output level and pollution. The derived pollution functions of Ordas

Criado et al. (2011) revealed emissions to be a byproduct of a production process. The interpretation of their findings is that, as investment in clean energy technologies increases over time, emissions per output decrease, and so economic growth promotes environment standards. Following the procedure for convergence equation of Mankiw, Romer, and Weil (1992), Brock and Taylor (2010) claim that, if investment in clean technologies is adequately high, then emissions would tend to converge to a steady state. However, technological progress with respect to emission intensity should at least equal the technological progress of the production process.[8] If the opposite holds, emissions per capita cannot diminish.

The literature displays a tendency of divergence in global samples but of convergence in developed economies, especially in OECD sample. Fossil fuel sources are not equally located across the world, and the transportation costs of transporting fossil fuels can account for the evidence of β-convergence (Patterson et al., 2014). Regarding cross-sectional dependencies and structural breaks in stochastic convergence, it is obvious that having similar idiosyncratic characteristics plays a significant role in determining convergence.

As Criado and Grether (2011) suggest, allowing for structural breaks and cross-sectional dependencies in the tendency to stochastically converge is more accurate, especially in OECD panels. Distributional analysis also demonstrates the same trends in stochastic convergence. Significant evidence of convergence occurs in developed countries, primarily in OECD ones, but there are persistent gaps in developing countries.

2.2. Theoretical Model: Augmenting Carbon Emissions into the Solow Growth Model

One of the main outcomes of the Solow growth model is that, under the decreasing returns to scale assumption, income per capita would converge to its long run as long as the parameters that determine the long-run values do not change. As shown in this paper, an augmented Solow model is developed, and it shows that carbon emissions converge to their long-run values as Solow (1956) proposed for income. Assume a standard Solow model with a fixed savings rate, s. Savings

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[8] Introducing Jevons paradox into the Solow growth model, in this paper, explicitly assumes that technological progress in clean energy technologies is as high as the improvements in technological progress of production process and abatement efforts in pollution reduction cannot be achieved when assuming otherwise.

generates capital accumulation that depreciates at the rate of δ. A Cobb-Douglas production function with exogenous technological progress then implies the following:

$$\dot{K}_t = s \cdot K_t^{\alpha} \cdot (A_t \cdot L_t)^{1-\alpha} - \delta \cdot K_t \tag{2.1}$$

where K_t equals physical capital, L_t is labor, and A_t is labor-augmented technology level. If equation (2.1) is expressed as the per capita effective labor force, $\tilde{k}_t = \frac{K_t}{A_t \cdot L_t}$, and the growth model can be written as the following:

$$\dot{\tilde{k}}_t = s \cdot \tilde{k}_t^{\alpha} - (n + \delta + x) \cdot \tilde{k}_t \tag{2.2}$$

In this equation $\tilde{y}_t = \tilde{k}_t^{\alpha}$. Defining $\hat{\tilde{y}}_t = \frac{\dot{\tilde{y}}_t}{\tilde{y}_t}$ and $\hat{\tilde{k}}_t = \frac{\dot{\tilde{k}}_t}{\tilde{k}_t}$, the log differentiated form of the production function yields $\hat{\tilde{y}}_t = \alpha \cdot \hat{\tilde{k}}_t$. Hence, equation (2.2) can be expressed in $\tilde{y}_t$as follows:

$$\frac{\dot{\tilde{y}}_t}{\tilde{y}_t} = \alpha \cdot \left[s \cdot \tilde{y}_t^{\frac{\alpha-1}{\alpha}} - (n + \delta + x) \right] \tag{2.3}$$

The Jevons paradox argues that the rate of consumption of a resource rises because of increasing demand and falls with technological progress, which increases the efficiency with which a resource is used. Hence, this study formulates the paradox in the following form:

$$c_t = \gamma \cdot y_t \,.\, e^{-xt} \tag{2.4}$$

In (2.4), c_t is energy consumption per capita; y_t is income per capita, reflecting overall demand; and x is the rate of technological change. γ in the equation measures the degree of the Jevons paradox. Equation (2.4) implies that energy consumption per capita is positively associated with income per capita and negatively associated with the rate of technological change. Hence, equation (2.3)[9] can be expressed as follows:

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[9] Pioneered by Copeland and Taylor (1994), Stokey (1998), Aghion and Hewitt (1998), and others, the Ω amount of pollution is assumed to accompany the consumption goods as a result of constant returns to scale in the technology-augmented production. In this study, it is also assumed that there is a fixed relationship ratio between energy consumption and carbon emissions. In the theoretical derivations to achieve algebraic simplicity, this relationship is assumed to be one-to-one. Assuming a non-unitary coefficient would not change the theoretical derivations since first-order conditions reduce the related parameter.

$$\frac{dLn[c_t]}{dt} = \alpha \cdot \left[s \cdot e^{\left(\frac{\alpha-1}{\alpha}\right)(Ln[c_t]-Ln[\gamma])} - (n+\delta+x)\right] \equiv \phi(Ln[c_t]) \tag{2.5}$$

The most common method for solving equation (2.5) is log-linearization, in which a Taylor series approximation is used. After substituting this equation with Taylor series expansion and following the standard procedure, one ends up with the following:

$$\frac{dLn[c_t]}{dt} \approx -(1-\alpha) \cdot (n+\delta+x)\big[Ln[c_t] - Ln[c_{ss}]\big] \tag{2.6}$$

Define $\nu = (1-\alpha)(n+\delta+x)$ in (2.6), and, for simplicity, rewrite equation (2.6) as the following:

$$\dot{z}_t = -\nu \cdot z_t + b \tag{2.7}$$

where $z_t = Ln[c_t]$ and $b = \nu \cdot Ln[c_{ss}]$. Multipling both sides with $e^{\nu \cdot t}$:

$$\dot{z}_t = -\nu \cdot z_t + b$$

$$\dot{z}_t \cdot e^{\nu \cdot t} + \nu \cdot z_t \cdot e^{\nu \cdot t} = b \ \cdot e^{\nu \cdot t}$$

$$\frac{d}{dt}[z_t \cdot e^{\nu \cdot t}] = b \cdot e^{\nu \cdot t} \Rightarrow$$

$$\int d[z_t \cdot e^{\nu \cdot t}] = \int b \cdot e^{\nu \cdot t} \cdot dt \Rightarrow$$

$$z_t \cdot e^{\nu \cdot t} = \frac{b}{\nu} \cdot e^{\nu \cdot t} + const \Rightarrow$$

$$z_t = \frac{b}{\nu} + const \cdot e^{-\nu \cdot t} \Rightarrow$$

$$Ln[c_t] = \frac{\nu \cdot Ln[c_{ss}]}{\nu} + const \cdot e^{-\nu \cdot t} \Rightarrow$$

$$Ln[c_t] = Ln[c_{ss}] + const \cdot e^{-\nu \cdot t} \tag{2.8}$$

Following Islam (1995), assume the initial time is $t = t_1$. In this case,:

$$Ln\left[c_{t_1}\right] = Ln[c_{ss}] + const \cdot e^{-\nu \cdot t_1} \Rightarrow cnst = \left\{Ln\left[c_{t_1}\right] - Ln[c_{ss}]\right\} \cdot e^{\nu \cdot t_1} \tag{2.9}$$

For $t_2 > t_1$ and $\tau = t_2 - t_1$,

$$Ln[c_{t_2}] = Ln[c_{ss}] + const \cdot e^{-\nu \cdot t_2} \Rightarrow$$

$$Ln[c_{t_2}] = Ln[c_{ss}] + \{Ln[c_{t_1}] - Ln[c_{ss}]\} \cdot e^{\nu \cdot t_1} \cdot e^{-\nu \cdot t_2} \Rightarrow$$

$$Ln[c_{t_2}] = (1 - e^{-\nu \cdot \tau}) Ln[c_{ss}] + Ln[c_{t_1}] \cdot e^{-\nu \cdot \tau} \tag{2.10}$$

Subtracting $Ln[c_{t_1}]$ from both sides:

$$Ln[c_{t_2}] - Ln[c_{t_1}] = (1 - e^{-\nu \cdot \tau}) Ln[c_{ss}] - (1 - e^{-\nu \cdot \tau}) Ln[c_{t_1}] \tag{2.11}$$

Lastly, substituting c_{ss} into equation (2.11) yields:

$$\begin{aligned} Ln[c_{t_2}] - Ln[c_{t_1}] & \\ &= -(1 - e^{-\nu \cdot \tau}) Ln[c_{t_1}] + (1 - e^{-\nu \cdot \tau}) \frac{\alpha}{1-\alpha} Ln[s] \\ &\quad - (1 - e^{-\nu \cdot \tau}) \frac{\alpha}{1-\alpha} Ln[n + \delta + x] + (1 - e^{-\nu \cdot \tau}) Ln[\gamma] \end{aligned} \tag{2.12}$$

Alternatively,

$$\begin{aligned} Ln[c_{t_2}] &= e^{-\nu \cdot \tau} Ln[c_{t_1}] + (1 - e^{-\nu \cdot \tau}) \frac{\alpha}{1-\alpha} Ln[s] \\ &\quad - (1 - e^{-\nu \cdot \tau}) \frac{\alpha}{1-\alpha} Ln[n + \delta + x] + (1 - e^{-\nu \cdot \tau}) Ln[\gamma] \end{aligned} \tag{2.13}$$

Equation (2.13) is more viable for panel data analysis (Islam, 1995, Equation 2.12).

2.3. Empirical Analysis

2.3.1 Data

Within the tradition of absolute and conditional convergence, an empirical analysis of carbon emission convergence for 41 Annex I countries[10] except Liechtenstein and Monaco over 1960-

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[10] The Annex I countries are as follows: Australia, Austria, Belarus, Belgium, Bulgaria, Canada, Croatia, Cyprus, Czech Republic, Denmark, Estonia, European Union, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Italy, Japan, Latvia, Liechtenstein, Luxembourg, Malta, Monaco, Netherlands, New Zealand, Norway, Poland, Portugal, Romania, Russian Federation, Slovakia, Slovenia, Spain, Sweden, Switzerland, Turkey, Ukraine, United Kingdom, and United States of America. Canada withdrew from the

2014 was examined. Carbon dioxide emissions (metric tons) per capita, and control variables for conditional convergence, population growth rate (in annual percentage), gross savings (in percentage of GDP), GDP per capita (at constant 2010 US$), energy usage (in kg of oil equivalent) per capita, net energy imports (in percentage of energy use), fossil fuel energy consumption (in percentage of total consumption), alternative and nuclear energy (in percentage of total energy use), an openness variable expressed as total trade in percentage of GDP, net inflows of foreign direct investment (in percentage of GDP), and value-added agricultural growth rate (in annual percentage) were drawn from World Development Indicators (WDI, 2019).

2.3.2 Identification of Time Series Properties of Panel Dataset

The existence of unit root is an indicator that shocks have permanent effects on series, and macroeconomic time series often have means, variances, or covariances that change over time. Hence, highly dependent time series are described as "non-stationary" (Burnett & Madariaga, 2016). Examining series that have unit root processes would end with incorrect results because of a spurious correlation (i.e., a strong relationship between variables not necessarily because of a real causal relationship but rather because of similar time trends).

Im, Pesaran, and Shin (IPS hereafter, 2003) developed a panel unit root test for heterogeneous panels that combines information from both time series and a cross-sectional dimensions and requires $t, N > 25$ test to have power where errors are serially correlated. Moreover, the IPS test is more powerful when rejecting the null hypothesis of the existence of a unit root than ADF and estimation equation targets specific panels through autoregressive parameter for each cross-sectional unit. Therefore, the IPS test is employed to check unit root processes for annual data series of each variable between 1960 and 2015.

The series in the panel has a unit root for all cross sections:

$$\Delta y_{i,t} = \alpha_i + \delta_i t + \beta_i \, y_{i,t-1} + \sum_{j=1}^{p} \rho_{ij} \, \Delta y_{i,t-j} + \varepsilon_{it} \tag{2.14}$$

Kyoto Protocol in December 2012. Liechtenstein and Monaco dropped from the panel due to a significant lack of data.

where the series y_{it} is a panel series such that $t = 1, \dots, T$ and $i = 1, \dots, N$ is the first difference of the variable of interest, α_i is the cross-sectional specific intercept, t is the time trend, p is the number of lags in the ADF regression to reduce serial correlation, and ε_{it} is the error term assumed to be IID (independently identically distributed; 0, σ_i^2) for all i and t. The IPS test relaxes the homogeneity assumption of the lagged dependent variable.

Table 2.1 represents the IPS test results and reveals that, except for gross savings and agriculture growth, the null hypothesis of the existence of the unit root cannot be rejected for the series. Containing the unit root in the series leads the methodology described in this paper to implement non-overlapping time intervals, a commonly accepted practice and a long-term tradition in the growth literature (Bond, Hoeffler, & Temple., 2001; Bonnefond, 2014; Caselli et al., 1996; Islam, 1995).

Table 2.1. Im - Pesaran - Shin Panel Unit Root Test for Annual Country-Level Series, 1960-2014

Variables	t-bar statistics	*p*-value
Carbon emissions per capita (metric tons per capita)	-0.467	0.32
Population growth rate (annual %)	1.803	0.964
Gross savings (% of GDP)	-1.234***	0.108
GDP per capita (constant 2010 US$)	1.114	0.867
Energy use per capita (kg of oil equivalent)	1.425	0.923
Energy imports (%of energy use)	0.454	0.675
Fossil fuel consumption (of total consumption)	2.814	0.997
Alternative & Nuclear energy consumption (%of total energy use)	0.447	0.672
Openness (total trade in percentage of GDP)	-1.125	0.13
Foreign direct investment, net inflows (% of GDP)	-0.187	0.425
Agriculture, value added (annual % growth)	-3.838*	0.0001

Notes: The null hypothesis of the IPS test is that the series contains a unit root. Hence, rejection of the null hypothesis implies that the series is stationary. Both trend and intercept are included for all series. The superscripts *, **, *** represent 1%, 5%, and 10% confidence intervals, respectively.

Following this tradition in the convergence literature along with assuming nonstationary data as in the study described in this paper, five-year time intervals for 11 data points are implemented to avoid short-term shocks to reduce serial correlation and to avoid business cycle fluctuations. The results reveal a long-run relationship between regressors. Hence, the panel data set was adapted to have fewer time periods and relatively large individuals and three panels, allowing us to check the robustness of the coefficients. In parallel with the core assumption of System GMM both three panels are fulfilled $N > T$ condition for 41 countries. Table 2.2 presents descriptive statistics for the series of annual panel data set.

Table 2.2. Descriptive Statistics of Annual Data, 1960-2014

Variables	Observations	Mean	Std. Dev.	Min.	Max.
Carbon emissions per capita (metric tons per capita)	1863	2.004	0.58	-0.49	3.70
GDP per capita (constant 2010 US$)	1780	9.97	0.77	7.43	11.61
Energy use per capita (kg of oil equivalent)	1934	8.06	0.590	5.67	9.81
Energy imports (%of energy use)	1933	35.48	92.94	-843.12	100
Fossil fuel consumption (of total consumption)	1905	80.30	17.53	10.26	100
Alternative & Nuclear energy consumption (%of total energy use)	1933	12.79	15.39	0	89.73
Openness (total trade in percentage of GDP)	1804	77.52	50.66	5.73	391.5

Note: Std. Dev., Min. and Max. denote standard deviation, minimum and maximum, respectively.

2.3.3 Dynamic Panel Data Model

In this paper, a dynamic panel data methodology, System Generalized Method of Moments (system GMM), developed by Arellano and Bover (1995) and Blundell and Bond (1998) is applied in order to determine if carbon emissions converged to a steady state level absolutely and/or conditionally among Annex I countries:

$$Y_{i,t} = \beta \, . \, Y_{i,t-1} + \gamma \, . X_{i,t} + \mu_i + \varphi_t + \varepsilon_{i,t} \tag{2.15}$$

$Y_{i,t}$ is equal to the natural logarithm of carbon emissions per capita over a five-year period and lagged dependent variable $Y_{i,t-1}$ is included in order to test convergence. The coefficient of the lagged dependent variable, β, is the coefficient of previous periods' carbon emissions per capita, which is expected to be between 0 and 1.[11] The control variables, $X_{i,t}$, are also structured as a

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[11] Note that $\beta = 1$ implies that the regressor is persistent over time, and $\beta > 1$ implies divergence.

five-year average period, and the corresponding coefficient, γ, adds the dynamic equation in case of conditional convergence estimation. The vector of control variables consists of GDP per capita, energy use per capita, energy imports, fossil fuel consumption, renewable and alternative energy usage, and openness. μ_i, φ_t, $\varepsilon_{i,t}$ indicate country-specific (fixed) effects, time-specific intercepts, and idiosyncratic shocks across countries i and time periods t, respectively. Time dummies are also included in the regressions in order to strengthen the assumption of no serial correlation across countries in the idiosyncratic disturbances (Roodman, 2009a).

The system GMM method has become prevalent in the growth literature (Bond, Hoeffler, & Temple., 2001; Burnett & Madariaga, 2016; Caselli et al., 1996; Hoeffler, 2002; Islam, 1995). Rather than other estimators, namely panel OLS, within-groups, and the first-differenced GMM, among others, the estimator might have superior finite sample properties in addressing fixed effects, endogeneity of regressors, and dynamic panel bias (Bond, Hoeffler, & Temple, 2001). However, these panel data estimators are conventional in the growth context but can yield biased and inconsistent results. OLS levels produce upwardly biased coefficients with country-specific (fixed) effects that are constant over time (Hsiao, 1986), and within-groups results in highly downwardly biased coefficients in short panels (Judson and Owen, 1999; Nickell, 1981). The reliable and consistent parameters estimated with OLS levels and within-groups can be regarded as lower and upper bounds, respectively (Blundell & Bond, 1998).

The first-differenced GMM developed by Arellano and Bond (1991) has significant advantages over panel OLS and within-groups, since (i) taking first differences eliminates unobserved, country-specific effects and removes omitted variable bias and (ii) using instruments allows consistent estimation in models that, in particular, have endogenous right-hand side variables. Still, the first-differenced GMM estimates suffer from large finite sample bias when time series observations are not long enough. Hence, lagged levels of variables are weak instruments for first-differenced equations because the autoregressive coefficient approaches unity or the variance of individual effects increases, depending on the variance of the transient shocks (Bond, Hoeffler, & Temple, 2001)

Therefore, in order to avoid these drawbacks of conventional dynamic panel data estimators, the system GMM suggested by Arellano and Bover (1995) and Blundell and Bond (1998) was employed. The System GMM provides consistent and efficient parameter estimates in the presence of heteroscedasticity and autocorrelation within individuals and where independent variables are not strictly exogenous (i.e., they may be correlated with the past and current realizations of error (Roodman, 2009a). Moreover, instrumenting lagged dependent variable and/or other endogenous variables that are assumed to not be correlated with fixed effects overcomes the endogeneity issue within the estimator.

The core of the first-differenced GMM is transforming all variables in the dynamic panel data model into first differences to reduce fixed effects and, under the assumption of no serial correlation in the time-varying disturbances in the original levels equations, instrument the right-hand side variables with levels of the variables lagged a minimum of two periods or more. The system GMM is more efficient than the first-differenced GMM, but the latter has the additional assumptions that there is no correlation between the first-differenced instrumental variables and that the fixed effects result in the inclusion of more instruments in the system and so improve efficiency (Roodman, 2009a). Thus, the system GMM combines first-differenced equations with proper lagged levels as instruments with an additional set of level equations with proper lagged first-differences acting as instruments.

In addition, Blundell and Bond (1998) emphasize that finite samples may also produce downwardly biased estimation coefficients. To overcome this possible bias, Windmeijer (2005) suggests a finite sample correction for the variance-covariance matrix.

The consistency of the system GMM's results depends on four key conditions. First, the instrumental variable set must be valid as these variables are not correlated with the error term. This hypothesis can be tested by using the Hansen (1982) J test that over-identifies restrictions under the null hypothesis that the error terms are uncorrelated with the instruments. Secondly, the residuals should be verified as not containing second-order serial correlation (AR2), although there may be negative first-order autocorrelation (AR1). The Arellano-Bond (1991) test is under the null hypothesis of no autocorrelation AR1 and AR2 in the residuals and is used to verify this condition. Thirdly, the additional moment restrictions proposed by Blundell and Bond (1998) must be valid. The difference-in-Hansen test under the null hypothesis of validity of additional moment conditions was used to test the validity of additional moment conditions. Lastly, the number of the instruments must be smaller than or equal to the number of groups in order to avoid overfitting (Roodman, 2009b).

The system GMM estimator was designed for relatively large cross-sections and small time dimensions (Blundell and Bond, 1998, 2000, 2001; Roodman, 2009a) and is suggested estimator due to its efficiency that provides more reasonable results in the empirical growth models (Bond, Hoeffler, & Temple, 2001; Roodman, 2009b). Hence, this study employs system GMM estimator with Windmeijer correction method for the variance-covariance matrix[12] in order to estimate growth equation.

2.3.4 Findings

Prior to presenting the empirical results, the cross-sectional data analysis in which the following estimation regression is given in the literature is examined:

$$eg_i = \alpha + \beta \cdot e_{0i} + \varepsilon_i \qquad (2.16)$$

where eg_i is the average growth rate of per capita carbon emissions and e_{0i} is the log of the initial per capita carbon emissions, i.e. carbon emissions in 1960 in this study. However, a graphical illustration of the data such as that shown in Figure 2.1 displays this pattern for Annex I countries, making an empirical examination redundant.

Figure 2.1 displays the convergence pattern across the Annex I countries. Luxembourg was an outlier. According to the OECD Economic Surveys (2017), it has the highest per capita income among OECD countries. Luxembourg's energy demand is met from fossil fuel imports, making it the most carbon-intensive economy in the OECD, and a significant portion of the carbon emissions are generated from international road transportation activities.

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[12] The "xtabond2" command was used in Stata 12 to obtain these results. The "collapse" command was also used in order to minimize the potential bias that arises from an increase in the number of instruments, which tend to overfit endogenous regressors (Roodman, 2009a).

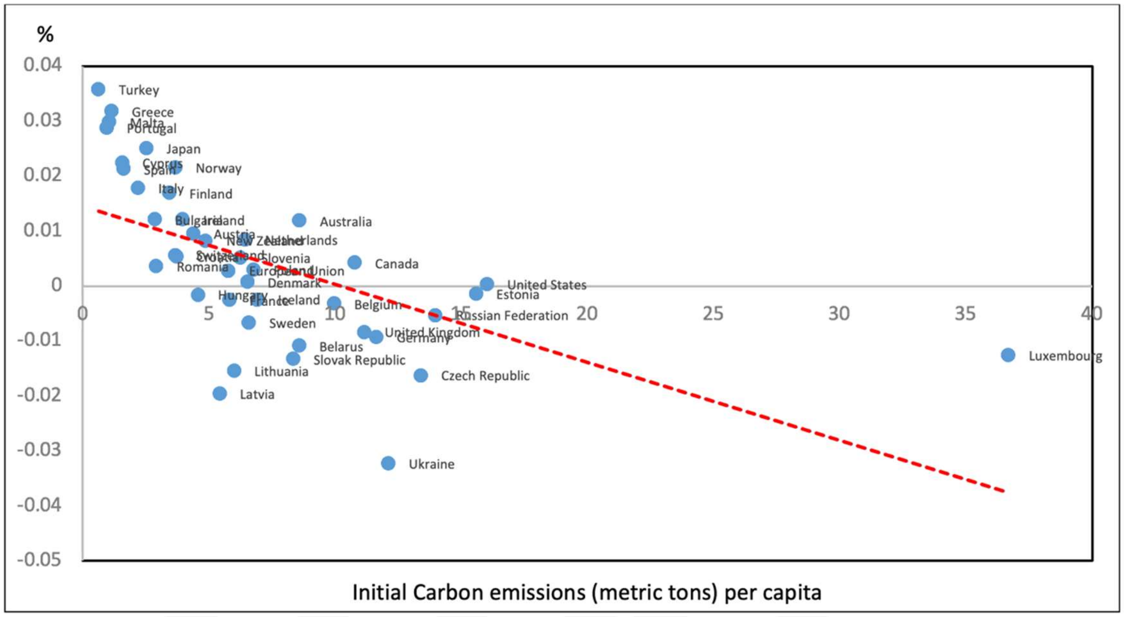

Figure 2.1: Carbon emissions convergence of Annex I countries, 1960-2014.
Data Source: World Development Indicators, Authors' calculations.

Table 2.3 shows the system GMM estimates based on the theoretical derivations. In the system GMM method, a two-step estimator is more efficient than a one-step one. Nevertheless, Monte Carlo simulations showed that the difference in efficiency between the one- and two-step GMMs was small, with the two-step estimator slowly converging to its asymptotic distribution. However, the asymptotic standard errors could have been downwardly biased in finite samples (Blundell and Bond, 1998; Hoeffler, 2002). As a result, the one-step system GMM method was employed. To examine the absolute and conditional β-convergences, the explanatory variables were introduced gradually into the estimation equation. Column (1) displays the absolute convergence results, and column (2) shows the savings rate and population growth rate, which originally came from the textbook model. Then, the GDP per capita, energy consumption per capita, energy imports, fossil fuel consumption, renewable and alternative energy consumption, openness, foreign direct investment, and agriculture growth were introduced progressively, and their coefficients are shown in columns (3) through (10), respectively.

Table 2.3: System GMM Estimations of Carbon Emissions Convergence from a 5-Year Span Panel Data, 1960-2014

Variables & Statistics	Dependent Variable: ln [carbon emissions per capita]									
	1	2	3	4	5	6	7	8	9	10
Lagged dependent variable	0.874*	0.832*	0.648*	0.521*	0.728*	0.663*	0.769*	0.752*	0.714*	0.816*
	(0.042)	0.(061)	(0.088)	(0.131)	(0.131)	(0.076)	(0.038)	(0.075)	(0.067)	(0.06)
Savings Rate	-	0.142**	0.2212***	0.171***	0.235*	0.557*	0.329*	0.245**	0.273*	0.276*
		(0.064)	(0.118)	(0.101)	(0.093)	(0.237)	(0.120)	(0.116)	(0.101)	(0.113)
Population Growth Rate	-	0.167**	-0.973	0.183	0.369	0.12	0.157***	0.273	0.237***	0.134
		(0.066)	(0.714)	(0.156)	(0.252)	(0.273)	(0.094)	(0.171)	(0.131)	(0.09)
GDP per capita	-	-	0.1525*	-	-	-	-	-	-	-
			(0.048)							
Energy Consumption per capita	-	-	-	0.2865***	-	-	-	-	-	-
				(0.164)						
Energy Imports	-	-	-	-	-0.0191	-	-	-	-	-
					(0.033)					
Fossil Fuel Consumption	-	-	-	-	-	0.1443**	-	-	-	-
						(0.069)				
Renewable and Alternative Energy Consumption	-	-	-	-	-	-	-0.0137**	-	-	-
							(0.007)			
Openness	-	-	-	-	-	-	-	-0.0208	-	-
								(0.034)		

FDI	-	-	-	-	-	-	-	-	0.0034 (0.009)	-
Agriculture Growth	-	-	-	-	-	-	-	-	-	0.0189*** (0.010)
Constant	0.175** (0.088)	-0.460* (0.111)	0.015 (0.701)	-2.265** (0.946)	-0.803*** (0.487)	-1.933** (0.787)	-0.87 (0.349)	-0.697** (0.326)	-0.742** (0.334)	-0.729** (0.398)
Implied Convergence Rate	0.027	0.037	0.087	0.131	0.064	0.082	0.052	0.057	0.068	0.041
Number of Groups	41	41	41	41	40	41	41	41	41	33
Number of Instruments	18	26	21	34	30	24	34	27	34	24
AR(1) p-value	0.009	0.019	0.013	0.062	0.024	0.033	0.014	0.012	0.019	0.081
AR(2) p-value	0.796	0.406	0.45	0.586	0.517	0.96	0.297	0.86	0.947	0.264
Hansen test *p*-value	0.255	0.242	0.58	0.46	0.356	0.605	0.315	0.325	0.128	0.509
Difference-in-Hansen test *p-value*	0.107	0.872	0.834	0.831	0.426	0.725	0.478	0.772	0.562	0.816

Notes: Heteroscedasticity-consistent standard errors are in parentheses. Windmeijer (2005) finite sample correction for standard errors is employed. The superscripts *, **, *** represents 1%, 5% and 10% confidence of intervals, respectively.

Failing to reject the null hypothesis that the error term was uncorrelated with the instruments implies that the instrumental variables in the regressions were valid. Negative first-order autocorrelation and no second-order autocorrelation also confirmed the validity of models one through 10. As shown in Table 2.3, the saving rate was positive and statistically significant in all models, while the population growth rate was found to be statistically significant for only three out of nine specifications. The population growth rate coefficient's sign was positive, in contrast to the theoretical expectation of the Burnett and Madariaga (2016) study, which reported the log of the working age population to be statistically insignificant with respect to energy-intensity convergence. Regarding the conditional convergence, the coefficients of energy imports and openness were negative but statistically insignificant, while foreign direct investment was positive but statistically insignificant. In line with theoretical expectations, renewable and alternative energy was found to reduce carbon emissions, contrasting with fossil fuel consumption, which had a positive effect on carbon emissions. On the other hand, overall energy consumption was found to increase emissions. Apparently, although renewable and nuclear energy lowers emissions levels, fossil fuel consumption dominates it in an energy-mix, resulting in higher emissions being generated from fossil fuel use. In parallel with demand, energy consumption was found to increase per capita emissions by 2.8% and fossil fuel consumption per capita increase emissions by 1.4%, while renewable and alternative energy consumption led to a reduction of 0.13% in per capita carbon emissions. Hence, it can be inferred that, in order to reduce carbon emissions levels, priority should be given to declining fossil fuel consumption. Lastly, the growth rate of agriculture growth was also found to increase per capita emissions by 0.18%.

Thus, per capita energy consumption is by far the most salient accelerator in the convergence of per capita carbon emissions. Per capita GDP and fossil fuel consumption appear to be following drivers in per capita carbon emissions convergence. The findings shown in column (3) of Table 2.3 show that per capita income has positive relationship with per capita carbon emissions, implying a 10% increase in per capita income leading to a 1.5% increase in carbon emissions. Using the LSDV estimator, Brock and Taylor (2010) estimated that the share of GDP to be around 0.7%, a greater percentage than the projected coefficients given in the literature. However, implementing a dynamic panel data approach led to the estimated coefficient of capital to decrease as expected (Islam, 2003).

The consensus over average income convergence is around 2% (Barro & Sala-I Martin, 2004: Mankiw Rome, & Weil, 1992). The implied convergence rates of absolute carbon emissions convergence as shown in columns (1) and (2) of Table 2.3 are in the accordance with generally accepted income convergence rates shown in the literature. Hence, strong empirical evidence suggests the existence of carbon emissions convergence for Annex I countries for the period of 1960 and 2014. The inclusion of control variables in the augmented model increased the strength of the convergence evidence. As an economy conditionally approaches a balanced carbon emissions path, the implied rate of convergence increases to 4%-13% per period.

Lastly, control variables such as FDI and openness were found to be statistically insignificant and to have negative coefficients, indicating that the financial development of an economy is not an indicator in targeting mitigation of per capita carbon emissions.

2.4. Concluding Remarks and Policy Implications

Brock and Taylor (2010) argue that carbon emissions convergence implies the existence of the environmental Kuznets curve. Despite the rapidly growing amount of literature dedicated to the topic, a consensus cannot be agreed upon with respect to both the EKC and the carbon emissions literature, since most studies are based on empirical methodologies rather than theoretical derivations. In the end, the results vary over a very large spectrum, depending upon the empirical approach adopted and the country set employed. The aim of this paper was to develop a simple extension of the neoclassical growth model for carbon emissions convergence augmented with the Jevons paradox hypothesis which claim that energy efficiency gains increase energy consumption. The time paths of per capita carbon emissions were examined for absolute convergence and conditional convergence. In parallel with Brock and Taylor (2010), the theoretical background is based on the neoclassical Solow growth model. However, this paper approaches the per capita carbon emissions convergence equation from a simpler perspective. In this regard, the neoclassical growth model was extended by the Jevons paradox hypothesis in order to consider the energy consumption equation, which is itself a function of per capita income and rate of technological progress.

The results shown in this paper appear to show that carbon emissions converged in Annex I countries for the sample period. Hence, reduced-carbon-concentration policies must have worked in these countries during that time period, at least to a certain extent, and should be encouraged to obtain further improvements in environmental quality. According to Romero-Avila (2008), high carbon-emitting developing economies, such as China and India, can be persuaded to stabilize and reduce emissions levels so as to exhibit a convergence pattern of carbon emissions. However, an IPCC timeline shows that these countries are far from achieving this target. Due to the national resources these countries have at their disposal, prioritization has employed domestic resources and then invested in clean energy technologies. If carbon-intensive economies (i.e., developing economies) agree to reduce emission levels, they tend to reach equilibrium faster than do developed-economies because they are further from equilibrium than the developed economies. Therefore, while the evidence of convergence is inevitable, the convergence rate would be achieved more quickly if carbon-intensive economies agreed to begin reducing emissions levels.

The environmental literature reveals the relationship between energy consumption, economic growth, and environmental degradation. Thus, the crucial importance of carbon emission convergence should be a crucial factor in the implementation of preservative policies through international agreements. In order to sustain positive economic growth in the long run, stabilizing emissions levels are a prerequisite. However, policy instruments should both maximize carbon-emission goals and minimize the costs arising from degradation policies.

According to the results reported herein, in order to lower per capita carbon emissions and simultaneously maintain positive economic growth, renewable energy consumption should definitely be increased. However, priority must be given to reducing fossil fuel consumption so as to decrease carbon intensity. Long-run per-capita carbon-emission convergence results imply that renewable portfolio standards are a must for economies in order for them to avoid short-term shocks that might adversely affect long-run results while implementing environmental-protection policies.

Given a group of developed and developing countries, switching economic activities to cleaner production process makes sense to with technological progress in abatement and lower carbon-based energy consumption. Rühl et al. (2012) indicate that developed economies exhibit declining per capita energy consumption. However, in the course of industrialization and urbanization, demands for developing countries to achieve lower rates of per capita carbon emissions would most likely remain unanswered, as energy consumption plays a major role in their economic development. Depending on the nature of the convergence theory, per capita income in developed economies has a minor effect on reducing per capita carbon emissions, while the inclusion of developing economies in protectionist movements would provide a major impact on their reducing emissions. Furthermore, developed countries have achieved the end of their urbanization process as a result of heavy carbon-based energy resource usage. Thus, these countries should assume an equal share in the burden of reducing per capita carbon emissions with developing countries through technology transfers and funding projects targeting improvements in environmental quality.

Lastly, the convergence assumption is assumed to be the basis for long-term carbon emission projections (Westerlund & Basher, 2008). As shown, this study, which augments the neoclassical convergence assumption with the Jevons paradox hypothesis, has shown that policymakers should explore projected future carbon emissions in order to bridge economies at differing developmental stages.

CHAPTER 3 : ENERGY INTENSITY CONVERGENCE: THEORY AND EVIDENCE

Increasing energy efficiency has become one of the criteria in judging policy makers' success, especially after the 1970s' oil price hikes. Policy makers' answer was audacious: several new tools and measures are developed to decrease production energy intensity. Samuelson (2014) employed this response to impart a warning: "Energy intensity improvement is happening surprisingly quickly, but not quickly enough to meet the world's energy challenges." This paper's aim is not to study the ideal described by Samuelson but rather to describe the improvements that be made: Can we make a conclusive judgment with respect to the improvement in energy intensity across the OECD countries? The paper presents a heuristic approach and answers the question by adapting an old technique, the income convergence approach. However, studying energy intensity by using the convergence argument is not as easy as it might seem, as Figure 3.1 shows.

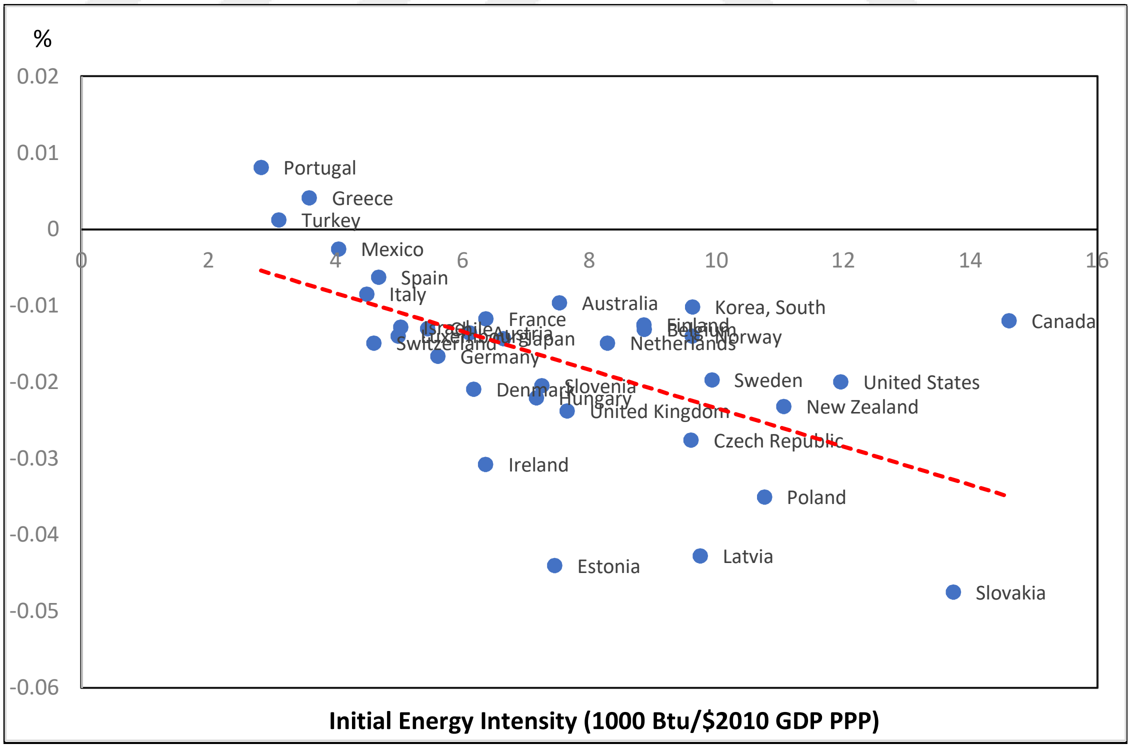

Figure 3.1: Energy intensity convergence of OECD countries, 1980-2015.
Data Source: Energy Information Administration, Authors' calculations.

Examining Figure 3.1 reveals two things. First, the (average) growth rate of energy intensity was negative for most countries during the 1980-2015 time period, that is, energy efficiency was increasing. Second, the direction of change appears to be from east to west. Both of these stylized facts contradict the stylized facts of income convergence where the average growth rate is positive, and the convergence is from west to east. On the other hand, using the income convergence as a starting point in deriving the energy intensity convergence equation is quite meaningful, because energy intensity is simply the energy per unit of output. Therefore, income dynamics must play a significant role in energy intensity dynamics. Although a study similar to this paper was not available in the literature, several studies examine energy intensity and its convergence.

Specifically, there is a handful number of studies on energy intensity convergence in the literature. One strand of research in this area utilizes the so-called stochastic convergence approach, which is based on the time series properties of energy intensity and which relies on unit root tests to determine convergence. This approach considers if the log difference of the energy intensity series and the sample average do not contain the unit root or display a deterministic trend. For example, Bulut and Durusu-Ciftci (2018) examined 27 OECD countries over 1980-2014 with both the standard unit root test of Dickey-Fuller (1981) and three different unit root tests that allow structural breaks (Enders & Lee, 2012; Narayan & Popp, 2010; Zivot & Andrews, 1992). The results show that allowing no structural break or allowing one or two structural breaks yields totally different findings, depending on the backgrounds of the methodologies. Another example is Le Pen and Sevi (2010), who tested the energy intensity series of 97 countries between 1971 and 2003 using the pairwise unit root test of Pesaran (2007). While convergence among some subgroups, i.e., the Middle East, OECD, and Europe, is founded, global convergence is rejected. The study of Le Pen and Sevi (2010) allows one structural break, which does not lead to a remarkable difference in results, thus contradicting those reported by Bulut and Durusu-Ciftci (2018).

The second strand of research considers the spatial distribution of energy intensity and adopts nonparametric approaches proposed by Quah (1993, 1996, & 1997). For example, Ezcurra (2007) reported findings for 98 countries for the period 1971-2001. Expanding Ezcurra's (2007) study, Liddle (2010) investigated energy intensity convergence for 134 countries over the period 1990–2006, both globally and for different country groups classified according to geography and development levels. Liddle (2010) found that, while convergence performances of groups varied, global convergence was. His findings also showed that international trade is a driving force for convergence, thus contradicting the idea that specialization through trade causes divergence. Focusing on the weighed distribution dynamics of energy intensity for 83 countries between 1971 and 2008, Herrerias (2012) also found convergence.

The large number of studies on energy intensity convergence have typically been based on income convergence. For example, Csereklyei et al. (2016) argues that unconditional and conditional energy intensity convergence rates are about 1.4% and 4%, respectively. However, their study neither considered the dynamic relationship between income and energy, and their methodology was acceptable. Markandya et al. (2006), Liddle (2012), Mulder and de Groot (2012), and Csereklyei and Stern (2015) also found energy intensity convergence for different country groups over differing time spans. Kander (2002) pointed out that the reduction in energy intensity and convergence is the outcome of changes in the composition of energy intensity within sectors rather than a structural change. The study of Mulder and de Groot (2012) supported that of Kander (2002).

In this study, we argue that a naïve adaptation of an income convergence hypothesis to energy intensity convergence would not generate the correct insight into the issue of controlling emission levels. Thus, this study differs sharply from those reported in the existing literature. In contrast to most of these, it reports the development of an energy intensity convergence equation by beginning with fundamentals.

The organization of this chapter is as follows. The next section presents the theoretical model and details the derivation of the energy intensity convergence equation. The third section is reserved for empirical analysis, and the last section summarizes this study with concluding remarks and policy implications.

3.1. Theoretical Model

3.1.1 Block I: Income Convergence

Suppose that there was an autarkic economy having no government. In such an economy, gross investment I_t must equal gross saving, S_t. Gross investment is defined as net investment $\dot{K}_t$ plus depreciation $\delta \cdot K_t$, where K_t is physical capital and δ is the depreciation rate. Gross saving is a constant share s of income, Y_t, which must equal production. Finally, we assume that physical capital K_t and technology-augmented labor $A_t \cdot L_t$ define the Cobb-Douglas production function. Hence, the fundamental equation of growth (FEG) at levels is as shown in equation (3.1).

$$\dot{K}_t = s \cdot K_t^{\alpha} \cdot (A_t \cdot L_t)^{1-\alpha} - \delta \cdot K_t \tag{3.1}$$

where $A_t = A_0 \cdot e^{xt}$ is the technology and x is the growth rate of that technology.

Expressing all variables in terms of *effective labor*, that is, $\tilde{k}_t = \frac{K_t}{A_t \cdot L_t}$ and $\tilde{y}_t = \frac{Y_t}{A_t \cdot L_t}$, and second, using $\tilde{y}_t = \tilde{k}_t^{\alpha}$, one can easily obtain the per effective labor version of the FEG:

$$\frac{\dot{\tilde{y}}_t}{\tilde{y}_t} = \alpha \cdot \left[s \cdot \tilde{y}_t^{\frac{\alpha-1}{\alpha}} - (n + \delta + x) \right] \tag{3.2}$$

After log linearization, Equation (3.2) becomes the following:

$$\frac{d \operatorname{Ln}[\tilde{y}_t]}{dt} \approx -(1-\alpha) \cdot (n + \delta + x) \big[Ln[\tilde{y}_t] - Ln[\tilde{y}_{ss}] \big] \tag{3.3}$$

We will assume that $(1-\alpha)(n+\delta+x) = v$. This linearized differential could be directly solved, as done in the literature. However, for our purposes, we need the solution of income per capita, y_t, and not $\tilde{y}_t$. To this end, we first transform eq. (3.3):

$$\frac{d}{dt} \operatorname{Ln}\left[\frac{y_t}{A_0 \cdot e^{xt}}\right] = -v \cdot \operatorname{Ln}\left[\frac{y_t}{A_0 \cdot e^{xt}}\right] + v \cdot \operatorname{Ln}[\tilde{y}_{ss}] \tag{3.4}$$

$$\frac{d}{dt} \operatorname{Ln}[y_t] = -v \cdot \operatorname{Ln}[y_t] + v \cdot \operatorname{Ln}[A_0] + v \cdot xt + v \cdot \operatorname{Ln}[\tilde{y}_{ss}] + x \tag{3.5}$$

Define $z_t \equiv \operatorname{Ln}[y_t]$ and $B = v \cdot (\ln[A_0] + \ln[\tilde{y}_{ss}]) + x$. Hence, equation (3.5) becomes $\dot{z}_t + v \cdot z_t = B + v \cdot xt$. The integrating factor method is employed to solve this linear differential equation. To this end, multiply both sides by e^{vt} and express the left hand side (hereafter, LHS) as total derivative $\frac{d}{dt}(z_t \cdot e^{vt}) = B \cdot e^{vt} + v \cdot xt \cdot e^{vt}$. Integrating both sides yields $z_t \cdot e^{vt} =$

$\frac{B}{v}e^{vt} + x\left[t \cdot e^{vt} - \frac{1}{v}e^{vt}\right] + constant$. Multiplying both sides with e^{-vt} implies $z_t = \frac{B}{v} + x \cdot t - \frac{x}{v} + constant \cdot e^{-v}$. Assume two subsequent times $t_1$and t_2. Then, both of the following must be true for these two times:

$$\ln y_{t_1} = x \cdot t_1 + \frac{B}{v} - \frac{x}{v} + constant \cdot e^{-vt_1} \tag{3.6}$$

$$\ln y_{t_2} = x \cdot t_2 + \frac{B}{v} - \frac{x}{v} + constant \cdot e^{-vt_2} \tag{3.7}$$

We assume $t_2 > t_1$, and therefore observations at t_1 are given. Using this information to eliminate the constant yields

$$\ln y_{t_2} = x \cdot t_2 + e^{-v\tau} \cdot \ln y_{t_1} + (1 - e^{-v\tau})\left[\left(\frac{B}{v} - \frac{x}{v}\right)\right] - e^{-v\tau} \cdot x \cdot t_1 \tag{3.8}$$

where $\tau = t_2 - t_1$..

3.1.2 Block II: Energy-use Convergence

Deriving the energy use convergence equation is necessary to derive the energy intensity convergence equation. Jevons (1856) formulated one relationship between energy use and income. The formulation, known as the Jevons paradox or rebound effect, argues that energy consumption is a function of output and technological progress: $ec_t = \gamma \cdot y_t \cdot e^{-xt}$. Hence, $ec_t = \gamma \cdot \tilde{y}_t$. Then, the FEG in output per effective capita in equation (3.2) can also be written as:[13]

$$\frac{d\ln[ec_t]}{dt} = s \cdot \left(\frac{ec_t}{\gamma}\right)^{\frac{\alpha-1}{\alpha}} - (n + \delta + x) \tag{3.9}$$

$$\frac{dLn[ec_t]}{dt} = \alpha \cdot \left[s \cdot e^{\left(\frac{\alpha-1}{\alpha}\right)(Ln[ec_t]-Ln[\gamma])} - (n + \delta + x)\right] \equiv \phi(Ln[ec_t]) \tag{3.10}$$

Substituting equation (3.10) with Taylor series expansion, the following equation is obtained:

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[13] This formulation was introduced in chapter 2.

$$\frac{dLn[ec_t]}{dt} \approx -(1-\alpha)\cdot(n+\delta+x)\big[Ln[ec_t] - Ln[ec_{ss}]\big] \tag{3.11}$$

Again define $\nu = (1-\alpha)(n+\delta+x)$. Hence, $\dot{z}_t = -\nu \cdot z_t + b$, where $z_t = Ln[ec_t]$and $b = \nu \cdot Ln[ec_{ss}]$. Multipling both sides with $e^{\nu \cdot t}$ and after similar algebraic manipulations, one obtains

$$Ln[ec_t] = Ln[ec_{ss}] + const \cdot e^{-\nu \cdot t} \tag{3.12}$$

Again, assume that the initial time is $t = t_1$. In this case,

$$\big[ec_{t_1}\big] = Ln[ec_{ss}] + const \cdot e^{-\nu \cdot t_1} \Rightarrow$$

$$const = \big\{Ln\big[ec_{t_1}\big] - Ln[ec_{ss}]\big\} \cdot e^{\nu \cdot t_1} \tag{3.13}$$

For $t_2 > t_1$ and $= t_2 - t_1$, one obtains equation (3.14):

$$Ln\big[ec_{t_2}\big] = (1 - e^{-\nu \cdot \tau})Ln[ec_{ss}] + Ln\big[ec_{t_1}\big] \cdot e^{-\nu \cdot \tau} \tag{3.14}$$

This is the second block of the solution.

3.1.3 Block III: Energy-intensity Convergence

Energy intensity is defined as $ei_t = \frac{ec_t}{y_t}$. Using the Jevons paradox, it is easy to see that $ei_t = \frac{\gamma \cdot y_t \cdot e^{-xt}}{y_t} = \gamma \cdot e^{-xt}$. Hence, in theory, energy intensity must be declining, and its dynamics are limited by thermodynamics. But the right hand side (hereafter, RHS) is not very informative. In order to understand energy intensity dynamics, therefore, instead of using the RHS, we will use the LHS and, in particular, its approximation. Note that $ei_t = \frac{ec_t}{y_t}$ implies that $\ln ei_t = \ln ec_t - \ln y_t$. Hence, using block 1 and block 2 yield the following:

$$\begin{aligned} Ln\big[ec_{t_2}\big] - \mathrm{Ln}\big[y_{t_2}\big] &= (1 - e^{-\nu \cdot \tau})Ln[ec_{ss}] + Ln\big[ec_{t_1}\big] \cdot e^{-\nu \cdot \tau} - x \cdot t_2 - e^{-\nu\tau} \\ &\quad \cdot \mathrm{Ln}\big[y_{t_1}\big] - (1 - e^{-\nu\tau})\left(\frac{B}{\nu} - \frac{x}{\nu}\right) + e^{-\nu\tau} \cdot x \cdot t_1 \end{aligned} \tag{3.15}$$

$$\begin{aligned} Ln\big[ei_{t_2}\big] = (1 - e^{-\nu \cdot \tau})Ln[ec_{ss}] + e^{-\nu \cdot \tau}Ln\big[ei_{t_1}\big] - xt_2 - (1 - e^{-\nu\tau})\left(\frac{B}{\nu} - \frac{x}{\nu}\right) \\ + e^{-\nu\tau} \cdot xt_1 \end{aligned} \tag{3.16}$$

$$\begin{aligned} Ln\left[ei_{t_2}\right] = (1 - e^{-\nu\cdot\tau})\{Ln[ec_{ss}] - \ln \tilde{y}_{ss}\} + e^{-\nu\cdot\tau} \cdot Ln\left[ei_{t_1}\right] - xt_2 \\ - (1 - e^{-\nu\tau})[lnA_0] + e^{-\nu\tau} \cdot xt_1 \end{aligned} \tag{3.17}$$

Given that $ec_{ss} = \gamma \cdot \tilde{y}_{ss}$,

$$\begin{aligned} Ln\left[ei_{t_2}\right] = (1 - e^{-\nu\cdot\tau})Ln[\gamma] + e^{-\nu\cdot\tau} \cdot Ln\left[ei_{t_1}\right] - xt_2 - (1 - e^{-\nu\tau})[lnA_0] + e^{-\nu\tau} \\ \cdot xt_1 \end{aligned} \tag{3.18}$$

$$\begin{aligned} Ln\left[ei_{t_2}\right] = (1 - e^{-\nu\cdot\tau})Ln[\gamma] + e^{-\nu\cdot\tau} \cdot Ln\left[ei_{t_1}\right] - x\tau - (1 - e^{-\nu\tau})[lnA_0] - (1 \\ - e^{-\nu}\ ) \cdot xt_1 \end{aligned} \tag{3.19}$$

Equation (3.19) could also be written as equation (3.20):

$$Ln\left[ei_{t_2}\right] = \beta_0 + \beta_1 Ln\left[ei_{t_1}\right] - \beta_2\tau \tag{3.20}$$

where, $\beta_0 = (1 - e^{-\nu\cdot\tau})Ln[\gamma] - (1 - e^{-\nu}\ )[lnA_0] - (1 - e^{-\nu\tau}) \cdot xt_1$.

As suggested by Islam (1995), the energy intensity convergence equation in dynamic form was derived [Equation (3.19)], and this dynamic equation shows that the growth of energy intensity is based on the initial level of energy intensity and on the time trend. Since it is theoretically proven that energy intensity must decrease over time, the movements towards east to west (energy intensity levels approaching zero) in Figure 3.1 is more conceivable to understand.

3.2. Empirical Analysis

3.2.1 Data

This study follows the tradition of previous absolute and conditional convergence studies and examines the empirical analysis on energy intensity convergence for 34 OECD countries[14] between 1980 and 2015. Energy intensity (1000 Btu/$2010 GDP PPP) data were drawn from the

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[14] The OECD countries are as follows: Australia, Austria, Belgium, Canada, Chile, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Israel, Italy, Japan, Korea, Latvia, Luxembourg, Mexico, Netherlands, New Zealand, Norway, Poland, Portugal, Slovakia, Slovenia, Spain, Sweden, Switzerland, Turkey, United Kingdom and United States of America. Iceland and Lithuania were dropped from the panel due to lack of data.

Energy Information Administration (2019), and control variables for conditional convergence, gross savings (in percentage of GDP), population growth rate (in annual percentage), openness variable as total trade in percentage of GDP and net inflows of foreign direct investment (in percentage of GDP) were drawn from World Development Indicators (WDI, 2018). Human capital index (based on years of schooling and returns to education) data are obtained from Penn World Table version 9.0 of Feenstra, Inklaar & Timmer (2015). Table 3.1 presents descriptive statistics for the series in the annual panel data set employed.

Table 3.1: Descriptive Statistics of Annual Data, 1980-2015

Variables	Observations	Mean	Std. Dev.	Min.	Max.
Energy Intensity (1000 Btu/$2010 GDP PPP)	1108	5.783	2.119	2.102	14.61
Population growth rate (annual %)	1223	0.601	0.731	-2.574	6.017
Gross savings (% of GDP)	985	23.38	5.787	2.126	41.69
Human Capital Index	1140	3.027	0.439	1.469	3.734
Openness (total trade in percentage of GDP)	1138	4.207	0.544	2.773	6.017
Foreign direct investment, net inflows (% of GDP)	1138	78.13	48.295	16.012	410.2

Note: Std. Dev., Min. and Max. denote standard deviation, minimum and maximum, respectively.

3.2.2 Methodology

Macroeconomic series frequently have means, variances, or covariances change over time, implying that shocks permanently affect these series. Analyzing series with a unit root process can result in incorrect estimations of the relationship between variables originating from similar trends.

Im, Pesaran, and Shin (IPS hereafter, 2003) developed a unit root test for heterogeneous panels that requires T and N > 25. In their analysis, both time series and cross-sectional dimensions were combined, and error terms were serially correlated. IPS is a more powerful unit root test than traditional unit root tests, and the estimation equation targets the autoregressive parameter for each cross-sectional dimension. Hence, this study employs the IPS unit root test for the annual data series 1980 through 2014.

$$\Delta y_{i,t} = \alpha_i + \delta_i t + \beta_i y_{i,t-1} + \sum_{j=1}^{p} \rho_{ij} \Delta y_{i,t-j} + \varepsilon_{it} \quad (3.21)$$

where the series y_{it} is a panel series such that t = 1, …, T and i = 1, … , N. $\Delta y_{i,t}$ is the first difference of the variable of interest, α_i is the cross-sectional-specific intercept, t is the time trend, p is the number of lags in the ADF regression to reduce serial correlation, and the error term ε_{it}, which is assumed to be IID (independently identically distributed; 0, σ_i^2) for all i and t. The IPS test relaxes the homogeneity assumption of lagged dependent variable.

Table 3.2 gives the IPS test results. The null hypothesis of the existence of the unit root for all cross sections cannot be rejected for the data series. Following the tradition of the growth literature (Bond, Hoeffler, & Temple., 2001; Bonnefond, 2014; Caselli et al., 1996; Islam, 1995) for non-overlapping time intervals, five-year time intervals for seven data points were employed to avoid business cycle fluctuations and short-term shocks in addition to serial correlation. Implementing these methodologies for non-stationary data also revealed a long-run relationship between regressors. Therefore, the core assumption of the system GMM method of $N > T$ was fulfilled for 34 countries with few time periods and relatively large individuals.

Table 3.2: The Im-Pesaran-Shin panel Unit Root Test for Annual Country-Level Series, 1980-2015

Variables	*t*-bar statistics	*p*-value
Energy Intensity (1000 Btu/$2010 GDP PPP)	0.91468	0.82
Population growth rate (annual %)	0.06556	0.5261
Gross savings (% of GDP)	-1.13006	0.1292
Human Capital Index	1.09604	0.8635
Openness (total trade in percentage of GDP)	-1.17367	0.1203
Foreign direct investment, net inflows (% of GDP)	0.46875	0.6804

Notes: The null hypothesis of IPS test is that the series contains a unit root. Hence, rejection of the null hypothesis indicates that the series is stationary. Both trend and intercept are included for all series. The superscripts *, **, and *** represent 1%, 5%, and 10% confidence of intervals, respectively.

In the empirical analysis, following the tradition of Islam (1995), Caselli et al. (1996), Bond, Hoeffler, and Temple (2001), and Hoeffler (2002), a dynamic panel data methodology, the system generalized method of moments (system GMM) developed by Arellano and Bover (1995) and Blundell and Bond (1998), was applied to examine the steady-state absolute and/or conditional convergence of energy intensity among OECD countries. Although it is common to examine convergence with Ordinary Least Squares estimator and Within Groups or a first- differenced GMM, these estimators typically suffer from providing biased and inconsistent estimations in the dynamic panel data framework where the system GMM has better finite sample properties to solve fixed effects, endogeneity of regressors, and dynamic panel bias (Bond, Hoeffler, & Temple, 2001). OLS levels ignore time-invariant, country-specific effects which yield upward bias and Within Groups generates upward bias since the lagged dependent variable is positively correlated with unobserved country-specific effects within a fixed period of time. Hence, OLS levels and Within Estimator generates lower and upper bounds of the lagged dependent variable estimation, respectively (Hsiao, 1986; Judson et al., 1999; Nickell, 1981)

However, first-differenced GMM (Arellano & Bond, 1991) and system GMM cope with these issues since they provide consistent and efficient parameter estimates. The first-differenced GMM eliminates unobserved country-specific effects and omits variable bias by using first differences of regressors, and the system GMM uses instruments in order to obtain consistent estimations with endogenous right-hand-side variables. Moreover, GMM estimators perform better in regressions with heteroscedasticity, autocorrelation within individuals, and independent variables that are not strictly endogenous. Nonetheless, the system GMM outperforms the first-differenced GMM since the estimations of first-differenced GMM might suffer from a large finite sample bias when the time series dimension is not sufficient. Hence, autoregressive coefficient approaches to unity or variance of fixed effects increase depending on the variance of transient shocks, since lagged levels of variables are weak instruments for first-differenced equations (Bond, Hoeffler, & Temple, 2001). Furthermore, the system GMM is more efficient than the first differenced GMM when first differences of instruments are assumed to be uncorrelated with fixed effects. This assumption enables the estimator to use more instruments. Lastly, when series closely resemble random walks, first differenced GMM estimations are subject to a large finite sample bias and, if the instruments are weak, the coefficient of the lagged dependent variable tends to be downwardly biased as with Within Groups (Blundell & Bond, 1998, 2000; Hoeffler, 2002). In order to overcome this issue, Windmeijer (2005) suggests employing a finite sample correction for the variance-covariance matrix to system GMM in order to provide efficient estimations.

Following tradition regarding the income convergence equation, the first-order autoregressive panel data equation is derived for estimating energy intensity convergence in OECD countries:

$$Y_{i,t} = \beta \, . \, Y_{i,t-1} + \gamma \, . X_{i,t} - \xi . \tau + \mu_i + \varphi_t + \varepsilon_{i,t} \tag{3.24}$$

where $Y_{i,t}$ represents energy intensity over a five-year period. β is the coefficient of the lagged dependent variable $Y_{i,t-1}$ and is expected to lie between 0 and 1.[15] The determinants of the conditional energy intensity convergence equation are specified in a vector of variables $X_{i,t}$, where the corresponding coefficient is γ. The vector of control variables consists of human capital index, openness, and foreign direct investment. τ indicates the time dimension of the income convergence equation and its coefficient ξ, which is expected to be negative. μ_i, φ_t denote country-specific fixed effects, time-specific intercepts, and idiosyncratic shocks across countries i, respectively. $\varepsilon_{i,t}$ measures idiosyncratic shocks across countries i and time periods t. In order to support the assumption of no serial correlation across individuals in the idiosyncratic disturbances, time dummies are included in the regression equation (Roodman, 2009a).

In order to confirm the consistency of the system GMM estimations, the following four key diagnostics must be satisfied: (i) as a rule of thumb, for avoiding finite sample bias by overfitting, the number of instruments must be less than or equal to the number of groups in the regression (Roodman, 2009b); (ii) the error term should be confirmed to not contain second-order autocorrelation (AR2), although there could be negative first-order autocorrelation (AR1); the Arellano-Bond (1991) test, which is used to verify if residuals meet this requirement, was employed to verify the first and second order autocorrelation in the first-differenced residuals; (iii) the validity of the instrument set must be confirmed, as they should not be correlated with the error term. The Hansen (1982) J test to detect over-identifying restrictions reports p-values for the null hypothesis of instrument validity; and (iv) the additional moment restrictions proposed by Blundell and Bond (1998) must be valid for the consistency of system GMM estimations. Under the null hypothesis of validity of additional moment conditions, the Difference-in-Hansen test provides p-values.

The system GMM estimator is designed for large individuals and for small time dimensions (Blundell & Bond, 1998, 2000, 2001; Roodman, 2009a). Depending on high efficiency and more accurate results in empirical growth models, the system GMM is a commonly used estimator in this literature. Accordingly, reckoned among all, this study estimates energy intensity equation

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[15] Note that $\beta = 1$ implies that the regressor is persistent over time, and $\beta > 1$ implies the divergence.

with the system GMM estimator with the Windmeijer correction method for the variance-covariance matrix.[16]

3.2.3 Findings

Table 3.3 presents the panel regression results from estimating equation (3.24) using the system GMM with a five-year span of data for 34 OECD countries over the time period 1980-2014. In order to examine the absolute and conditional β-convergence, control variables were gradually introduced into the estimation equation. In Table 3.3, column (1) presents the absolute convergence estimations where the energy intensity of the previous five-year span is the only determinant of energy intensity convergence. Column (2) also presents the absolute convergence model with the inclusion of the savings rate and population growth rate variables that come from the original textbook model. In order to examine conditional convergence, human capital index, FDI, and openness are included in columns (2) to (4), respectively. In addition, the time trend is also included in columns (1) to (4) as it appears to be negative in equation (3.19).

In Table 3.3, the lagged dependent variable is assumed to be predetermined, and all control variables are endogenous. The first row represents $\hat{\beta}$, the estimated coefficient of the lagged dependent variable, which is expected to be between 0 and 1. Hence, $\beta^* = \hat{\beta} - 1$ is between -1 and 0, providing evidence of energy intensity convergence. The implied speed of convergence is calculated from the theoretical model as $\vartheta = -\frac{\ln \hat{\beta}}{\tau}$ where $\tau = t_2 - t_1 = 5$. In addition, the speed of convergence in conditional convergence is expected to be higher than in absolute convergence as inclusion of control variables enhances the implied convergence rate.

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[16] The Stata 12 command "xtabond2" to obtaining results. The "collapse" command is also used to minimize the potential bias that arises from the increase in number of instruments, which leads instruments to overfit endogenous regressors (Roodman, 2009a).

Table 3.3: System GMM Estimations of Energy Intensity Convergence from a 5-year span panel data, 1960-2014

Variables and Statistics	Dependent Variable: ln [energy intensity (1000 Btu/$2010 GDP PPP]			
	1	2	3	4
Lagged dependent variable	0.811*	0.723*	0.793*	0.756*
	(0.055)	(0.118)	(0.040)	(0.035)
Savings Rate	0.069	-0.186**	0.061	0.055
	(0.045)	(0.076)	(0.054)	(0.057)
Population Growth Rate	0.009	0.025	0.017	-0.006
	(0.006)	(0.033)	(0.015)	(0.012)
Time Trend	-0.004*	-0.007*	-0.003*	-0.004*
	(0.0006)	(0.002)	(0.001)	(0.0006)
Human Capital Index	-	0.244	–	–
	–	(0.173)	–	–
Foreign Direct Investment	–		-0.015**	–
	–	–	(0.006)	–
Openness	–	–	–	-0.033***
	–	–	–	(0.017)
Constant	9.542*	16.200*	7.925*	8.922*
	(1.268)	(4.730)	(1.947)	(1.405)
Implied Convergence Rate	0.042	0.065	0.046	0.056
Number of Groups	31	31	31	31
Number of Instruments	25	17	23	20
AR(1) p-value	0.031	0.081	0.041	0.028
AR(2) p-value	0.238	0.64	0.274	0.132
Hansen test *p-value*	0.768	0.61	0.359	0.507
Difference-in-Hansen test *p-value*	0.636	0.49	0.304	0.475

Notes: Heteroscedasticity-consistent standard errors are in parentheses. Windmeijer (2005) finite sample correction for standard errors is employed. The superscripts *, **, *** represents 1%, 5% and 10% confidence of intervals, respectively.

As discussed in the previous section, the validity of the system GMM output depends on four key diagnostics. All system GMM estimates are consistent and robust since the information shown in Table 3.3 indicates that all key features are supported: in all estimations: (i) number of instruments are smaller than number of groups; (ii) negative first-order autocorrelation and no second-order autocorrelation also confirm the validity of the models 1 to 4; (iii) the Hansen (1982) J test results indicate the validity of the models 1-4 instrumental variables; and (iv) the Difference-in-Hansen test confirms the validity of the additional moment conditions.

The coefficient of the lagged dependent variable is between 0 and 1 and was found to be statistically significant in all estimations, supplying concrete evidence of both absolute and conditional energy intensity convergence in 34 OECD countries between 1980 and 2014. Confirming expectations, the absolute convergence reveals the highest coefficient, 0.811, and the lowest implied speed of convergence, 4.19% per period. Adding the control variables into the model one by one results in lowered coefficients of the lagged dependent variable, $\hat{\beta}$, hence rising the $\widehat{\beta^*}$, as expected.

The speed of convergence rises to 6.49%, 4.64%, and 5.59% when the model was augmented with human capital index, foreign direct investment, and openness, respectively. However, even though the speed of convergence is the highest in model two, the coefficient of human capital index is statistically insignificant, implying that years of schooling and returns from education make no contribution to energy intensity convergence. As Hoeffler (2002) explains, inclusion of a variable, though insignificant, supports the instrument set in the GMM regressions. On the other hand, FDI and openness were statistically significant, indicating that each accelerates conditional energy intensity convergence. Moreover, the signs of these coefficients were consistent with *a priori* expectations, as increases in FDI and openness would lead to a decline in energy intensity because a decline in energy consumption or an increase in GDP would lead to a decline in energy intensity. In the estimates of other permanent variables in the neoclassical income convergence model, savings rate and population growth rate were statistically insignificant; the only exception was that savings rate was found to be statistically significant, as shown in column (2). Lastly, but foremost, the coefficient of time is negative and was statistically significant with a 1% confidence interval. Supporting the theoretical findings of this paper, the empirical evidence of 34 OECD countries suggests that energy intensity decreases over time. Considering that energy intensity convergence occurs in the fourth quantile of the Cartesian coordinate system, decreasing energy intensity is a desirable result of this study.

3.3. Concluding Remarks and Policy Implications

In a world where production is highly dependent on energy usage, the efficient use of energy is one of the most important criteria for measuring the policy maker success. In order to measure their performances, new tools such as energy intensity and energy efficiency were developed. Hence, this paper has examined the absolute and conditional energy intensity convergence behavior of 34 OECD countries theoretically and empirically for the period of 1980 and 2014 in order to measure improvements in energy intensity. Solow-Swan neoclassical model provided a benchmark for developing the theoretical model.

However, studying energy intensity employing the income convergence argument is not as easy as it seems. Firstly, the negative (average) growth rate of energy intensity implies that energy intensity is decreasing. Secondly, the direction of change is from right to left. By its nature, energy intensity is defined as energy consumption per unit of GDP, and both of these stylized facts contradict the stylized facts related to income convergence. Concurrently, adopting income convergence as a benchmark is valid in the derivation of the energy intensity convergence equation because income dynamics must play a significant role in energy intensity dynamics.

The literature lacks studies that support the theoretical background of energy intensity convergence, but several studies do examine it. In contrast to the literature, as this paper describes, the energy use function presented in the second chapter of this thesis is not considered to be a factor of production. The major novelty in the derived equation is that energy intensity convergence is treated as a function of time and is expected to lower energy intensity. Moreover, the income convergence equation provides the implied speed of convergence. In the empirical part, a dynamic panel data equation was estimated with the system GMM estimator for a five-year span of data for 34 OECD countries over the period 1980-2014. The efficient and consistent system GMM estimates for absolute and conditional convergence equations present concrete evidence of energy intensity convergence across OECD area for the sample period. Furthermore, introducing each control variable into the model one by one -—human capital index, FDI, and openness—yields a higher speed of convergence. In the estimated conditional convergence models, FDI and openness are negative, thereby confirming the theoretical expectations of Rühl et al. (2012), who suggest that changes in economic structure and in energy mix decrease energy intensity levels as observed in both developing and developed economies in recent years. Hence, it is important for countries that support trade openness and promote FDI to experience declining energy intensity levels. For absolute and conditional convergence, it is theoretically and empirically proven that energy intensity is a function of time. Even though the impact is minor, the empirical evidence shows that the estimated coefficient is negative, meaning that energy intensity is declining, *ceteris paribus*. However, it must be emphasized that basic physical principles indicate that energy is essential for a production process (Stern, 2011). The mass-balance principle suggests that, an equal or greater amount of input must be used to produce a certain amount of a good. In addition, in order to conduct a physical work, a minimum quantity of energy must be expended, according to the second law of thermodynamics. Hence, the desirable amount of energy used in a production process is the minimum amount of energy. Therefore, the negative time trend in energy intensity convergence implies that energy intensity approaches zero (but never reaches zero according to the second law of thermodynamics) and is independent of previous levels of energy intensity

CHAPTER 4 : ENVIRONMENTAL KUZNETS CURVE UNDER NONCARBOHYDRATE ENERGY

The world has witnessed a dramatic increase in energy consumption over the last four decades due to increasing output demand and supply. Energy sources, especially fossil fuels, have become more important than ever as a result of this growing energy demand, and fossil fuel consumption has increased 85% between 1970 and 2013 (British Petroleum (BP) Statistical Review of World Energy, 2014), reaching 66% of World's energy consumption in 2014 (International Energy Agency (IEA), World Energy Statistics and Balances, 2014). The substantial and continuous increase in fossil fuel consumption has emphasized the issue of global warming, caused by a 134% increase in carbon emissions in the last four decades (British Petroleum (BP) Statistical Review of World Energy, 2014). Along with the rising awareness on environmental issues, IPCC (International Panel on Climate Change), UNFCCC (United Nations Framework Convention on Climate change) and Kyoto Protocol all confirmed the existence of the global warming phenomenon. Moreover, reversing the increasing rate of carbon emission has become essential and time constraints have been imposed to accomplish these targets for developed countries. Namely, imposed targets aimed to reduce greenhouse gases (GHG) to 5.2% below 1990 levels between 2008 and 2012. In 2008, three years after it came into the force, 178 countries ratified the protocol which expired in 2012. Paris Agreement was adopted as a continuation of Kyoto protocol in 2015 but has not yet come into force. It will open for signature in April 2016 by 197 parties of the UNFCCC, and valid conditions of the Paris Agreement will come into force is 55 countries that generate at least 55% of the global GHG's ratify or accept the agreement (UNFCCC, Historic Paris Agreement on Climate Change 195 Nations Set Path to Keep Temperature Rise Well Below 2 Degrees Celsius, 2016). However, with the withdrawal of Canada and non-participation of Japan, Russia and New Zealand the Paris agreement may fulfill only about 15 percent of the reduction in global emissions (Stoutenburg, 2015).

In all, the relationship between economic development and environmental degradation has become a subject of growing importance in the literature (Huang, Hwang and Yang, 2008). On one hand, there is no attempt to decarbonize energy supply where carbon and energy intensities are driving forces on global emission growth (Raupach et al., 2007), Acaravci and Ozturk (2010) states that the existing literature is not sufficient to provide an evidence of policy recommendations for countries. Moreover, it is observed that there has been no comprehensive examination of either the effects of nuclear energy consumption or renewable energy consumption on carbon emissions. Hence, this study aims to fill these gaps by examining the long-run effects of GDP per capita, primary energy consumption per capita and alternative and nuclear energy consumption (noncarbohydrate) on carbon emissions for 27 OECD countries by using the autoregressive lag distributed (ARDL) model proposed by Pesaran, Shin and Smith (2001). It is expected that decreasing the primary energy consumption and increasing the noncarbohydrate energy consumption would promote the carbon mitigation under the EKC framework, which presumes inverse non-linear quadratic relationship between carbon emissions and GDP per capita. Alternative and nuclear energy, which is defined as clean energy because it does not generate carbon emissions (World Development Indicators, 2019). The organization of this paper is as follows: the next section reviews the literature. The third section presents the data, methodology and results. The last section is reserved for concluding remarks and policy implications.

4.1. Literature Review

There exist many studies on the relationship between carbon emissions and economic growth, which is commonly referred to as the EKC hypothesis. Moreover, the literature so far seems to acknowledge the EKC hypothesis; however, the results are both controversial and ambiguous (Huang, Hwang and Yang, 2008; Pao and Tsai, 2011). According to EKC hypothesis, in early stages of development of an economy, income per capita starts to increase in relation to the growth of environmental degradation. There is, however, a threshold for environmental degradation, after which the level decreases. The explanation behind this non-linear relationship is as follows: In early stages of economic development, the consumption of carbon-based energy resources creates a relatively low level of waste accumulation. During the process of industrialization, however, carbon-based energy consumption increases dramatically and constructs a positive relationship between environmental degradation and income per capita. In the later stages of development, namely post-industrialization, due to the higher level of economic growth resulted from the higher share of service sector in GDP, and technological developments; emission levels caused by production sector is mitigated (Panayotou, 1993).

EKC literature can be divided into three strands. The first can be called absolute EKC, in which the bivariate relationship between the environmental degradation and income is examined (Acaravci and Ozturk, 2010; López-Menéndez, Pérez and Moreno, 2014; Ozturk and Acaravci, 2013; Hamit-Haggar, 2012; Lee and Lee, 2009; Coondoo and Dinda, 2002). The second strand can be called augmented EKC in which energy consumption is frequently added to the absolute EKC model, based on the idea that higher economic development is achieved by higher energy consumption (Halicioglu, 2009). Hence, energy consumption and economic development jointly determine the level of environmental degradation. Furthermore, studies examine energy consumption – economic development nexus provide basis for development of energy and energy consumption related environment policies Apergis and Payne, 2009). Most of empirical studies can be classified in this strand (Pao and Tsai, 2011; Shahbaz, Mutascu and Azim, 2013; Jalil and Mahmud, 2009; Soytas, Sari and Ewing, 2007; Liu, 2005; Kasman and Duman, 2015; Shahbaz et al., 2014; Begum et al., 2015; Tiwari, Shahbaz and Adnan Hye, 2013; Al-Mulali and Ozturk, 2016). The third strand is noncarbohydrate EKC, in which either renewable energy or nuclear energy is included into the augmented EKC. Iwata, Okada and Samreth (2010) is the first study to take nuclear energy with country specific data into account. Noncarbohydrate EKC was examined by Iwata, Okada and Samreth (2011, 2012), Baek and Kim (2013), Apergis and Payne (2012), Apergis et al. (2010), Menyah and Wolde-Rufael (2010), Richmond and Kaufmann (2006), Al-Mulali (2014). However, all noncarbohydrate EKC studies consider renewable energy consumption and nuclear energy consumption individually. In contrast, this paper is the first study in which alternative and nuclear energy consumption account to the total amount of renewable energy consumption and nuclear energy consumption.

4.2. Empirical Analysis

4.2.1 Data and Methodology

Diverse empirical evidences from EKC hypothesis in the literature complicate the policy analysis. Furthermore, lack of data availability forces most studies to rely on panel data analysis, in which, under homogeneity assumption, sample size is larger, compared to country specific analysis (List and Gallet, 1999). However, some relatively less developed economies are unable to provide sufficient data, and may therefore deteriorate the dataset. In addition, the development process and environmental degradation levels may vary across economies, depending on different social, economic and political factors. Therefore, a general environment related indicator for a panel should not be generalized for other economies (Baek and Kim, 2013; Apergis and Payne, 2012; Apergis et al., 2010; Menyah and Wolde-Rufael, 2010; Richmond and Kaufmann, 2006; Al-

Mulali, 2014; List and Gallet, 1999; Dinda, 2004) and finding a single turning point for a whole dataset cannot provide evidence for every individual economy (de Bruyn, van den Bergh and Opschoor, 1998). Hence, individual country analysis may be more suitable for labeling the primary elements that affect environment related indicators. It is, therefore, recommended that EKC studies should focus on time series datasets rather than panel datasets (List and Gallet, 1999; de Bruyn, van den Bergh and Opschoor, 1998; Dijkgraaf and Vollebergh, 2005; Kaika and Zervas, 2013).

According to Ang (2007), the key component of carbon emissions is energy consumption. However, the EKC hypothesis suggests that an economic development indicator, such as GDP has a negative quadratic relationship with carbon emissions. Acaravci and Ozturk (2010) claim that bivariate models, which include only two variables, may suffer from omitted variable problems. To avoid this problem, this study employs a multivariate model. Stern (2004) states that most EKC studies are weak, and should work on a natural logarithmic form of the following equation in order to avoid zero or negative indicators. Furthermore, this reduced-form of model allows the identification of the direct impact of income on environmental degradation (Grossman and Krueger, 1995). So, following the existing literature, long run relationship between carbon emissions per capita, primary energy consumption, GDP per capita, and alternative and nuclear energy can be written as:

$$lnco_t = \alpha_0 + \alpha_1 lneu_t + \alpha_2 lny_t + \alpha_3 lny_t^2 + \alpha_4 lnae_t + \varepsilon_t \tag{4.1}$$

where cot is carbon emissions (measured in metric tons per capita), $eu_t$is the primary energy use (kt of oil equivalent per capita), $y_t$is real GDP per capita (constant 2005 US$), $y_t^2$is the square of real per capita GDP, $ae_t$is alternative and nuclear energy (kt of oil equivalent), and $\varepsilon_t$is the error term. The model above is estimated for 27 OECD countries: Australia, Austria, Belgium, Canada, Chile, Denmark, Finland, France, Greece, Iceland, Ireland, Israel, Italy, Japan, Korea Republic, Luxembourg, Mexico, Netherlands, New Zealand, Norway, Portugal, Spain, Sweden, Switzerland, Turkey, United Kingdom and United States of America. Real GDP per capita, carbon emissions, alternative and nuclear energy data, primary energy consumption are drawn from World Development Indicator (WDI) online database (The World Bank, World Development Indicators, 2015). The range of annual time series data for countries is selected according to availability. All variables are used in natural logarithm form due to reduce heteroskedasticity problem, and the differenced natural logarithm of coefficient provides the growth rate of relevant variable. The parameters $\alpha_i = 1,..,4$ are long-run elasticities of primary energy consumption, real GDP, real GDP squared and alternative and nuclear energy respectively and t denotes time.

4.2.2 Unit Root Test

In order to test the existence of unit roots, determining the stationarity and order of integrations for dependent and for four independent variables, Augmented Dickey Fuller (ADF hereafter, 1981), Phillips – Perron (PP hereafter, 1988) and Dickey Fuller GLS (1996) tests were conducted. The advantage of conducting ARDL bounds test is that the order of variables can be either integrated of order zero I(0), or integrated in order one I(1). However, higher integration orders must be controlled, because ARDL bounds test was not designed for I(2) or higher integration orders, and does not fit the critical values provided in Pesaran, Shin and Smith (2001). In other words, unit root test results control the robustness of parameters. The null hypothesis of ADF, PP and DF - GLS is that the variable has unit root and alternative hypothesis is no unit root. All tests include trend and intercept in levels, and include an intercept in first differences. Since unit root tests provide evidence of an integration order higher than one for natural logarithm of carbon emissions and energy usage in Luxembourg and Spain, and natural logarithm of carbon emissions in Portugal, these countries are eliminated from the country set. The remaining countries are fulfill the I(0) and I(1) criteria.[17]

4.2.3 Autoregressive Distributed Lag (ARDL) co-integration methodology

The ARDL bounds test, developed by Pesaran and Shin (1999) and Pesaran, Shin and Smith (2001), is a general dynamic model, which uses the lagged values of dependent and independent variables to estimate short-run elasticities directly, and long-run elasticities indirectly (Wang et al., 2011). These methodologies consist of three steps: the first is to test for cointegration among the variables through bounds test approach. To apply this step, firstly, optimal lag orders must be selected where the model is quite sensitive to the lag lengths. According to Pesaran and Shin (1999), Schwarz – Bayesian information criterion (SBC) is more consistent than other selection criterion, such as Akaike information criteria (AIC) or Hannan – Quinn information criterion (HQ). In addition, in the absence of any feedback and the direction of long run relationship, Monte

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[17] See Appendix B.

Carlo evidence presents reliable lag order through SBC and AIC (Panopoulou and Pittis, 2004; Shahe Emran, Shilpi, and Alam, 2007). The second step is to estimate the long run coefficients identified in the first step, and the final step is to estimate short run coefficients and error correction term.

ARDL has numerous advantages over other cointegration methodologies, such as Engle – Granger (1987), Johansen (1998). Firstly, order of integration is not problematic, unlike other methods, for which all variables must be the same order of integration. Secondly, ARDL approach allows different variables have different optimal lag orders. Thirdly, the model runs with a single reduced form equation, and lastly, the model can deal with small samples even when some variables are endogenous, given estimators are efficient. According to Wolde-Rufael (2010), the model corrects the endogeneity problem, even for small samples.

In ARDL approach of cointegration, there are two steps to estimating long-run relationship: The first step is to examine the existence of long-run relationship among variables:

$$\begin{aligned}\Delta lnco_t = {} & \alpha_1 + \sum_{i=1}^{n} \alpha_2 \Delta lnco_{t-i} + \sum_{s=0}^{m} \alpha_3 \Delta lneu_{t-s} + \sum_{j=0}^{k} \alpha_4 \Delta lny_{t-j} \\ & + \sum_{q=0}^{p} \alpha_5 \Delta lny_{t-q}^2 + \sum_{h=0}^{l} \alpha_6 \Delta lnae_{t-h} + \delta_1 lnco_{t-1} \\ & + \delta_2 lneu_{t-1} + \delta_3 lny_{t-1} + \delta_4 lny_{t-1}^2 + \delta_5 lnae_{t-1} + \varepsilon_{1t}\end{aligned} \tag{4.2}$$

where ε_{it} is white noise error term, Δ is difference operator. The long-run relationship is testing the joint significance of the lagged variables by Wald test or *F*-statistics which test the null of no cointegration, $\delta_{1,2,..,5} = 0\delta_{1,2,..,5} = 0$, against the alternative hypothesis $\delta_{1,2,..,5} \neq 0\delta_{1,2,..,5} \neq 0$. The asymptotic distributions of the two sets are represented in Pesaran, Shin and Smith (2001), and modified version for smaller samples of between 30 and 80 are represented in Narayan (2005). The *F*-test has non-standard distribution, which depends on whether variables are I(0) or I(1), number of variables, and whether the regression has intercept or trend. Pesaran, Shin and Smith (2001) assumes that upper value indicates variables are I(1), and lower value indicates variables are I(0), in nature. If computed *F*-statistics are greater than upper bound, the null hypothesis is rejected, and cointegration is implied. If the calculated *F*-statistics are below the lower bound, the null hypothesis cannot be rejected, indicating no cointegration. Lastly, computed F-statistics lying between the upper and lower bound designate inconclusive inference without any information of integration orders of regressors. This paper is constructed with limited time series data for OECD countries, therefore, the critical values of Narayan (2005) rather than Pesaran, Shin and Smith (2001) are employed.

The second step, after finding evidence of cointegration, is to estimate long-run and short-run models represented below respectively.

$$\begin{aligned} lnco_t = \beta_1 &+ \sum_{i=1}^{n} \beta_2 lnco_{t-i} + \sum_{s=0}^{m} \beta_3 lneu_{t-s} + \sum_{j=0}^{k} \beta_4 lny_{t-j} \\ &+ \sum_{q=0}^{p} \beta_5 lny_{t-q}^2 + \sum_{h=0}^{l} \beta_6 lnae_{t-h} + \varepsilon_{2t} \end{aligned} \tag{4.3}$$

$$\begin{aligned} \Delta lnco_t = \gamma_1 &+ \sum_{i=1}^{n} \gamma_2 \Delta lnco_{t-i} + \sum_{s=0}^{m} \gamma_3 \Delta lneu_{t-s} + \sum_{j=0}^{k} \gamma_4 \Delta lny_{t-j} \\ &+ \sum_{q=0}^{p} \gamma_5 \Delta lny_{t-q}^2 + \sum_{h=0}^{l} \gamma_6 \Delta lnae_{t-h} + \varphi\, ECT_{t-1} + \varepsilon_{3t} \end{aligned} \tag{4.4}$$

where φ is the error correction term, which shows the how fast variables converge to the equilibrium under the conditions of statistical significance and negative coefficients.

Table 4.1: Estimated Bounds of *F*-Test Results for Cointegration

Country	Periods	Optimal Lag	*F*-Statistics
Australia	1960 - 2010	1	2.617
Austria	1960 - 2010	1	1.311
Belgium	1960 - 2010	1	2.413
Canada	1960 - 2010	1	5.412*
Chile	1971 - 2010	1	4.025**
Denmark	1960 - 2010	1	5.530*
Finland	1960 - 2010	1	2.3
France	1960 - 2010	1	4.100**
Greece	1960 - 2010	1	5.536*
Iceland	1960 - 2010	1	3.146

Ireland	1970 - 2010	1	3.139
Israel	1971 - 2010	2	4.845**
Italy	1960 - 2010	1	4.934**
Japan	1960 - 2010	1	2.987
Korea Republic	1971 - 2010	1	4.478**
Luxembourg	1960 - 2010	1	1.952
Mexico	1971 - 2010	1	2.041
Netherland	1960 - 2010	1	2.673
New Zealand	1977 - 2010	2	5.118**
Norway	1960 - 2010	1	2.689
Portugal	1960 - 2010	1	2.207
Spain	1959 - 2010	0	1.854
Sweden	1960 - 2010	1	4.694**
Switzerland	1980 - 2010	1	1.138
Turkey	1960 - 2010	1	1.991
United Kingdom	1960 - 2010	1	2.075
United States	1960 - 2010	1	2.33
n=35	I(0)	I(1)	
CV at 1%	3.9	5.42	
CV at 5%	2.8	4.01	
CV at 10%	2.33	3.42	
n=40	I(0)	I(1)	
CV at 1%	3.66	5.26	
CV at 5%	2.73	3.92	
CV at 10%	2.31	3.35	
n=45	I(0)	I(1)	
CV at 1%	3.67	5.02	
CV at 5%	2.69	3.83	
CV at 10%	2.28	3.3	
n=50	I(0)	I(1)	
CV at 1%	3.59	4.98	
CV at 5%	2.67	3.78	
CV at 10%	2.26	3.26	

Note: F-Statistics refer for ARDL cointegration test. The critical values for the lower I(0) and upper I(1) bounds are taken from Narayan (2005, Appendix: Case II). *, **and *** represent 1, 5, 10% significance levels, respectively.

4.2.4 Findings

This study uses SBC for selecting appropriate lag order for ARDL model. Table 1 represents estimated ARDL models, optimal lag lengths and year interval for each country. Bounds *F*-test for cointegration show evidence of a long run relationships between carbon emissions and GDP, GDP per capita, energy consumption and nuclear and alternative energy at 1% confidence of interval for Canada, Denmark and Greece, and at 5% confidence of interval for Chile, France, Israel, Italy, Korea Republic, New Zealand and Sweden. However, no long run cointegration relationship was found for the remaining countries: Australia, Austria, Belgium, Finland, Iceland, Ireland, Japan, Luxembourg, Mexico, Netherlands, Norway, Portugal, Spain, Turkey, United Kingdom and Unites States of America.

Estimated coefficients from ARDL models are represented in Table 2. Under the EKC hypothesis, the signs of long run coefficient estimate of GDP per capita and of squared GDP per capita are expected to be positive and negative, respectively. This refers to the pattern that environmental damage increases in line with the rise in per capita income during economic growth, until a threshold is reached $\beta_4/2\beta_5$, after which carbon emission per capita begin to decline. In this study, carbon emissions and GDP per capita have a positive statistically significant relationship in Denmark, Korea Republic, France and Israel. Canada, Greece, Italy and New Zealand have positive insignificant coefficients. On the other hand, there is a negative statistically significant relationship between carbon emissions and squared GDP per capita for Denmark and Korea Republic, France and Israel. Negative insignificant coefficients have been found for Canada, Greece, Italy and New Zealand. Therefore, Denmark, France, Israel and Korea Republic provide evidence for EKC hypothesis, while the hypothesis is statistically insignificant in Canada, Greece, Italy and New Zealand. Ang (2007) claims that statistically insignificant GDP per capita squared coefficients indicate a monotonic increase in the relationship between carbon emissions and GDP per capita. It can therefore be stated that output increases monotonically with the level of carbon emissions in these countries. Acaravci and Ozturk (2010), in particular, found EKC evidence in Denmark and Italy and monotonic EKC in Greece.

Since energy consumption promotes carbon emissions, the sign of α_1 in equation 4.1 is expected to be positive. In this respect, this study found evidence of a positive long run relationship between primary energy consumption and carbon emissions for Canada, Denmark, Greece, Israel, Italy, Korea Republic, New Zealand, Sweden and France. In contrast to the positive relationship between energy consumption and carbon emissions, nuclear and alternative energy consumption is expected to reduce carbon emissions. This study found that Canada, Chile, France, Italy, New Zealand and Sweden have negative and statistically significant relationship between carbon emissions and nuclear and alternative energy use. Our results have partial consistency with the literature. For example, Al-Mulali (2014) founds that fossil fuel consumption increases carbon emissions in Canada, France, Korea Republic and Sweden where nuclear energy consumption decreases carbon emissions in Canada, increases in Korea Republic and has no effect in France and Sweden.

All coefficients of error correction terms are also negative and statistically significant at 1% significance level, except for Chile, which is statistically significant at 10% significance level. Error correction terms indicate how fast short run coefficient converges to the long run equilibrium and corrects itself every year. In addition, turning points for countries supporting EKC lie between dataset.[18]

Lastly, cumulative sum (CUSUM) and cumulative sum of squares (CUSUMSQ) tests indicate the stability of long-run and short-run coefficients (Brown, Durbin and Evans, 1975). Figure C1 in Appendix C illustrate the plots of CUSUM and CUSUMSQ tests lie between the critical bounds of 5% significance level that shows estimated parameters for per capita carbon emissions are stable over the periods.

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[18] Turning points for countries that support EKC hypothesis: Denmark 9.926; France 9.983; Israel 9.697; Republic of Korea 9.486.

Table 4.2: Estimated Long-Run and Short-Run Coefficients for the Environmental Kuznets Curve

Indicators/Countries	Canada	Chile	Denmark	France	Greece	Israel	Italy	Korea Republic	New Zealand	Sweden
Estimated long-run coefficients										
lny	2.635	-7.535***	11.048*	9.125***	0.937	15.71***	1.5269	2.049**	33.28	-10.94
	(3.08)	(4.348)	(4.05)	(4.763)	(2.008)	(9.10)	(2.0784)	(0.858)	(32.58)	(12.68)
lny2	-0.126	0.486***	-0.556*	-0.457**	-0.049	-0.81***	-0.08	-0.108*	-1.625	0.505
	(0.14)	(0.275)	(0.197)*	(0.228)	(0.099)	(0.47)	(0.102)	(0.04)	(1.61)	(0.606)
lneu	1.13*	0.676	1.02*	0.793**	0.959*	1.157*	0.96*	0.771*	1.375*	2.121*
	(0.16)	(0.671)	(0.125)	(0.364)	(0.132)	(0.361)	(0.089)	(0.164)	(0.299)	(0.53)
lnae	-0.206*	-0.541*	0.029	-0.198*	-0.074	-0.005	-0.253*	-0.038	-0.751*	-0.5*
	(0.032)	(0.182)	(0.018)	(0.033)	(0.062)	(0.013)	(0.068)	(0.027)	(0.218)	(0.056)
Constant	-18.85	28.879	-60.744*	-47.951**	-9.329	-83.018***	-10.49	-13.4*	-173.54	47.66
	(14.56)	(19.53)	(20.305)	(22.398)	(9.454)	(44.104)	(10.44)	(3.64)	(162.61)	(62.10)
Estimated short-run coefficients										
lny	1.83	-8.037**	6.587*	3.261	0.489	5.637	0.624	1.29**	13.947	-4.25
	(2.19)	(3.13)	(2.399)	(2.187)	(1.014)	(3.427)	(0.94)	(0.61)	(13.48)	(4.126)
lny2	-0.088	0.487**	-0.331*	-0.163	-0.026	-0.175	-0.002	-0.043	-0.699	0.171
	(0.10)	(0.19)	(0.118)	(0.106)	(0.050)	-0.29	(0.051)	(0.037)	(0.67)	(0.194)
lneu	0.787*	1.492*	1.405*	0.983*	0.501*	0.415*	0.392*	0.488*	1.26*	1.572*
	(0.130)	(0.182)	(0.093)	(0.137)	(0.155)	(0.109)	(0.076)	(0.12)	(0.215)	(0.166)
lneu (-1)	-	-	-	-	-	-	-	-	-0.529*	-
	-	-	-	-	-	-	-	-	(0.178)	-
lnae	-0.143*	-0.129**	0.017	-0.071*	-0.038	-0.001	-0.103*	-0.024	-0.31*	-0.169*
	(0.026)	(0.055)	(0.011)	(0.016)	(0.028)	(0.004)	(0.023)	(0.016)	(0.058)	(0.035)
Constant	-13.138	6.928***	-36.22*	-17.138	-4.877	-29.79***	-4.296	-8.49*	-72.7	16.145
	(10.54)	(3.824)	(12.176)	(10.64)	(4.663)	(16.68)	(4.976)	(2.88)	(67.33)	(19.989)
Ect (-1)	-0.696*	-0.239***	-0.596*	-0.357*	-0.522*	-0.358*	-0.409*	-0.633*	-0.418*	-0.338*

	(-0.087)	(-0.125)	(-0.114)	(-0.092)	(-0.119)	(-0.098)	(-0.08)	(-0.14)	(-0.108)	(-0.071)
ARDL	1-0-0-0-0	1-1-1-1-0	1-0-0-1-0	1-0-0-1-0	1-0-0-0-0	1-0-0-0-0	1-0-1-0-0	1-0-1-0-0	1-0-1-2-0	1-1-0-1-0
adj. R2	0.966	0.989	0.947	0.968	0.994	0.967	0.997	0.996	0.974	0.977
RSS	0.021	0.026	0.042	0.033	0.09	0.065	0.01	0.034	0.013	0.057
LM	0.368	1.786	0.808	1.084	0.013	0.491	0.38	2.472	0.263	6.009
	[0.54]	[0.192]	[0.374]	[0.304]	[0.909]	[0.488]	[0.541]	[0.126]	[0.613]	[0.019]
HET	1.138	1.688	0.637	1.89	17.759	0.119	4.295	0.295	0.024	1.678
	[0.291]	[0.202]	[0.428]	[0.176]	[0.000]	[0.732]	[0.044]	[0.590]	[0.876]	[0.201]

Notes: *, ** and *** represent 1%, 5%, 10% significance levels, respectively. LM and HET are the Lagrange multiplier statistics for the null hypothesis that are residuals have no serial correlation and heteroskedasticity, respectively. RSS is the residual sum of squares. (-1) refers to one lag of relevant variables and t-statistics for coefficients represented in (), *p*-values are represented in [].

4.3. Conclusion and Policy Implications

In this paper, the non-linear quadratic long run relationship between carbon emissions per capita, primary energy consumption, GDP per capita and alternative and nuclear energy (noncarbohydrate) is examined for 27 OECD countries by using the autoregressive lag distributed (ARDL) model proposed by Pesaran and Shin (1999) and Pesaran, Shin and Smith (2001). The estimated coefficients of error correction terms (ECTs) are negative and significant, implying adjustment to long run equilibrium.

The bounds *F*-test for cointegration provided evidence of a long run relationship between these variables in Canada, Chile, Denmark, France, Greece, Israel, Italy, Korea Republic, New Zealand and Sweden. This study shows that EKC hypothesis holds for Denmark, France, Israel and Korea Republic. Hence, after a threshold, an increase in a GDP per capita presumably reduces carbon emissions per capita in these countries. According to Akbostanci, Turut-Asik, and Tunc (2009) EKC hypothesis claims that the best way to apply policies is to take no action, since as output increases the problem will be solved spontaneously. However, Dinda (2004) states that simply stimulating economic growth is sufficient to hinder environmental degradation. Furthermore, the EKC hypothesis is statistically insignificant in Canada, Greece, Italy and New Zealand, indicating a monotonic increase in relationship between carbon emissions and GDP per capita.

As expected, primary energy consumption has a positive and significant coefficient except in Chile, indicating that it increases carbon emissions in the long-run. Moreover, the results derived from ARDL reveal that energy consumption is the main driver to carbon emissions in the countries. These results clearly emphasize that the need for countries to decrease the ratio of fossil fuel consumption in their energy mix in order to decrease carbon emissions. The noncarbohydrate energy consumption has a negative significant relationship in Canada, Chile, France, Italy, New Zealand and Sweden. For instance, noncarbohydrate energy consumption reduces carbon emissions by 0.75% in New Zealand and 0.5% in Sweden. Hence, this study reveals that, as a substitute for fossil fuels, noncarbohydrate energy consumption may reduce carbon emissions in the long run.

Comparing primary energy consumption and noncarbohydrate energy consumption in absolute values, coefficient of primary energy consumption is greater than the coefficient of noncarbohydrate energy consumption in all countries in which there is a long run relationship indicating that one percent decrease in primary energy consumption results in a greater reduction of carbon emissions compared to a one percent increase in noncarbohydrate energy. In agreement with the literature, this paper argues that lowering levels of primary energy consumption is also vital to reduce carbon emissions. Furthermore, fossil fuel conservation policies and enhancing noncarbohydrate energy policies can be an efficient approach to reducing carbon emission levels. Furthermore, the results indicate that noncarbohydrate energy consumption can contribute to the creation of an inverted U-shaped relationship between economic development and environmental degradation.

This paper highlights the importance of reducing the level of primary energy consumption as much as increasing noncarbohydrate energy consumption due to the low shares of noncarbohydrate energy consumption in most economies at absolute levels. For example, even in Denmark, with the highest renewable energy consumption in 2010 among the economies analyzed in this study, the share of noncarbohydrate energy consumption is reached 13% (British Petroleum (BP), Statistical Review of World Energy, 2011). Hence, there is far to go before reaching environmental targets stated by the Kyoto Protocol. The encouraging progress is that the production capacity of noncarbohydrate energy is rapidly increasing. Between 2004 and 2014, the renewable energy power capacity more than doubled, and increased 1712 GW. Furthermore, in 2014, 270 billion dollars invested in renewable energy sources (REN21, Renewables 2015 Global Status Report, 2015). Therefore, regardless of the ratio of reduction of carbon emissions provided from non-conventional energy resources, noncarbohydrate energy consumption should be promoted in order to decrease carbon emission levels. Moreover, it can be argued that these countries with a relatively have mature noncarbohydrate energy infrastructure and more effective policies should cooperate in developing joint policies in order to enhance environmental protection. However, it must be underlined that most important factor in nuclear power plant generation is the potential danger to the environment and humankind arising from a possible accident. This emphasizes the need for adequate safety precautions implemented as part of nuclear energy policy.

APPENDIX A : IMPORTANT DATES FOR CLIMATE CHANGE CONVENTION AND KYOTO PROTOCO.

	Climate Change Convention			Kyoto Protocol		
ANNEX I	**Date of Signature**	**Date of Ratification**	**Date of Entry into Force**	**Date of Signature**	**Date of Ratification**	**Date of Entry into Force**
Australia	04.06.1992	30.12.1992	21.03.1994	29.04.1998	12.12.2007	11.03.2008
Austria	08.06.1992	28.02.1994	29.05.1994	29.04.1998	31.05.2002	16.02.2005
Belarus	11.06.1992	11.05.2000	09.08.2000		26.08.2005	24.11.2005
Belgium	04.06.1992	16.01.1996	15.04.1996	29.04.1998	31.05.2002	16.02.2005
Bulgaria	05.06.1992	12.05.1995	10.08.1995	18.09.1998	15.08.2002	16.02.2005
Canada*	12.06.1992	04.12.1992	21.03.1994	29.04.1998	17.12.2002	16.02.2005
Croatia	11.06.1992	08.04.1996	07.07.1996	11.03.1999	30.05.2007	28.08.2007
Cyprus	12.06.1992	15.10.1997	13.01.1998		16.07.1999	16.02.2005
Czech Republic	18.06.1993	07.10.1993	21.03.1994	23.11.1998	15.11.2001	16.02.2005
Denmark	09.06.1992	21.12.1993	21.03.1994	29.04.1998	31.05.2002	16.02.2005
Estonia	12.06.1992	27.07.1994	25.10.1994	03.12.1998	14.10.2002	16.02.2005
European Union	13.06.1992	21.12.1993	21.03.1994	29.04.1998	31.05.2002	16.02.2005
Finland	04.06.1992	03.05.1994	01.08.1994	29.04.1998	31.05.2002	16.02.2005
France	13.06.1992	25.03.1994	23.06.1994	29.04.1998	31.05.2002	16.02.2005
Germany	12.06.1992	09.12.1993	21.03.1994	29.04.1998	31.05.2002	16.02.2005
Greece	12.06.1992	04.08.1994	02.11.1994	29.04.1998	31.05.2002	16.02.2005
Hungary	13.06.1992	24.02.1994	25.05.1994		21.08.2002	16.02.2005
Iceland	04.06.1992	16.08.1993	21.03.1994		23.05.2002	16.02.2005
Ireland	13.06.1992	20.04.1994	19.06.1994	29.04.1998	31.05.2002	16.02.2005
Italy	05.06.1992	15.04.1994	14.07.1994	29.04.1998	31.05.1998	16.02.2005
Japan						
Latvia	11.06.1992	23.03.1995	21.06.1995	14.12.1998	05.07.2002	16.02.2005
Liechtenstein	04.06.1992	22.06.1994	20.09.1994	29.06.1998	03.12.2004	03.03.2005
Lithuania	11.06.1992	24.03.1995	22.06.1995	21.09.1998	03.01.2003	16.02.2005
Luxembourg	09.06.1992	09.05.1994	07.08.1994	29.04.1998	31.05.2002	16.02.2005
Malta	12.06.1992	17.03.1994	15.06.1994	17.04.1998	11.11.2001	16.02.2005
Monaco	11.06.1992	24.11.1992	21.03.1994	29.04.1998	27.02.2006	28.05.2006
Netherlands	04.06.1992	20.12.1993	21.03.1994	29.04.1998	31.05.2002	16.02.2005
New Zealand	04.06.1992	16.09.1993	21.03.1994	22.05.1998	19.12.2002	16.02.2005
Norway	09.06.1992	09.06.1993	21.03.1994	29.04.1998	30.05.2002	16.02.2005
Poland	05.06.1992	28.07.1994	26.10.1994	15.07.1998	13.12.2002	16.02.2005
Portugal	13.06.1992	21.12.1993	21.03.1994	29.04.1998	31.05.2002	16.02.2005
Romania	05.06.1992	08.06.1994	06.09.1994	05.01.1999	19.03.2001	16.02.2005
Russian Federation	13.06.1992	28.12.1994	28.03.1995	11.03.1999	18.11.2004	16.02.2005
Slovakia	19.05.1993	25.08.1994	23.11.1994	26.02.1999	31.05.2002	16.02.2005
Slovenia	13.06.1992	01.12.1995	29.02.1996	21.10.1998	02.08.2002	16.02.2005
Spain	13.06.1992	21.12.1993	21.03.1994	29.04.1998	31.05.2002	16.02.2005
Sweden	08.06.1992	23.06.1993	21.03.1994	29.04.1998	31.05.2002	16.02.2005
Switzerland	12.06.1992	10.12.1993	21.03.1994	16.03.1998	09.07.2003	16.02.2005
Turkey		24.02.2004	24.05.2004		28.05.2009	26.08.2009
Ukraine	11.06.1992	13.05.1997	11.08.1997	15.03.1999	12.04.2004	16.02.2005
UK	12.06.1992	08.12.1993	21.03.1994	29.04.1998	31.05.2002	16.02.2005
US	12.06.1992	15.10.1992	21.03.1994	12.11.1998		

* Canada withdrew convention on 15.12.2012

Source: United Nations Framework Convention on Climate Change, http://unfccc.int/parties_and_observers/parties/annex_i/items/2774.php

APPENDIX B : UNIT ROOT TEST RESULTS FOR CARBON EMISSIONS (MEASURED IN METRIC TONS PER CAPITA)

	LEVEL (*Trend & Intercept*)			1st difference (*Intercept, no trend*)		
	ADF	DF- GLS	PP	ADF	DF- GLS	PP
Australia						
lnae	-3.370*** (0)	-1.705 (0)	-3.574** (5)	-7.788* (0)	-2.243** (2)	-7.79* (1)
lnco	-1.256 (1)	-0.84 (0)	-0.282 (9)	-7.043* (0)	-6.66* (0)	-7.045* (1)
lneu	-1.663 (1)	-1.094 (0)	-1.506 (3)	-7.915* (0)	-7.992* (0)	-7.861* (4)
lny	-1.988 (0)	-1.92 (0)	-2.133 (1)	-5.948* (0)	-5.067* (0)	-5.897* (3)
lny2	-1.967 (0)	-1.955 (0)	-2.12 (1)	-5.963* (0)	-5.049* (0)	-5.907* (4)
Austria						
lnae	-2.075 (1)	-1.714 (1)	-2.041 (8)	-8.900* (0)	-8.298* (0)	-9.598* (11)
lnco	-2.52 (0)	-1.691 (0)	-2.421 (2)	-7.699* (0)	-7.464* (0)	-7.684* (3)
lneu	-2.271 (0)	-1.408 (0)	-2.273 (1)	-6.182* (0)	-6.193* (0)	-6.171* (2)
lny	-0.966 (0)	-0.600 (1)	-0.994 (1)	-5.115* (0)	-4.412* (1)	-5.189* (3)
lny2	-0.869 (0)	-0.665 (1)	-0.909 (1)	-5.282* (0)	-4.712* (0)	-5.345* (3)
Belgium						
lnae	-0.874 (4)	-1.107 (4)	-1.363 (3)	-4.275* (3)	-4.303* (3)	-6.000* (3)
lnco	-2.573 (0)	-1.775 (0)	-2.597 (2)	-6.786* (0)	-6.625* (0)	-6.793* (2)
lneu	-2.776 (1)	-1.655 (1)	-2.311 (3)	-5.397* (0)	-5.414* (0)	-5.407* (2)
lny	-1.494 (0)	-0.755 (2)	-1.494 (0)	-2.966** (1)	-2.358** (1)	-5.163* (2)
lny2	-1.357 (0)	-0.806 (2)	-1.357 (0)	-5.329* (0)	-2.558** (1)	-5.349* (2)
Canada						
lnae	0.0780 (0)	-0.727 (1)	0.078 (1)	-4.839* (0)	-4.167* (0)	-4.819* (2)
lnco	-1.603 (0)	-1.191 (1)	-1.611 (1)	-5.587* (0)	-5.234* (0)	-5.729* (3)
lneu	-2.172 (1)	-1.173 (1)	-1.522 (2)	-3.885* (0)	-3.929* (0)	-3.911* (1)
lny	-2.545 (1)	-1.545 (1)	-1.808 (2)	-4.765* (0)	-4.674* (0)	-4.780* (1)
lny2	-2.505 (1)	-1.621 (1)	-1.787 (2)	-4.844* (0)	-4.738* (0)	-4.863* (1)
Chile						
lnae	-3.734** (1)	-3.726** (1)	-2.765 (6)	-5.718* (1)	-4.952* (1)	-5.917* (3)
lnco	-2.781 (1)	-1.934 (1)	-2.191 (2)	-4.254* (0)	-4.283* (0)	-4.247* (2)
lneu	-2.906 (1)	-1.805 (1)	-2.584 (1)	-4.387* (0)	-4.371* (0)	-4.343* (1)
lny	-5.718*** (1)	-2.121 (1)	-3.166 (0)	-3.943* (0)	-2.489** (0)	-4.154* (3)
lny2	-3.339*** (1)	-2.053 (1)	-3.173 (0)	-3.914* (0)	-3.834* (0)	-4.127* (3)
Denmark						
lnae	-2.331 (1)	-1.419 (1)	-2.184 (4)	-3.999* (0)	-3.911* (0)	-4.003* (3)
lnco	-3.451*** (0)	-1.524 (1)	-3.451*** (0)	-4.099* (3)	-7.655* (0)	-8.301* (2)

lneu	-3.481*** (3)	-1.501 (0)	-3.580** (3)	-5.832* (4)	-5.400* (0)	-5.796* (2)
lny	-1.510(1)	-1.036 (1)	-1.622 (3)	-5.736* (0)	-4.346* (0)	-5.726* (1)
lny2	-1.554 (1)	-1.179 (1)	-1.575 (3)	-5.733* (0)	-4.498* (0)	-5.726* (1)
Finland						
lnae	-1.766 (4)	-1.907 (4)	-1.221 (2)	-4.487* (1)	-0.864 (3)	-8.073* (3)
lnco	-2.620 (0)	-1.452 (0)	-2.870 (10)	-6.282* (0)	-6.258* (0)	-6.282* (0)
lneu	-2.106 (0)	-1.174 (0)	-2.156 (10)	-6.516* (0)	-6.514* (0)	-6.516* (0)
lny	-2.177 (2)	-1.672 (2)	-1.838 (1)	-4.833* (1)	-2.451** (2)	-4.351* (5)
lny2	-2.240 (2)	-1.838 (2)	-1.618 (0)	-4.921* (1)	-4.064* (1)	-4.369* (5)
France						
lnae	-1.322 (3)	-1.904 (3)	-0.344 (5)	-3.611* (1)	-2.903* (1)	-6.827* (5)
lnco	-2.648 (0)	-1.410 (0)	-2.660 (1)	-6.910* (0)	-6.695* (0)	-6.935* (3)
lneu	-1.697 (0)	-0.764 (0)	-1.697 (0)	-5.606* (0)	-5.602* (0)	-5.695* (3)
lny	-1.750 (1)	-0.857 (0)	-1.507 (0)	-3.735* (0)	-3.414* (0)	-3.628* (2)
lny2	-1.606 (1)	-0.879 (1)	-1.279 (0)	-3.877* (0)	-3.624* (0)	-3.793* (2)
Greece						
lnae	-3.269*** (0)	-2.445 (0)	-3.272*** (1)	-6.396* (0)	-6.694* (0)	-7.844* (5)
lnco	-2.912 (2)	-0.856 (4)	-1.176 (3)	-3.131** (1)	-3.140* (1)	-5.617* (3)
lneu	-1.839 (0)	-0.758 (2)	-1.792 (1)	-3.643* (0)	-0.223 (5)	-3.602* (3)
lny	-2.029 (1)	-1.263 (3)	-2.430 (3)	-4.113* (0)	-0.737 (2)	-4.207* (4)
lny2	-1.961 (1)	-1.328 (3)	-2.281 (3)	-4.082* (0)	-0.870 (2)	-4.178* (4)
Iceland						
lnae	-2.162 (2)	-1.780 (2)	-1.618 (2)	-5.170* (0)	-3.149* (1)	-5.170* (0)
lnco	-3.219*** (0)	-3.292** (0)	-3.125 (2)	-9.411* (0)	-2.009** (2)	-9.411* (0)
lneu	-2.289 (0)	-2.368 (0)	-2.368 (3)	-8.652* (0)	-1.969** (2)	-8.652* (0)
lny	-1.317 (4)	-1.410 (2)	-1.620 (3)	-4.227* (3)	-1.899*** (5)	-4.272* (3)
lny2	-1.339 (4)	-1.518 (2)	-1.663 (3)	-4.227* (3)	-1.870*** (5)	-4.285* (3)
Ireland						
lnae	-0.100 (1)	-1.872 (0)	-1.937 (0)	-10.076* (0)	-0.623 (3)	-9.766* (2)
lnco	-0.742 (0)	-1.752 (2)	-1.157 (3)	-6.717* (0)	-1.338 (1)	-6.626* (3)
lneu	-1.172 (0)	-1.532 (0)	-1.459 (3)	-6.893* (0)	-1.095 (2)	-6.847* (2)
lny	-2.643 (5)	-2.828 (5)	-1.449 (4)	-2.850*** (0)	-2.848* (0)	-2.831*** (2)
lny2	-2.723 (5)	-2.860 (5)	-1.508 (4)	-2.777*** (0)	-2.770* (0)	-2.766*** (2)
Israel						
lnae	-1.998 (0)	-2.057(0)	-2.156 (1)	-5.472* (0)	-5.527* (0)	-5.458* (2)
lnco	-2.660 (5)	-2.751 (5)	-1.325 (3)	-7.210* (0)	-7.298* (0)	-7.130* (3)
lneu	-3.818** (0)	-3.834* (0)	-3.904** (3)	-11.73* (0)	-4.853* (1)	-11.759* (3)
lny	-2.658 (1)	-2.654 (1)	-2.033 (0)	-5.907 (0)	-3.531* (0)	-5.908* (3)
lny2	-2.651 (1)	-2.613 (1)	-1.994 (0)	-5.815* (0)	-3.626* (0)	-5.815* (3)

Italy						
lnae	-2.514 (0)	-2.656 (0)	-2.435 (1)	-8.538* (0)	-8.033* (0)	-8.514* (3)
lnco	-4.229* (0)	-0.684 (3)	-3.928** (3)	-2.526 (2)	-0.526 (2)	-3.744* (3)
lneu	-4.500* (0)	-1.310 (4)	-4.389* (3)	-2.247 (3)	-0.191 (3)	-4.392* (3)
lny	-0.433 (0)	-0.311 (3)	-0.299 (4)	-4.779* (0)	-1.858*** (1)	-4.774* (3)
lny2	-0.151 (0)	-0.318 (3)	0.039 (4)	-4.854* (0)	-2.039** (1)	-4.854* (3)
Japan						
lnae	-1.053 (5)	-1.883 (5)	0.103 (3)	-1.190 (4)	-0.835 (4)	-7.292* (2)
lnco	-2.415 (1)	-1.636(3)	-3.002 (4)	-2.022 (2)	-0.606 (2)	-4.935* (4)
lneu	-2.751 (1)	-1.688 (3)	-2.662 (4)	-1.951 (2)	-1.131 (2)	-3.896* (4)
lny	-2.347 (2)	-1.127 (4)	-2.242 (3)	-2.064 (3)	-0.766 (3)	-3.923* (2)
lny2	-2.027 (2)	-1.121 (4)	-1.853 (3)	-2.010 (3)	-0.887 (3)	-4.075* (2)
Korea Republic						
lnae	-0.795 (0)	-0.927 (0)	-0.551 (9)	-5.721* (0)	-5.635* (0)	-5.708* (4)
lnco	-1.467 (0)	-1.281 (0)	-1.387 (1)	-6.226* (0)	-6.091* (0)	-6.226* (2)
lneu	-0.509 (0)	-0.659 (0)	-0.4855 (2)	-5.382* (0)	-5.418* (4)	-5.439* (3)
lny	-0.462 (0)	-0.634 (0)	-0.421 (2)	-5.093* (0)	-5.035* (0)	-5.104* (1)
lny2	-0.671 (0)	-0.939 (0)	-0.706 (1)	-5.527* (0)	-5.353* (0)	-5.527* (0)
Luxembourg						
lnae	-4.633* (1)	-4.193* (1)	-6.274* (0)	-10.799* (0)	-0.110 (5)	-26.563* (20)
lnco	-2.554 (1)	-2.581 (1)	-2.144 (1)	-5.312 (0)	-5.333 (0)	-5.239* (4)
lneu	-2.314 (1)	-2.312 (1)	-1.889 (0)	-5.700 (0)	-5.719 (0)	-5.635* (6)
lny	-2.280 (1)	-2.135 (1)	-1.924 (1)	-5.597* (0)	-5.652* (0)	-5.561* (3)
lny2	-2.283 (1)	-2.066 (1)	-1.949 (1)	-5.559* (0)	-5.617* (0)	-5.549* (2)
Mexico						
lnae	-0.089 (1)	-0.821 (0)	-0.258 (1)	-7.159* (0)	-7.254* (0)	-7.092* (3)
lnco	-2.263 (0)	-1.585 (0)	-2.223 (1)	-3.201** (1)	-3.267* (1)	-6.868* (3)
lneu	-2.816 (0)	-1.310 (2)	-2.710 (2)	-4.357* (0)	-2.130** (1)	-4.398* (3)
lny	-2.901 (1)	-2.283 (1)	-2.734 (1)	-4.910* (0)	-4.344* (0)	-4.853* (3)
lny2	-2.900 (1)	-2.316 (1)	-2.717 (1)	-4.941* (0)	-4.412* (0)	-4.884* (3)
Netherlands						
lnae	-1.623 (2)	-2.060 (5)	-1.320 (3)	-4.660* (1)	-4.582* (1)	-4.485* (9)
lnco	-2.636 (0)	-1.553 (0)	-2.634 (3)	-6.680* (0)	-6.662* (0)	-6.680* (0)
lneu	-2.793 (0)	-1.412 (1)	-2.713 (2)	-4.815* (0)	-4.812* (0)	-4.880* (3)
lny	-2.741 (1)	-1.744 (1)	-1.669 (2)	-4.738* (0)	-3.643* (0)	-4.865* (3)
lny2	-2.688 (1)	-1.826 (1)	-1.669 (2)	-4.771* (0)	-3.675* (0)	-4.878* (3)
New Zealand						
lnae	-1.969 (0)	-2.186 (0)	-1.922 (1)	-6.547* (0)	-2.354** (1)	-6.532* (3)
lnco	-1.265 (0)	-1.459 (0)	-1.754 (3)	-5.531* (0)	-1.936* (1)	-5.531* (0)

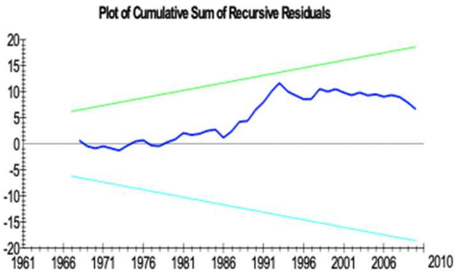
lneu	-0.918 (0)	-1.085 (0)	-1.162 (2)	-4.558* (0)	-4.075* (0)	-4.512* (2)
lny	-1.874 (1)	-1.964 (1)	-1.734 (1)	-4.670* (0)	-4.547* (0)	-4.708* (2)
lny2	-1.848 (1)	-1.935 (1)	-1.719 (1)	-4.676* (0)	-4.549* (0)	-4.714* (2)
Norway						
lnae	-2.070 (4)	-1.046 (1)	-2.422 (0)	-4.362* (3)	-8.760* (0)	-9.064* (0)
lnco	-2.690 (2)	-1.565 (2)	-2.381 (3)	-4.245* (1)	-4.247* (1)	-10.397* (3)
lneu	-4.096** (5)	-1.510 (2)	-3.024 (8)	-3.235** (1)	-3.270* (1)	-6.916* (3)
lny	0.412 (1)	-0.517 (1)	0.740 (2)	-3.604* (0)	-2.902* (0)	-3.626* (3)
lny2	0.238 (1)	-0.726 (1)	0.765 (2)	-3.568** (0)	-3.034* (0)	-3.592* (3)
Portugal						
lnae	-3.830** (3)	-2.086 (4)	-5.444* (3)	-5.368* (3)	-4.289* (3)	-11.322* (3)
lnco	0.574* (5)	-1.263 (3)	0.086 (4)	-1.622 (2)	-1.232 (2)	-6.145* (5)
lneu	0.143 (0)	-0.239 (0)	0.243 (2)	-6.086* (0)	-1.940*** (2)	-6.271* (4)
lny	-2.101 (4)	-1.030 (4)	-1.497 (3)	-2.921*** (3)	-2.863* (3)	-4.353* (4)
lny2	-1.959 (4)	-1.073 (4)	-1.410 (3)	-3.087** (3)	-3.084* (3)	-4.421* (4)
Spain						
lnae	-1.755 (0)	-1.779 (0)	-1.786 (4)	-7.714* (0)	-7.779* (0)	-7.686* (3)
lnco	-1.709 (3)	-1.304 (3)	-1.078 (4)	-0.756 (2)	-0.432 (2)	-5.048* (4)
lneu	-1.483 (4)	-1.419 (3)	-0.830 (4)	-1.488 (3)	-1.470 (3)	-4.194* (4)
lny	-2.096 (1)	-1.091 (1)	-3.052 (4)	-3.332** (0)	-3.332** (0)	-3.332** (0)
lny2	-2.101 (1)	-1.218 (1)	-2.808 (4)	-3.287** (0)	-1.687*** (0)	-3.287** (0)
Sweden						
lnae	-0.226 (0)	-0.972 (3)	-0.216 (4)	-6.797* (0)	-5.360* (0)	-6.870* (4)
lnco	-2.769 (0)	-1.706 (0)	-2.769 (0)	-7.668* (0)	-7.668* (0)	-7.695* (3)
lneu	-2.656 (5)	-1.144 (0)	-2.172 (0)	-6.841* (0)	-6.764* (0)	-6.926* (4)
lny	-2.788 (1)	-1.850 (1)	-2.677 (0)	-5.122* (0)	-4.140* (0)	-5.040* (3)
lny2	-2.779 (1)	-1.965 (1)	-2.583 (0)	-5.172* (0)	-4.299* (0)	-5.059* (4)
Switzerland						
lnae	-2.708 (0)	-2.376 (0)	-2.502 (6)	-6.018* (0)	-5.536* (0)	-6.240* (4)
lnco	-4.352* (0)	-4.492* (0)	-4.354* (1)	-6.684* (1)	-6.747*(0)	-13.70* (17)
lneu	-2.017 (0)	-2.175 (0)	-1.559 (5)	-6.489* (0)	-5.737* (0)	-6.747* (5)
lny	-3.136 (1)	-3.238** (1)	-2.295 (3)	-4.383* (1)	-4.458* (1)	-3.771* (13)
lny2	-3.124 (1)	-3.224** (1)	-2.294 (3)	-4.376* (1)	-4.450* (1)	-3.778* (13)
Turkey						
lnae	-2.424 (0)	-2.122 (0)	-2.424 (0)	-9.056* (0)	-7.548* (0)	-9.129* (3)
lnco	-2.480 (0)	-1.360 (0)	-2.502 (6)	-7.002* (0)	-6.712* (0)	-7.003* (1)
lneu	-2.325 (0)	-2.133 (0)	-2.360 (1)	-6.942* (0)	-6.241* (0)	-6.943* (1)
lny	-3.798** (3)	-2.919*** (0)	-3.048 (1)	-4.590* (3)	-6.506* (0)	-7.274* (1)
lny2	-3.798** (3)	-3.027 (0)	-3.085 (1)	-4.667* (3)	-6.629* (0)	-7.300* (2)

United Kingdom						
lnae	-3.113 (0)	-1.481 (3)	-3.029 (3)	-4.557* (0)	-2.269** (2)	-4.712* (4)
lnco	-2.725 (0)	-2.552 (0)	-2.788 (2)	-7.773* (0)	-7.586* (0)	-7.859* (4)
lneu	-1.305 (0)	-1.054 (0)	-1.332 (2)	-6.407* (0)	-6.390* (0)	-6.463* (3)
lny	-2.700 (1)	-2.861 (1)	-1.767 (1)	-5.108* (0)	-5.126* (0)	-5.084* (2)
lny2	-3.023 (1)	-3.181*** (1)	-1.464 (0)	-5.085* (0)	-5.089* (0)	-5.060* (2)
United States						
lnae	-0.458 (1)	-1.627 (3)	-0.250 (4)	-2.371 (1)	-2.400** (1)	-3.749* (4)
lnco	-2.782 (1)	-1.910 (1)	-1.705 (0)	-4.715* (0)	-4.430* (0)	-4.778* (1)
lneu	-2.754 (1)	-1.513 (3)	-1.795 (0)	-4.350* (0)	-4.320* (0)	-4.350* (0)
lny	-3.201*** (1)	-2.592 (1)	-1.472 (5)	-4.787* (1)	-4.519* (1)	-4.905* (5)
lny2	-3.380*** (1)	-2.871 (1)	-1.692 (4)	-4.843* (1)	-4.538* (1)	-4.901* (6)

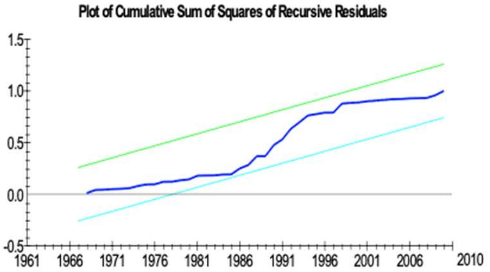
Notes: Unit root tests ADF, DF-GLS and PP include intercept and trend in levels, include intercept in first differences. Numbers of lags are represented in (). *, **and *** represent 1%, 5%, 10% significance levels, respectively.

APPENDIX C: PLOT OF CUSUM AND CUSUMSQ TESTS FOR PARAMETER STABILITY.

Canada

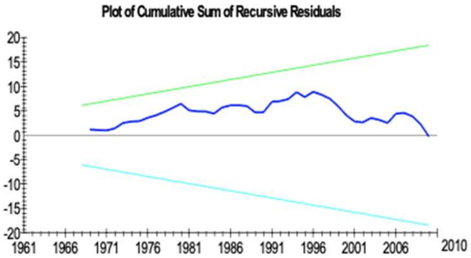

Plot of Cumulative Sum of Recursive Residuals

The straight lines represent critical bounds at 5% significance level

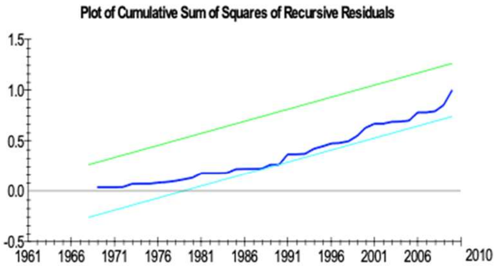

Plot of Cumulative Sum of Squares of Recursive Residuals

The straight lines represent critical bounds at 5% significance level

Denmark

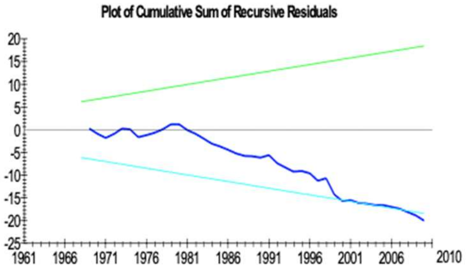

Plot of Cumulative Sum of Recursive Residuals

The straight lines represent critical bounds at 5% significance level

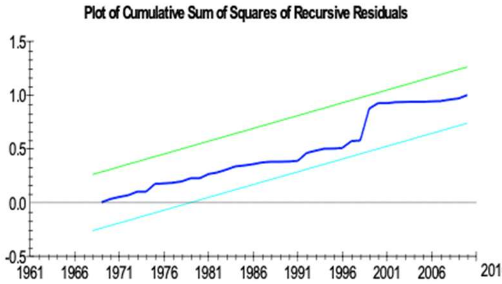

Plot of Cumulative Sum of Squares of Recursive Residuals

The straight lines represent critical bounds at 5% significance level

France

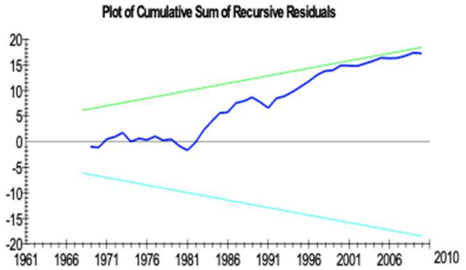

Plot of Cumulative Sum of Recursive Residuals

The straight lines represent critical bounds at 5% significance level

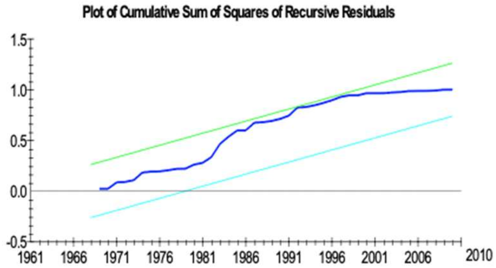

Plot of Cumulative Sum of Squares of Recursive Residuals

The straight lines represent critical bounds at 5% significance level

Greece

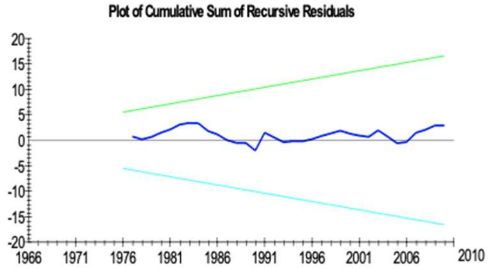


The straight lines represent critical bounds at 5% significance level

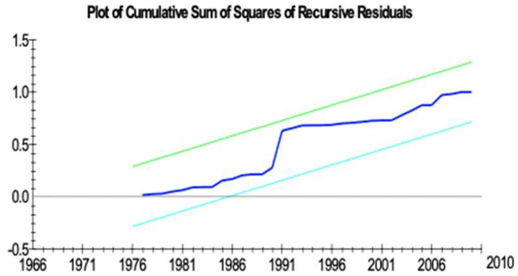


The straight lines represent critical bounds at 5% significance level

Hungary

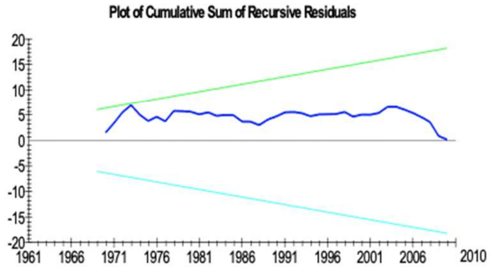


The straight lines represent critical bounds at 5% significance level

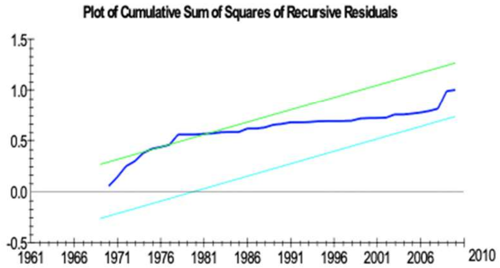


The straight lines represent critical bounds at 5% significance level

Italy

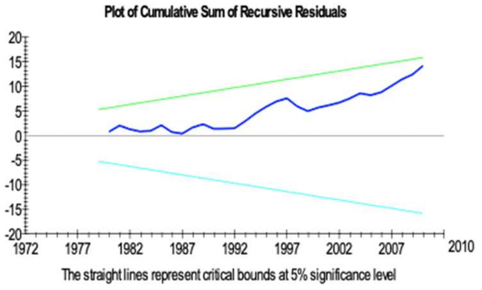


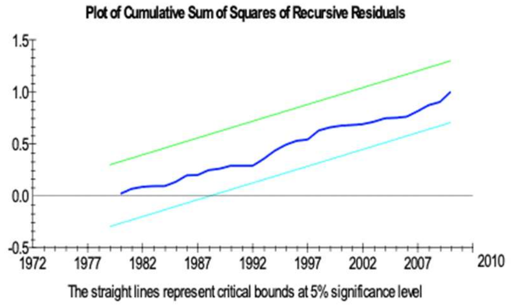
The straight lines represent critical bounds at 5% significance level



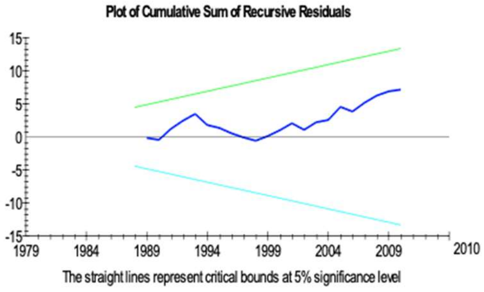
The straight lines represent critical bounds at 5% significance level

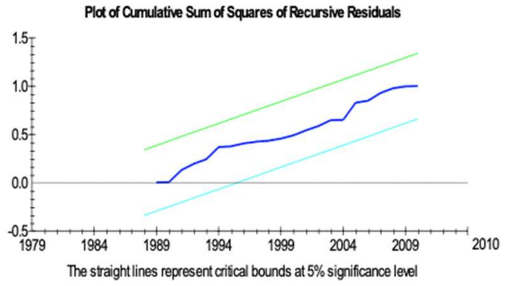
Korea





New Zealand





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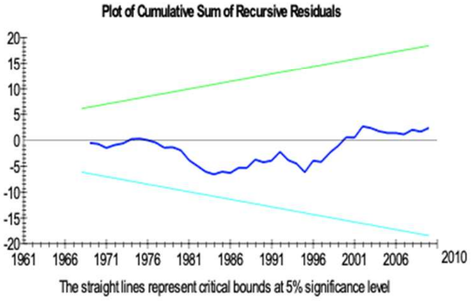

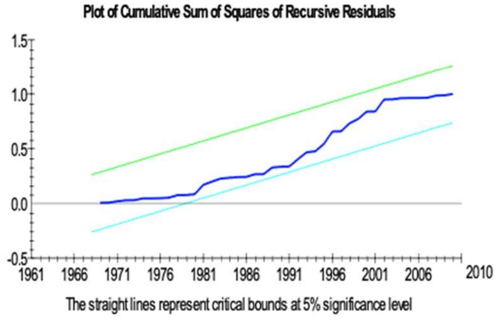

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Academic Activities

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“The Relationship between Greenhouse Gases and Coal: Does coal responsible for all?” Fortune Turkey, June 2013

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