Master's Thesis of City Planning in Environmental Studies

The impact of renewable energy production on fossil fuel imports

– Evidence from OECD countries –

재생에너지 생산이 화석연료 수입에 미치는 영향: OECD 국가를 중심으로

August 2022

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City Planning in Environmental Studies

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Confirming the master's thesis written by
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August 2022

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Abstract

The key purpose of this research is to empirically investigate the impact of domestic renewable energy production on fossil fuel imports. The data sample is composed of 17 OECD countries for the time period 2000–2019. A panel Autoregressive Distributed Lag (ARDL) model with 1 lag for each variable was used for analysis with Mean Group (MG), Pooled Mean Group (PMG), and Dynamic Fixed Effects (DFE) estimators. The Hausman test showed that PMG estimator is most suitable for all fossil fuel econometric models. PMG analysis results reveal that the renewable energy production reduces coal and natural gas imports but not for oil imports. Furthermore, from examining additional explanatory variables, the real GDP per capita variable indicates that OECD countries are reducing coal and oil imports but are increasing natural gas imports in the long–run while showing economic growth. Crude oil prices also positively affect coal imports while negatively affecting natural gas imports in the long–run. The percentage of GDP in manufacturing also indicate that higher shares mean higher imports for coal and oil. Lastly energy consumption in the transport sector positively affect oil and natural gas imports. The analysis results imply that renewable energy can reduce coal and natural gas imports and thus enhance energy security. Countries are also reducing coal and oil imports while experiencing economic growth in the context of climate change but are increasing natural gas imports due to its role as a transition fuel. Future climate change policies for the industrial and transport sector which increase efficiency and reduce consumption may also aid countries in reducing fossil fuel imports and enhance energy security, indicating that climate change objectives and energy security objectives are simultaneously achievable.

Keywords: renewable energy, fossil fuel imports, energy security, panel ARDL, PMG estimation
Student Number: 2020–23881

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Chapter 1. Introduction

Energy is considered to be a key driver for economic growth as it is a necessity for production of all goods and services. Nobel laureate economist E. F. Schumacher once stated that energy is the "precondition of all commodities, a basic factor equal with air, water, and earth" (Paravantis and Kontoulis, 2020). Therefore, maintaining a sustainable energy supply is essential for all countries and hence energy security is considered to be a priority for all national governments.

While energy security is considered a crucial objective, there is no universal definition for this concept. According to Sovacool and Mukherjee (2011), based on their synthesised mixed methods assessment of energy security, the concept can be categorised into 20 separate dimensions which are represented through 320 simple and 52 complex indicators. In addition, Ang et al. (2015) conducted a literature survey covering 104 energy security studies. Within this literature, a total of 83 energy security definitions could be identified based on seven major themes (ibid.).[①] These studies show that the definition of energy security is very broad and subsequently, a standardised method for measuring and assessing is absent.

While the concept of energy security can be ambiguous, this paper attempts to analyse one of its key aspects, that being energy imports. Since the Industrial Revolution, the consumption of fossil fuel played a key part in inducing economic growth. According to

[①] 1) Energy Availability, 2) Infrastructure, 3) Energy Prices, 4) Societal Effects, 5) Environment, 6) Governance, and 7) Energy Efficiency

Figure 1.1, the global consumption amount in fossil fuels has increased significantly, with coal showing increases since the mid-19th Century, while oil and natural gas consumption has increased since the early and mid-20th Century, respectively.

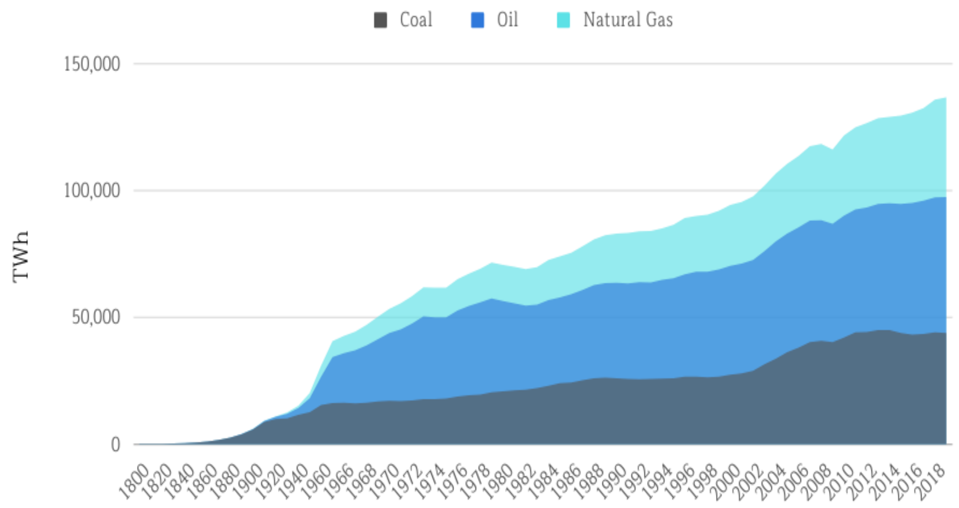

Figure 1.1. Global Fossil Fuel Consumption (Ritchie and Roser, 2020)

However, fossil fuel itself is considered to be unequally distributed among countries. As shown in Table 1.1, it is shown that the share of total proved reserves for the top 5 highest countries for coal, oil and natural gas are 75.9%, 61.9% and 64% respectively in 2020. Such figures highlight the biased distribution in proven reserves.

Despite such biased proven reserves, globalisation and trade openness have led to countries with no domestic fossil fuel production being able to import the energy resources necessary for economic growth. However, the rise of exporter-importer relationships has led to importing countries becoming vulnerable in conflicts with other exporting countries. Over the past half-century, there have been numerous examples of conflicts where energy resources have been weaponised by exporting countries.

Table 1.1. Share of Total Proved Reserves at end 2020 (BP, 2021)

Coal		Oil		Natural Gas	
Country	**Share of Total**	**Country**	**Share of Total**	**Country**	**Share of Total**
US	23.2%	Venezuela	17.5%	Russia	19.9%
Russia	15.1%	Saudi Arabia	17.2%	Iran	17.1%
Australia	14.0%	Canada	9.7%	Qatar	13.1%
China	13.3%	Iran	9.1%	Turkmenistan	7.2%
India	10.3%	Iraq	8.4%	US	6.7%
Total	**75.9%**	**Total**	**61.9%**	**Total**	**64%**

The first-time energy security was articulated was during the 1970s oil shock, which is described by Dannreuther (2017) as the "first energy security crisis". Oil exporting countries in the Middle East imposed an embargo for retaliation against the United States and other industrialised countries which supported Israel in the Yom Kippur War against Egypt (Macalister, 2011). Due to these imposed sanctions, crude oil prices increased drastically from 3 USD per barrel to 12 USD per barrel in 1974 (ibid.). Since then, such drastic patterns have constantly occurred in oil markets as shown in the US Crude oil Prices presented in Figure 1.2. Drastic price fluctuations can be harmful to an economy, as high price volatility of oil can damage economic growth through its influence on stock market returns and bilateral trade (Rentschler, 2013).

In addition, conflicts also arise for natural gas and coal. As for natural gas, in January 2009, supply negotiations between Russia and the Ukraine broke down, resulting in the gas supply to Europe becoming completely cut off for approximately two weeks (Pirani et al., 2009).

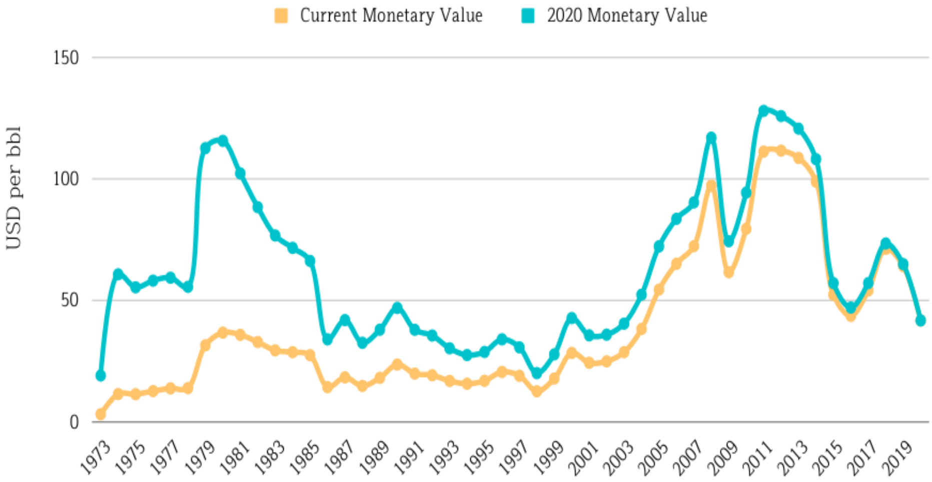

Figure 1.2. US Crude Oil Prices since 1973 (BP, 2021)

Such conflicts in natural gas have also re−risen today as a result of the Ukrainian War (Race, 2022; Rashad, 2022). The Russian government threatened to cut off natural gas exports to Western countries as a retaliation for imposed sanctions. Because Russia is a leading exporter, responsible for 21.0% of all inter−regional pipeline exports in 2020 (BP, 2021), this may cause significant damages to the European Economy.

Coal also shows possibility of conflicts, as shown with the case between Australia and China. With the rise of the COVID−19 pandemic, the Australian government called for an independent investigation into China’s handling of the outbreak, which led to China posing sanctions against importing Australian coal as an act of retaliation (Okano, 2021). This led to China facing a severe energy crisis due to shortage of coal supply (Choudhury, 2021). While the characteristics of the energy crisis of China is somewhat different to the other examples introduced for oil and natural gas, all three examples show how conflicts between nations can lead to significant shocks in the energy supply chain due to high dependence on imports.

Renewable energy, in this context, can alleviate the problems arising from the overdependence of fossil fuel imports as most renewable energy is produced from domestic sources. Many countries are increasing their generation capacity for renewable energy as a means to achieving the Paris Agreement Goal of limiting global warming to well below 2℃. Thus, while the environmental benefits of renewable energy are widely recognized in its role in tackling climate change, its contribution to substituting fossil fuel imports is given less attention.

Domac et al. (2005) stated that increasing renewable energy could increase GDP (C+I+G+X−M) in two ways. The first being expansion of new businesses related to the renewable energy sector (increase in I) and the second being the improvement in trade balance (increase in X−M) through the decreases in energy imports, the latter being defined as an import substitution effect. This research attempts to empirically present such effects.

Countries within the Organisation for Economic Co−operation and Development (OECD) possess significant potential regarding import substitution, as member countries are rapidly deploying renewable energy in their total energy supply but are still highly dependent on energy imports. However, research is rarely conducted on investigating the substituting relationship regarding this range of countries.

Therefore, this paper contributes to the existing literature by empirically investigating the effect of renewable energy on fossil fuel energy imports using data from 17 OECD countries over a 20-year period (2000-2019) using the Panel Autoregressive Distributed Lag (ARDL) model with Mean Group (MG), Pooled Mean Group (PMG) and Dynamic Fixed Effects (DFE) estimators.

The rest of the paper is structed as followed. Chapter 2 examines the existing literature related to this research. Chapter 3 presents the data and econometric model while also explaining the methodology in detail. Chapter 4 presents the analysis results and its interpretations. Chapter 5 presents the conclusion.

Chapter 2. Literature Review

As mentioned with regards to energy imports, there is lack of research within the literature compared to other more commonly looked factors such as economic growth, measured by GDP, and environmental quality, measured by CO_2 emissions. Therefore, this literature review also looks into other energy factors such as fossil fuel demand and electricity production as it is closely linked to imports. The existing literature is categorised into two parts. The first part reviews literature focusing on import dynamics, whereas the second part reviews its relationship with renewable energy.

2.1. Energy import dynamics

With regards to import dynamics, a majority of the studies focuses on oil imports and their relationship with other factors. Researchers have conducted various time-series data analysis for individual countries on their crude oil import demand.

Zhao and Wu (2007) conducted analysis on the determinants of China's oil imports. Explanatory variables considered were crude oil prices, domestic energy production, industrial output, and traffic volume. Using cointegration and vector error correction model (VECM) techniques for quarterly data between 1995-2006 (1998-2006 due to data availability for some variables), the authors deduced that international oil prices is not a major determinant of China's oil imports. On the contrary, industrial output and expansion in the transport sector shows positive effects on such imports, while domestic energy production, for coal and oil, presents a substitution effect towards energy imports.

Altinay (2007) conducted similar research for the case of Turkey. Two econometric models are incorporated with the difference being the use of nominal price (measured in US dollars) or real price (measured in Turkish lira) of crude oil while also including the real GDP variable. By using an ARDL bound testing approach to co-integration for annual data for the period 1980-2005, the bounds test results reveal that a long-run cointegration relationship exist for the first model including the nominal price variable, but not in the model that included real price in the local currency. Based on these ARDL model results, it was shown that income and price elasticities were inelastic for oil import demand in both the short-run and long-run.

Ghosh (2009) also gives research on the import dynamics for the case of India, using ARDL bounds testing approach of cointegration and Granger causality tests. Based on data for the time span 1970-2006, empirical results show that oil import prices have insignificant effects on quantities, both in the short and long-run. On the contrary, there exists a high-income elasticity for imported oil and the Granger causality results indicate a unidirectional long-run causality from economic growth to crude oil imports.

Last but not least, Kim and Baek (2013) look into the case for Korea, using the ARDL model for annual data between 1986-2010. Similar to other country level research, its variable of focus is import quantities and price with income. The ARDL model showed that in the long-run, income level is more important in determining the behaviour of oil imports, while in the short-run, oil prices are more significant. To summarise the literature on oil imports, it focuses more from an economic point of view, looking into price and income elasticities, rather than from the energy security context.

As for coal and natural gas imports, research on these resources are scarcer than oil imports. For coal, Wu and Zhang, (2016) look at the driving factors behind coal demand in China between 1997 to 2012 using input-output structural decomposition analysis for six major industries.[②] It was estimated that increase in domestic demand for five main industries, excluding mining industry, and foreign trade for all six industries positively contribute to the increase in coal demand. However, it also stated that industrial upgrading, in the form of improving utilisation efficiency and reducing coal intensity, is effective in alleviating such positive contributions to demand.

As for natural gas, Maxwell and Zhu (2011) empirically analyse the relationship between natural gas imports, consumption, prices, and transportation costs. By using Granger causality techniques alongside with error variance decomposition and VAR models, it shows that gas prices and shipping costs affect LNG imports, while the imports respond higher to shocks in gas prices rather than the shipping costs.

2.2. Relationship between renewable energy and energy imports

In the link between energy imports and renewable energy, some

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② 1) Electrical Power Industry, 2) Energy Processing Industry, 3) Metal Industry, 4) Mining Industry, 5) Building Materials Industry, and (6) Chemical Industry studies indicated that imports led to higher deployment for renewable energy. For instance, Marques et al. (2010) investigated on the possible motivations driving renewable energy in European countries using original least squares (OLS), random effects (RE), fixed effects (FE), and fixed effects vector decomposition (FEVD) techniques. Based on a panel data composed of 24 European countries between 1990-2006, they deduced that higher import dependency creates a positive effect on renewable energy development.

Research conducted by Bloch et al. (2015) examines the relationship between economic growth and the consumption of coal, oil and renewable sources for the case of China. ARDL and VECM methods are used with annual data between 1977-2013 for supply-side analysis and 1965-2011 for the demand-side analysis. Within the empirical results, it states that coal and oil prices have strong positive elasticities with respect to renewable energy consumption, highlighting that there is high opportunity of fuel substitution in the region.

Ibrahiem and Hanafy, (2021) investigated possible factors affecting renewable energy deployment for North African countries. Based on annual data from 1971-2014 for 3 countries (Egypt, Morocco and Tunisia), and using the PMG-ARDL model, it was shown that energy imports negatively affected the deployment of renewable energy, which is contrary to what Marques et al. (2010) and Bloch et al (2015) had presented. The authors imply that this may be due to the pressure of lobbies from traditional energy sources to local policies.

While it may be that the high dependence on fossil fuel imports led to countries increasing capacity for renewables, whether this increase successfully reduced such imports also need to be examined, which is also the focus of this research.

To empirically test the theory proposed by Domac et al. (2005), Chien and Hu (2008) conducted macroeconomic path analysis of whether renewable energy can contribute to economic growth by adopting 'structural equation modelling (SEM)'. By using cross-sectional data from 116 economies for the year 2003, the SEM results show that renewable energy positively contributes to GDP through capital formation (increase in I). However, contrary to the theory, it showed that the relationship between renewables and energy imports was significantly positive. The researchers explained that this may be due to exploitation of both renewables and energy imports when the country is in high demand. When conducting ceteris paribus analysis, controlling for all other variables so that the effect of renewables and energy imports was isolated, there was still no significant negative relationship to empirically support energy import substitution.

In research conducted by Xu et al. (2019), analysis was focused on the effect of energy imports on economic growth using the panel fixed effects model. Based on a balanced panel data set of 31 countries, consisting of both high-income OECD countries and low-income developing countries, over a period between 1996-2015, they empirically analysed that dependency for oil, coal, and natural gas all imposed a statistically significant negative effect on per capita GDP growth. However, through a positive interaction term, it had been showed that renewable energy can mitigate the negative effects of dependency on per capita GDP growth, but only for the case of oil imports. On the contrary, no significant signs showed for the interaction terms between renewable energy and dependency for coal and natural gas respectively.

Vaona (2016) investigates on a more direct effect of renewable energy on import demand. The paper uses data from 26 countries over different time periods, and adopts the panel system-GMM estimator with finite sample correction. The variables considered in the model were based on percentage changes rather than the absolute values, controlling for nuclear and fossil fuel electricity as well. It was shown that renewable energy production growth showed a significant negative effect on import growth. However, it should be noted that the main dependent variable was based on imported goods and services in general rather than specifically towards energy imports.

Research by Gökgöz and Güvercin (2018) also attempts to empirically confirm the substitution effect of renewables for energy imports. In their paper, based on 28 EU countries between the period 1992-2014, they construct multiple econometric panel models for coal, oil and natural gas and also electricity imports. The main independent variable was share of electricity generated from renewable sources, whereas that generated from combustion and nuclear sources alongside with GDP were considered as control variables. The empirical results confirm that renewable energy deployment has a statistically significant negative relationship with all three fossil fuel imports.

While the main focus was not fossil fuel imports and rather fossil fuel electricity production, Marques et al. (2018) also looked at whether a substitution effect existed between renewables and fossil fuels. Using a panel ARDL model and Driscoll and Kraay estimator with data for 10 EU countries between 1990-2014, it was shown that solar and hydro energy showed a statistically significant and negative effect on fossil fuel power generation but not for the case for wind power.

Last but not least, Najm and Matsumoto (2020) also investigated on whether renewable energy reduces liquified natural gas (LNG) international trade using the trade gravity model. The research uses unbalanced panel data from 1988 to 2017, where the cross-sectional dimension is not individual countries but observations of 1359 global trading partners of LNG. Based on the fixed effects OLS and GLS estimations, it was deduced that a higher ratio of renewable energy to the importer side led presented a statistically significant negative effect on import volume and value, both in its absolute term and per GDP terms. This indicated that renewables and natural gas are partial substitutes at the global level. However, sub-sample analysis by country group showed that the negative effect of renewable energy on LNG imports was significant only for OECD countries and was insignificant in the case for non-OECD countries. In addition, sub-sample analysis by time period showed that the negative effect of renewables on LNG imports was insignificant for the time period 2008-2017, for which the authors implied that the rising political will to support shale resources may have influenced this.

2.3. Contribution to the existing literature: Analysing OECD countries

Appendix (II) summarises the related literature on energy imports described in Section 2.1 and 2.2. Based on this literature, studies specifically looking at imports or demand for each fossil fuel focus on EU countries, which seem to yield positive results supporting the import substitution effect. However, the scope on OECD is given less attention. While OECD countries are included in the research sample by Xu et al. (2019) as 'high-income' countries, its focus was on the effects of energy imports on economic growth, rather than focusing on the relationship between renewables and energy imports.

While research on the EU is arguably significant, interconnecting characteristics between member countries may significantly influence the effects of renewable energy production on energy imports. For instance, cross-border electricity trade is significant in Europe, with electricity imports accounting for 9.1% of total electricity supplied in 2018, compared to 4.5%, 1.9% and 0.6% in Africa, the Americas, and Asia respectively (IEA, 2020). This is due to European countries having stronger interconnection capability and the most harmonised energy markets, with EU members functioning as a single market (ibid.). Such characteristics are more difficult to observe outside the European continent due to more limited interconnections and thus expanding outside the EU scope is necessary.

Therefore, this research attempts to expand from the EU scope to countries which are members of the OECD. OECD promotes free trade as one of its key objectives (CFI, 2021), and thus members actively engage in trading goods and services, including energy, with other countries. A majority of OECD members are considered to be net-importers of energy (World Bank, 2022), relying significantly on energy imports. Figure 2.1 highlights the energy import rates of selected OECD countries.

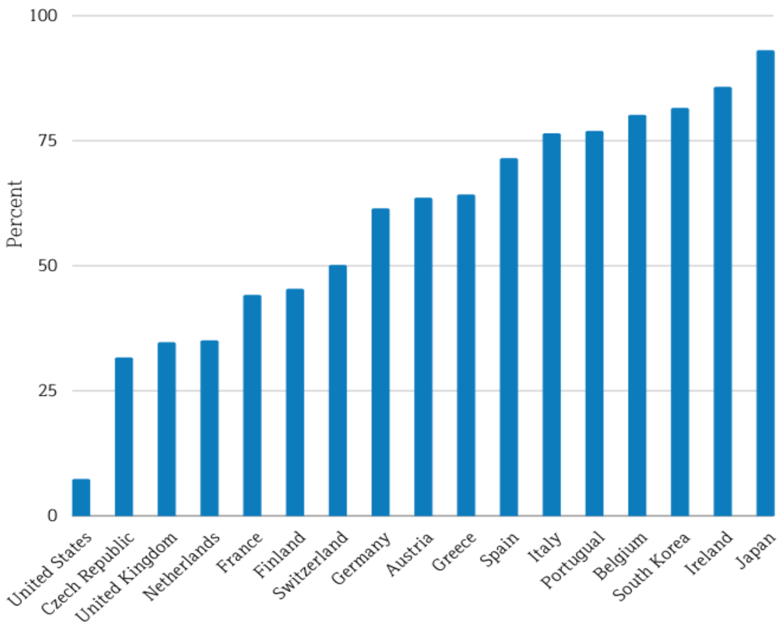

Figure 2.1. 2015 Energy Import Rates from Selected Net Importing OECD Countries (World Bank, 2022)[③]

While energy import rates are high, OECD members are also leading renewable energy deployment. According to BP (2021), approximately 56.8% of all renewable energy production are from members of the OECD. Therefore, research on the scope of the OECD

[③] Percentage rates are estimated as (consumption-production)/consumption*100 and excludes nuclear energy related imports.

presents a significant potential for investigating the import substitution effect, as both energy imports and renewable energy production are high.

Out of the 17 countries in the OECD analysis sample, the United States, South Korea, and Japan are the countries which are not members of the EU. These countries possess characteristics which differ from countries in the EU. In the case of Japan and South Korea, the two countries have high dependence on imports as production of energy from domestic sources is insufficient. Unlike EU countries, cross-border electricity trade is infeasible due to the two country's geographic status. South Korea and Japan share no land borders with other countries, with the exception of South Korea and North Korea, which is reflected in the fact that both nations rely exclusively on tanker shipments of LNG and crude oil rather than international pipelines (EIA, 2020a; 2020b).

In the case of the U.S., the country meets its high energy consumption rates from both domestic sources and imports. While the EIA (2022b) states that the U.S. has recently become a net-exporter since 2019, import quantities are still significantly higher than any other country in absolute terms. According to the IEA (2020), the U.S. engages in limited cross-border electricity trade with neighbouring countries, although it is not as active compared to the EU due to a large domestic market and limited interconnections.

In addition to expanding the research scope to the OECD, the existing research on the relationship between renewables and energy imports do not reflect on industry and transport sectors, which are crucial in determining energy demand. Therefore, this research also contributes by including these factors as variables in the econometric model and improving its explaining ability.

Chapter 3. Data and Methodology

3.1. Data and Econometric Model

The study uses data from 17 OECD countries given in Appendix (I) over the time period 2000–2019. The variables used in the models are summarised in Table 3.1. The choice of country and time period is based on data availability alongside with whether the country is a net–importer of energy and imports all three types of fossil fuel for the given period.[④] While the U.S became a net–exporter in 2019, the country is still included in the sample period due to its significant influence as an importer in the World Energy Market. Key statistics, namely the data representing the beginning (2000) and end (2019), is given in Appendix (III) for all variables.

Table 3.1 Variable definition

Variable		Description	Source
Dependent Variable	$COAL_{it}$	Coal imports (PJ)	IEA
	OIL_{it}	Oil imports (PJ)	IEA
	$NATGAS_{it}$	Natural gas imports (PJ)	IEA
Explanatory Variable	RE_{it}	Renewable energy production (PJ)	IEA
	$NONRE_{it}$	Non-renewable energy production (PJ)	IEA
	GDP_{it}	Real GDP per capita (constant 2015 US $)	World Bank
	PRI_{it}	Average real crude oil import prices (2015 USD/bbl)	IEA
	$MANU_{it}$	Share of GDP in the manufacturing sector (%)	World Bank
	$TRAN_{it}$	Total energy consumption for freight/passenger transport (PJ)	IEA

The dependent variables of focus are coal, oil and natural gas

④ Canada was excluded from the sample despite data availability as they are a net–exporter of energy imports while the main explanatory variable of interest is renewable energy production. This includes energy production from all renewable energy sources. Domestic non-renewable energy production, which includes production from all fossil fuels, nuclear and waste sources, is also included in the model. All energy related variables are measured in petajoules (PJ) and is collected using the International Energy Agency (IEA) World Energy Balances database (IEA, 2021b).

Table 3.2 Descriptive Statistics

Variable	Obs	Mean	S.D.	Min	Max
$COAL_{it}$	340	749.2738	1203.746	3.055016	5133.349
OIL_{it}	340	4416.887	5813.808	328.2554	30036.87
$NATGAS_{it}$	340	1228.21	1215.389	59.00859	4489.408
RE_{it}	340	671.0031	1257.997	9.789756	7379.438
$NONRE_{it}$	340	5687.769	16430.53	3.647	89326.73
GDP_{it}	340	38037.21	15630.09	12312.5	88413.19
PRI_{it}	340	63.86721	28.77693	22.07	115.64
$MANU_{it}$	340	16.20258	5.443368	7.61416	34.90355
$TRAN_{it}$	340	2382.506	5753.128	105.16	26149.02

Other explanatory variables used in the econometric models are real GDP per capita, measured in Constant 2015 US $, collected from the World Development Indicators provided by the World Bank (2022), average annual real oil import prices measured in 2015 USD per barrel which are provided by the IEA Energy Prices and Taxes statistics (OECD iLibrary, 2022). Lastly, share of GDP in the manufacturing sector and total energy consumption for freight and passenger transport, obtained from the World Development

Indicators (World Bank, 2022) and Energy Efficiency Indicators (IEA, 2021a) respectively, was included in the model to represent the manufacturing and transport sectors of a country. Table 3.2 represents the descriptive statistics of all variables.

As shown in the descriptive statistics table, all variables show high variance due to the different social and economic situations for each country. Therefore, to reduce such high variances, the natural logarithms of each variable, except for GDP share in manufacturing, is used within the econometric model. Based on these variables, the three basic econometric equations (1) ~ (3) can be constructed as below for each fossil fuel import.

$$LNCOAL_{it} = \alpha + \beta_1 LNRE_{it} + \beta_2 LNNONRE_{it} + \beta_3 LNGDP_{it} + \beta_4 LNPRI_{it} + \beta_5 MANU_{it} + \beta_6 LNTRAN_{it} + \varepsilon_{it} \cdots\cdots (1)$$

$$LNOIL_{it} = \alpha + \beta_1 LNRE_{it} + \beta_2 LNNONRE_{it} + \beta_3 LNGDP_{it} + \beta_4 LNPRI_{it} + \beta_5 MANU_{it} + \beta_6 LNTRAN_{it} + \varepsilon_{it} \cdots\cdots (2)$$

$$LNNATGAS_{it} = \alpha + \beta_1 LNRE_{it} + \beta_2 LNNONRE_{it} + \beta_3 LNGDP_{it} + \beta_4 LNPRI_{it} + \beta_5 MANU_{it}\, \beta_6 LNTRAN_{it} + \varepsilon_{it} \cdots\cdots (3)$$

Appendix (IV) represents the correlation matrix of the given variables. As shown, the correlation coefficient between the explanatory variables do not show high concern regarding the multicollinearity issue within the models. To further test for the issue of multicollinearity among the explanatory variables, the Tolerance statistics and the Variance Inflation Factor (VIF) for each explanatory variable is computed. Table 3.3 presents the results for these statistics and indicates that such multicollinearity does not exist among the explanatory variables. As stated in Mensah et al. (2019), Tolerance statistics must be lower than 0.2 while VIF statistics should be higher than 5 to be of concern for multicollinearity.

Table 3.3 Test of Multicollinearity

Explanatory Variable	Collinearity Statistics	
	Tolerance	**VIF**
$LNRE_{it}$	0.364634	2.74
$LNNONRE_{it}$	0.351941	2.84
$LNGDP_{it}$	0.869305	1.15
$LNPRI_{it}$	0.929385	1.08
$MANU_{it}$	0.921262	1.09
$LNTRAN_{it}$	0.210282	4.76

3.2. Methodology

3.2.1. Cross-sectional Dependence

According to Asafu-Adjaye et al. (2016), it is important to test for cross-sectional dependence as this can occur through spatial or spill-over effects or unobservable common factors. Such cross-sectional dependence may lead to certain panel unit root tests not being robust. Therefore, a cross-sectional dependence (CSD) test procedure proposed by Pesaran (2004) is implemented. The Pesaran CSD test is based on the pairwise correlation coefficient as shown below where $\hat{p}_{ij} = \sum_{t=1}^{T} \frac{e_{it} e_{jt}}{\left(e_i^{'} e_i\right)^{1/2} \left(e_j^{'} e_j\right)^{1/2}}$.

$$CD = \sqrt{\frac{2T}{N(N-1)}}\left(\sum_{i=1}^{N-1}\sum_{j=i+1}^{N}\hat{p}_{ij}\right) \cdots\cdots (4)$$

The CD−test follows the N (0,1) distribution. From this test, the null hypothesis is cross−sectional independence, which can be shown as H_0: $p_{it}=p_{jt}=corr(e_{it}, e_{jt})=0$ for all t and all $i \neq j$ whereas the alternative hypothesis is H_1: $corr(e_{it}, e_{jt}) \neq 0$. The results of the test decide whether the conventional panel unit root tests or second−generation unit root tests accounting for cross−sectional dependence will be conducted.

3.2.2. Panel Unit Root Tests

Unit root tests are deployed for time−series data as the existence of non−stationary variables may lead to spurious regression, meaning that statistically significant regression results may show despite not having a relationship. Panel unit root tests also test for non−stationary variables and, as stated by Bosah et al. (2021), tend to possess more power than their individual time−series counterparts. This is important as the panel ARDL approach may be applied for variables only if they are I (0) or I (1), or mutually cointegrated (Sari et al., 2008).

For panel data, various first−generation unit root tests exist such as Levin−Lin−Chu test (Levin et al. 2002), Harris–Tzavalis test (Harris and Tzavalis, 1999), and Im−Pesaran−Shin test (Im et al., 2003). However, these tests do not account for cross−sectional dependence which can be detected between the variables. While Levin et al. (2002) stated that a limited degree of dependence can be allowed via time−specific aggregate effects by subtracting from the cross-sectional averages through a demeaning option, Pesaran (2007) argues such a strategy would not work in general where pairwise cross-section covariances of error terms differed across individual time-series.

To account for cross-sectional dependence, this paper adopts the Cross-sectional Im-Pesaran-Shin (CIPS) test proposed by Pesaran (ibid.) where the null hypothesis states that the variable is non-stationary, i.e. the variable is I(1), whereas the alternative hypothesis states that the variable is stationary, i.e. the variable is I(0). The CIPS test is a second-generation unit root test where the simple averages of the cross-sectionally augmented Dickey-Fuller statistics (CADF) are used (ibid.). CADF statistics are derived from the standard Dickey-Fuller statistics which are augmented with the cross-sectional averages of lagged levels and first differences within the individual series (ibid.). The CIPS test estimates the test value and are tabulated based on three types of models, namely in the case of models without intercepts and trends, models with individual-specific intercepts only, and models with such intercepts and with incidental linear trends. In this research, the CIPS test statistics estimated from the latter two models are presented.

3.2.3. Panel Autoregressive Distributed Lag (ARDL) Model

For estimating the model, this paper uses the panel Autoregressive Distributed Lag (ARDL) Model. According to Marques et al. (2018), it is expected that renewable energy deployment would lead to different dynamic effects in the short-run and long-run on coal, oil and natural gas consumption. This is due to several factors such as the oil price shocks, the take-off phase of renewable energy deployment, and recent social and political pressure from the international society to substitute such fossil fuel sources with renewables.

Therefore, the use of a panel ARDL model can be justified as it can assess both short-run and long-run dynamics. In addition, the panel ARDL model can be used regardless of whether the variables are I(0) or I(1) from the panel unit root tests but cannot be used if variables are higher than I(2), i.e., the first differences also contain panel roots. In the model, long-run coefficients can be interpreted as elasticities when variables are in logarithms (Asafu-Adjaye et al., 2016).

According to Pesaran et al. (1999), the general equation form for the panel ARDL model (p, q) is shown below as Equation (5).

$$y_{it} = \sum_{j=1}^{p} \lambda_{ij} y_{i,t-j} + \sum_{j=0}^{q} \delta'_{ij} X_{i,t-j} + \mu_i + \varepsilon_{it} \cdots\cdots (5)$$

Within this equation, $X_{i,t-j}$ represents the n*k vector of the explanatory variables, while δ_{ij} is the k*1 vector for coefficients. Equation (5) can be re-parameterised into a VECM form shown as Equation (6).

$$\Delta y_{it} = \sigma_{1,i}\left(y_{i,t-1} - \theta'_i X_{i,t}\right) + \sum_{j=1}^{p-1} \gamma_{ij} \Delta y_{i,t-j} + \sum_{j=0}^{q-1} \delta^{*\prime}_{1,i} \Delta X_{it} + \mu_i + \varepsilon_{it} \cdots (6)$$

where $\sigma_{1,i} = -(1-\lambda_i)$ and $\theta_i = \frac{\sum_{j=0}^{1} \delta_{ij}}{1-\lambda_i}$.

σ represents the error correction term (ECT). The ECT is important within the panel ARDL as it can also provide an estimate for the speed of adjustment from the inverse of its absolute value

(Asafu-Adjaye et al., 2016). A negative and statistically significant value would indicate that there is a cointegrating long-run relationship. θ denotes the long-run coefficients while γ and δ denote the short-run coefficients for the dependent and independent variables respectively. A lag of 1 is selected for each dependent and independent variable in each econometric model. While other criterion such as the Akaike Information Criterion (AIC) and Schwartz Information Criterion (SIC) are used for deducing the optimal lag length, the lag length was decided based on the analysis sample being annual data as many papers did such as Mensah et al. (2019) and Asafu-Adjaye et al. (2016).

Alongside with the panel ARDL model, this research adopts the Mean Group (MG) estimator proposed by Pesaran et al. (1995), Pooled Mean Group (PMG) estimator proposed by Pesaran et al. (1999), and the Dynamic Fixed Effects (DFE) estimator. The three estimators are based on different assumptions (Sohag et al., 2015). First, the MG estimator is based on the assumption that both the short-run coefficients and long-run coefficients may vary between groups. Hence, the overall estimated coefficients presented are the averages of the coefficients estimated from each individual time series. On the other hand, while it still assumes different intercepts across groups, the DFE estimator is based on the assumption that the short-run and long-run coefficients as well as the speed of adjustment coefficient are homogeneous across groups. Last but not least, the PMG estimator attempts to find a balance between the contrasting MG and DFE estimators based on a maximum loglikelihood estimation (MLE) approach. The estimator allows variation of the short-run coefficients between countries, while the long-run coefficients are assumed to be homogenous across all cross-sections.

To test on which estimator is most suitable for the model, the paper adopts the Hausman test proposed by Hausman (1978) for testing between the MG and PMG estimator, and between the PMG and DFE estimator. The null hypothesis for the Hausman test is that there is no systematic difference between the two estimators, which indicates that the more efficient PMG estimator should be used instead of the MG or DFE estimator.

Chapter 4. Analysis Results

4.1. CSD Test Results

As shown in the test results in Table 4.1, all variables of interest reject the null hypothesis of cross−section independence at the 1% significance level, indicating that cross−sectional dependence exists for all variables. Therefore, this justifies the use of the CIPS panel unit root test as stated in the Methodology section, rather than the conventional first−generation unit root tests which are widely used.

Table 4.1 Cross-sectional Dependence (CSD) Test Results

Variable	CD value	p-value	corr	Abs(corr)
$LNCOAL_{it}$	8.86	0.000	0.170	0.480
$LNOIL_{it}$	5.105	0.000	0.098	0.564
$LNNATGAS_{it}$	14.827	0.000	0.284	0.562
$LNRE_{it}$	47.474	0.000	0.910	0.910
$LNNONRE_{it}$	8.583	0.000	0.165	0.570
$LNGDP_{it}$	31.355	0.000	0.601	0.738
$LNPRI_{it}$	52.091	0.000	0.999	0.999
$MANU_{it}$	22.714	0.000	0.436	0.590
$LNTRAN_{it}$	6.914	0.000	0.133	0.477

*, **, *** represent statistical significance of 10%, 5%, and 1%

4.2. Panel Unit Root Test Results

Table 4.2 represents the results for the CIPS panel unit root tests. For the variables at level, it shows that the variables $LNNATGAS_{it}$, $LNNONRE_{it}$, $LNGDP_{it}$, and $LNTRAN_{it}$ are unable to reject the null hypothesis of non−stationary at the 5% significance level, for both models of individual−specific intercepts and with incidental linear trend. While the variables $LNCOAL_{it}$ and $MANU_{it}$ are able to reject the null hypothesis of non−stationary at the 5% significance level in the case of the CIPS statistics estimated for the model regarding individual−specific intercepts only, this was not the case for the CIPS statistics estimated for the model also including the incidental trend. On the contrary, $LNOIL_{it}$ was unable to reject this null hypothesis for the case of individual−specific intercepts, but could reject for models with incidental linear trend. Lastly, $LNRE_{it}$ and $LNPRI_{it}$ reject the null hypothesis of non−stationary at the 5% significance level, for both cases.

While variables at level present mixed results for the panel unit root tests, it shows that all variables reject the null hypothesis of non−stationary at the 5% significance level, regardless of model type. Therefore, as all variables at first differences are tested to be stationary, using the panel ARDL model is suitable.

Table 4.2 Panel Unit Root Test (CIPS) Results

Variable	**Level**		**First Differences**	
	No Trend	**With Trend**	**No Trend**	**With Trend**
$LNCOAL_{it}$	-2.234**	-2.663*	-4.638***	-4.693***
$LNOIL_{it}$	-1.212	-2.850**	-4.462***	-4.483***
$LNNATGAS_{it}$	-2.202*	-2.638*	-4.079***	-4.279***
$LNRE_{it}$	-2.419***	-3.072***	-4.627***	-4.859***
$LNNONRE_{it}$	-1.558	-2.197	-3.464***	-3.801***
$LNGDP_{it}$	-1.117	-1.291	-2.565***	-2.872**
$LNPRI_{it}$	-2.879***	-3.200***	-4.984***	-4.995***
$MANU_{it}$	-2.273**	-2.362	-4.136***	-4.427***
$LNTRAN_{it}$	-1.265	-2.274	-3.837***	-4.079***

*, **, *** represent statistical significance of 10%, 5%, and 1%

4.3. Panel ARDL Results

Table 4.3 ~ 4.5 represents the panel ARDL estimation results for Coal, Oil, and Natural Gas Import Models of Equation (1) ~ (3) using the MG, PMG and DFE estimators and the subsequent Hausman test results. The Hausman test results fail to reject the null hypothesis of no systematic difference, for both comparison between MG and PMG and between PMG and DFE, regarding all three econometric models. Therefore, while the results of all three estimators are presented in each Table, discussion will be focused on the PMG results.

4.3.1. Coal Imports ARDL Model

Table 4.3 Panel ARDL Estimation Results (Coal Imports Model)

Estimator	MG	PMG (★)	DFE
Long-run Coefficients			
$LNRE_{it}$	-0.1096453	-0.3424222***	-0.4432085*
$LNNONRE_{it}$	-0.1788976	-0.0406384	-0.3986242*
$LNGDP_{it}$	-1.274572	-2.198924***	-4.158163**
$LNPRI_{it}$	-0.2611222	0.2178987***	0.360996**
$MANU_{it}$	-0.0428537	0.0330511***	0.0593576
$LNTRAN_{it}$	-0.3067158	-0.1364373	3.987827***
Short-run Coefficients			
ECT (Speed of Adjustment)	-0.9965842***	-0.4697992***	-0.2053976***
$\triangle LNRE_{it}$	0.1395393	0.1498906	-0.2103653
$\triangle LNNONRE_{it}$	-0.2228246	-0.0738666	0.019757
$\triangle LNGDP_{it}$	1.645415	3.486254***	0.9849297
$\triangle LNPRI_{it}$	-0.0047568	0.0066428	0.0552721
$\triangle MANU_{it}$	-0.0234516	-0.1081442*	0.0160204
$\triangle LNTRAN_{it}$	0.6330686	0.9202976	-0.2169529
_cons	22.3071***	13.84039***	5.212265***
Hausman Test Result			
	MG PMG		**DFE PMG**
Chi2	0.25		0.15
p-value	0.9997		0.9999
Estimator Support	PMG		PMG

From the Coal Imports Model, according to the PMG estimation results, it is shown that the ECT term is approximately −0.47, which is statistically significant at the 5% significance level. This indicates a cointegrating long-run relationship between the variables where the speed of adjustment is approximately 2.13 years.

When observing other coefficients which are statistically significant at the 5% level in the PMG model, the coefficient for renewable energy indicates that an 1% increase in renewable energy production leads to an approximate 0.34% reduction in coal imports. This presents supporting evidence of an import substituting effect between renewable energy and coal. According to the Government of Canada (2022), the main use of coal is for electricity and heat generation which accounted for approximately 67% of all global demand in 2019. Similarly, the main usage of renewable energy is also focused on electricity generation which explains the substituting relationship between coal and renewable energy.

The effort of OECD countries to reduce coal imports is also supported by the real GDP per capita variable. In the short-run it is shown that an 1% increase in real GDP per capita leads to an approximate 3.49% increase in levels of coal imports. However, in the long-run, an 1% increase led to contrasting results of an approximate 2.2% decrease in coal imports. This result indicates that countries are reducing their coal consumption as the economy grows (within country dimension) and developed countries with higher real GDP per capita are importing less coal (cross-country dimension). According to research on the relationship between coal consumption and economic growth in OECD countries by Apergis and Payne (2010), a bidirectional causality between coal consumption and economic growth existed within a panel vector error correction model. However, it is shown that coal consumption negatively affects economic growth, for which the authors argued it may be due to the "possibility that the immediate economic benefit associated with the use coal is outweighed by the economic costs imposed on the environmental by carbon dioxide emissions" (ibid). Governments of these countries may be aware of such insights and thus this can explain the reduction of coal imports with higher real GDP per capita, contributing to the explanation for the other side of this bidirectional causal relationship.

Regarding average real crude oil import prices, the analysis results indicate that an 1% increase in prices lead to an approximate 0.22% increase in coal imports, presenting the substitutional relationship between coal and oil. According to Jinke et al. (2008), increases in oil and natural gas prices made coal fossil fuels more competitive, which made it the world's fastest-growing fuel in 2005, with consumption rates rising by 5% per annum.

Lastly, regarding the coefficient on share of manufacturing sector within a country's total GDP, an 1% increase in GDP share indicated an approximate 3.31% increase in coal imports. While a significant share of coal is used for electricity generation globally, demand for industry is also significant as approximately 12% of global demand in 2019 came from the iron and steel industry alone (Government of Canada, 2022). In addition, coal is used to produce other manufactured goods such as cement, aluminium, and chemicals (World Coal Association, 2022). Therefore, higher shares in manufacturing would indicate higher demand for coal and subsequently higher imports when assuming all other explanatory variables are constant.

4.3.2. Oil Imports ARDL Model

Table 4.4 Panel ARDL Estimation Results (Oil Imports Model)

Estimator	MG	PMG (★)	DFE
Long-run Coefficients			
$LNRE_{it}$	0.1263834	0.02689	0.1171897
$LNNONRE_{it}$	0.1346432	-0.023439	0.072636
$LNGDP_{it}$	0.4648412	-1.086935***	-0.1379238
$LNPRI_{it}$	-0.0862152	0.0064133	-0.1760213**
$MANU_{it}$	-0.0248824	0.0493978***	0.0030286
$LNTRAN_{it}$	0.1497054	0.8450195***	0.0349321
Short-run Coefficients			
ECT (Speed of Adjustment)	-0.9706599***	-0.2601101***	-0.1155937***
△ $LNRE_{it}$	-0.0577696	-0.0770423	-0.0230712
△ $LNNONRE_{it}$	0.014954	-0.0425559	-0.0218568
△ $LNGDP_{it}$	0.2359138	0.4392965*	0.3582882**
△ $LNPRI_{it}$	0.0221662	0.0010112	0.0170597
△ $MANU_{it}$	0.0039158	0.0125523	0.0047674
△ $LNTRAN_{it}$	0.3099904	0.0041387	-0.026566
_cons	9.093139*	3.265065***	0.9749474**
Hausman Test Result			
	MG PMG		**DFE PMG**
Chi2	2.75		0.01
p-value	0.8390		1.0000
Estimator Support	PMG		PMG

Within the Oil Imports Model, according to the PMG estimation results, it is shown that the ECT term is approximately −0.26, which is statistically significant at the 5% significance level. Similar to the Coal Imports Model, this also indicates a cointegrating long−run relationship between the variables where the speed of adjustment is approximately 3.84 years.

Unlike the Import Model for Coal, and for Natural Gas which will be presented in the next section, both the short-run and long-run coefficient for renewable energy was not statistically significant at the 5% significance level. While significant levels of coal and natural gas is used for electricity generation, oil does not contribute significantly within this sector. According to the Organization of the Petroleum Exporting Countries (OPEC), only 4.9% of world oil demand was used for electricity generation in 2019 (OPEC, 2021). Therefore, as prime use of renewable energy is for electricity generation, an import substitution of renewable energy for oil imports may not show within OECD countries.

While it can be deduced that renewable energy does not reduce oil imports, it can still be considered that developed countries are currently trying to reduce oil imports. The short-run coefficient for real GDP per capita is not statistically significant, whereas the long-run coefficient present trends similar to its relationship within the Coal Imports Model, where an 1% increase in real GDP per capita leads to an approximate 1.09% decrease in oil imports. This differs from other studies such as Bashiri Behmiri et al. (2012), which concludes that economic growth positively affects oil consumption and vice versa. However, as the industrial and transport sector are reflected in other independent variables in the model, such negative analysis results can be an outcome of OECD countries reducing oil consumption in other sectors, such as residential, commercial, and agricultural sectors.

In contrast to the real GDP per capita variable, an 1% rise in the share of GDP in manufacturing and total energy consumption for freight and passenger transport leads to an approximate 4.94% and 0.85% increase in oil imports respectively. According to OPEC (2021), 26.6% of world oil demand came from the industrial sector whereas 57.3% accounted for the transport sector in 2019, highlighting the significance of oil fossil fuels in these sectors.

4.3.3. Natural Gas Imports ARDL Model

Table 4.5 Panel ARDL Estimation Results (Natural Gas Imports Model)

Estimator	MG	PMG (★)	DFE
Long-run Coefficients			
$LNRE_{it}$	-2.178751	-0.1016333**	-0.17233
$LNNONRE_{it}$	-4.609068	-0.263503***	-0.1370019
$LNGDP_{it}$	1.629165	0.8230925***	1.803472
$LNPRI_{it}$	0.7911907	-0.0592985**	-0.4286306***
$MANU_{it}$	-0.166893	-0.0522216***	-0.0722802**
$LNTRAN_{it}$	2.563554	-0.0128986	0.0176167
Short-run Coefficients			
ECT (Speed of Adjustment)	-0.905584***	-0.3561684***	-0.1346709***
△ $LNRE_{it}$	-0.0733508	0.2264047	-0.0366166
△ $LNNONRE_{it}$	0.3278764	-0.0779801	-0.1318331***
△ $LNGDP_{it}$	-1.326952	-0.1721091	-0.0462997
△ $LNPRI_{it}$	0.1602555***	0.0910555***	0.0666353***
△ $MANU_{it}$	0.0762343	0.033389*	0.0113324
△ $LNTRAN_{it}$	0.7124608	1.014801**	-0.1726492
_cons	-2.336305	0.3694952**	-1.01527
Hausman Test Result			
	MG PMG		**DFE PMG**
Chi2	0.36		0.08
p-value	0.9992		1.0000
Estimator Support	PMG		PMG

Lastly, for the Natural Gas Imports Model, the PMG estimation results show that the ECT term is approximately −0.36 and is statistically significant at the 5% significance level. Similar to the previous two models, this also indicates a cointegrating long-run relationship between the variables where the speed of adjustment is approximately 2.81 years.

Regarding the renewable energy variable, an 1% increase in renewable energy production leads to a 0.1% reduction in natural gas imports. This indicates the presence of an import substitution effect between renewable energy and natural gas. Similar to coal, natural gas is also important for electricity production. According to the World Bank (2022), 26.2% of total electricity production originated from natural gas sources in 2015. As stated previously renewable energy is also important for generating electricity which can contribute to explaining the relationship between renewable energy and natural gas.

However, unlike in the Coal Imports Model, which presented a non-significant coefficient for non-renewable energy production, it showed that an 1% increase in non-renewable energy leads to an approximate 0.26% decrease in natural gas imports. This indicates that non-renewable energy sources, such as waste, nuclear, and domestic fossil fuel resources, can also contribute to reducing natural gas imports.

Furthermore, in contrast to the results in the Coal and Oil Imports Model, the results for the Natural Gas Imports Model presented that an 1% increase in real GDP per capita increases natural gas imports by approximately 0.82%. While developed countries may desire to reduce coal and oil consumption in the context of Climate Change, this trend may differ for natural gas due to its relatively low carbon emission rates compared to the other two fossil fuels. According to Gürsan and de Gooyert (2021), natural gas approximately has only half the CO_2 polluting effects compared to other fossil fuels and thus acts as a transition fuel, which means a substitute low-carbon fuel for higher content fossil fuels. Without the aid of such transition fuels, they argue that the reconfiguration of energy systems into renewable technologies may be infeasible (ibid.). OECD countries may therefore be increasing such imports to aid the feasible transition to a low-carbon energy system.

When observing the crude oil import price variable, a substitute relationship exists between natural gas and crude oil in the short-run, similar to the relationship of coal and oil, as an 1% increase in oil prices lead to an approximate 0.09% increase in natural gas imports. However, a contrasting effect is detected in the long-run as an 1% increase in crude oil prices lead to an approximate 0.06% reduction. The positive relationship between prices of crude oil and natural gases may explain for this. Chiappini et al. (2019) demonstrate the existence of a long-term cointegrating positive relationship between crude oil and natural gas prices in in the US, and in various nations in Europe and Asia. If price of crude oil increases, this would make natural gas more competitive compared to oil and hence demand would increase, which is also reflected in the short-run coefficient of the econometric model. However, a rise in natural gas prices, as a result of the positive correlation between oil and natural gas prices, would explain the reduction in natural gas imports in the long-run.

In contrast to the results shown in the Coal and Oil Imports Model, an 1% increase in share of GDP in manufacturing indicated an approximate 5.22% decrease in natural gas imports. This result is unexpected as natural gas consumption is significant in the industrial sector similar to coal and oil. While econometric misspecification cannot be ruled out, a possible explanation for this is electrification in industry. Natural gas is used for heat processing in combined heat and power systems (EIA, 2022a). Such heat processing can be substituted by electrification of heating systems (Deason et al., 2018) and thus natural gas imports may decrease despite higher shares in manufacturing. However, this only presents a partial explanation as gas is also used to produce chemicals and fertilizers (EIA, 2022a), and thus further examination is still required to explain this negative relationship between the two variables.

Lastly, while no statistical significance is present in the long-run results for the total energy consumption for freight and passenger transport variable, it shows that in the short-run, an 1% increase in such energy consumptions leads to a 1.01% increase in natural gas imports. Similar to oil, natural gas is used in the transport sector in the form of compressed natural gas (CNG) and liquified natural gas (LNG) (OECD, 2019). The fuel source emits lower levels of carbon emissions compared to its oil counterparts. Therefore, with the rise in energy consumption for transport, natural gas imports are likely to increase in the context of climate change.

Chapter 5. Conclusion

This study attempts to analyse the effects of renewable energy production on fossil fuel energy imports in the scope of energy security. The argument was that domestically produced energy from renewable sources would reduce fossil fuel imports and thus countries would gain energy independence, enhancing energy security.

To empirically analyse this effect, the panel ARDL model was used with a data sample consisting of 17 OECD countries based on a time period between 2000 and 2019. Within the panel ARDL model, considering the yearly characteristics of the data, a lag of 1 was used for both the dependent and explanatory variables and was estimated using the MG, PMG, and DFE estimators. The Hausman test is also adopted to test for systematic difference between the estimators, which resulted in the PMG estimator being the most suitable estimator for all three import models. In addition, the ECT analysis results show that there is a cointegrating relationship between the variables, justifying the use of panel ARDL model.

The results empirically show that renewable energy production reduces coal and natural gas imports, which can be explained by the potential for substitution in the electricity generation sector. Oil imports, on the other hand, were not affected by renewable energy production as significance is higher in other sectors such as industry and transport.

In addition, the negative relationship between real GDP and imports of coal and oil in the long-run can be interpreted as a sign of countries adopting policies to phase out coal and oil in the context of Climate Change, regardless of renewable energy production. However, contrasting results for natural gas imports highlight its significance as a transition fuel. As it relatively emits less carbon emissions compared to the two other fossil fuels, countries may be increasing natural gas imports with economic growth to reduce carbon emissions in the transition period.

Oil prices also seem to positively affect coal and natural gas imports in the long-run and short-run respectively. This shows that the characteristics of substitutes exist between the fossil fuels. However, it was shown that in the long-run, increases in crude oil import prices reduced natural gas imports, which could be explained by the positive relationship between oil and natural gas prices mentioned in other literature. Therefore, countries attempting to increase natural gas imports in the context of climate change, as explained above, should be aware that exogenous shocks in the oil supply, which increase oil prices, may affect natural gas prices as well and subsequently make the natural gas supply unstable.

Lastly, the analysis results show that the manufacturing and transport sector is a key aspect when it comes to fossil fuel imports. Coal and oil are considered to be significant in manufacturing while oil and natural gas are significant in the transport sector. Therefore, countries should adopt policies to improve efficiency in these sectors to subsequently reduce fossil fuel consumption. For instance, in the iron and steel sector, the usage of green hydrogen can be adopted to power furnaces instead of using coal, while fuel transition from coal to non−recyclable plastics is a possible option in the cement industry. In addition, introduction of electric and biomass furnaces for heating and transition in primary materials from oil to bio naphtha and recycling of plastic waste are all viable options of reducing oil consumption in the petrochemical industry. Furthermore, the increased supply of electric and biofuel vehicles can substitute for oil and natural gas consumption in the transport sector. Such policies can lead to the enhancement of the existing reduction effect of renewable energy production for coal and natural gas and can also induce the effect for oil imports as well.

This research contributes to the existing literature by conducting an in−depth research by looking at each fossil fuel imports separately instead of looking at energy imports as a whole. This is necessary as each fossil fuel showed different trends regarding the independent variables. In addition, while past literature focuses, to a limited extent, on demand−side factors such as prices and GDP only, this research expands this focus by incorporating other factors such as manufacturing and transport sectors into the econometric analysis, which has been proven to be significant in importing fossil fuels.

However, limitations still exist in this research. Firstly, while the econometric model includes oil price factors into analysis, it fails to do so for prices regarding coal and natural gas. Prices are crucial determinants of the demand for a particular good or service and thus such prices should be incorporated into the model if possible. However, while finding prices for individual time−series may be more feasible, data was not available on a panel−data level from a single source, which was the main reason why it could not be included in the analysis. If such price data is available in the future, it can be incorporated into the model for a more sophisticated analysis.

Another limitation is that the scope of the research was focused on developed countries in the OECD which are net importers. While the reasoning for the selection of this research is justified, different trends and policy implications may be derived from including emerging economies. Therefore, expanding the research scope to further enhance external validity can be a significant opportunity for future research.

In the context of future research, while import substitution may positively contribute to energy security of importing countries, it may also mean that exporters of such fossil fuels will lose a part of income. Therefore, looking into dynamics of exporting countries can also be considered when expanding the research scope.

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Appendix (I) List of OECD Countries for Analysis

- Austria
- Belgium
- Czech Republic
- Finland
- France
- Germany
- Greece
- Ireland
- Italy
- Japan
- South Korea
- Netherlands
- Portugal
- Spain
- Switzerland
- United Kingdom
- United States

Appendix (II) Summary of Literature Review

Studies related to energy import dynamics

Research	Data	Model Estimator	Key Findings
		Oil Imports	
Zhao and Wu (2007)	China 1995-2006 (1998-2006)	VECM	Industrial output and expansion in the transport sector contribute to oil imports. Domestic energy production substitutes imports.
Altinay (2007)	Turkey 1980-2005	ARDL bound testing	Income and price elasticities were inelastic for oil import demand in short-run and long-run
Ghosh (2009)	India 1970-2006	ARDL bound testing	Oil import prices have insignificant effect on quantities. High income elasticity and long-run causality for oil imports
Kim & Baek (2013)	South Korea 1986-2010	ARDL model	In long-run, income level is more important for oil imports. In short-run oil prices are more important.

		Coal Imports	
Wu and Zhang (2016)	China 1997-2012	Structural Decomposition Analysis	Domestic demand for five main industries and foreign trade for six positively contribute to coal demand. Enhancement in industrial efficiency negatively effects demand.
		Natural Gas Imports	
Maxwell and Zhu (2011)	United States 1997-2007	Granger Causality Test, Error Variance Decomposition, and VAR Model	Gas prices and shipping costs affect LNG imports. Import respond higher to shocks in gas prices than shipping costs

Studies viewing the relationship between renewable energy and energy imports

Research	Data	Model Estimator	Key Findings
		Energy Imports -> Renewable Energy	
Marques et al. (2010)	24 European Countries 1990-2006	Panel OLS, RE, FE, and FEVD models	Energy import dependency contributes to higher renewable energy deployment
Bloch et al. (2015)	China 1977-2013 1965-2011	ARDL, VECM modelling	Coal and oil prices have strong positive elasticities towards renewable energy consumption
Ibrahiem and Hanafy (2021)	Egypt, Morocco, and Tunisia 1971-2014	PMG-ARDL model	Energy imports negatively affects renewable energy deployment

Renewable Energy -> Energy Imports			
Chien and Hu (2008)	116 economies 2003	Structural Equation Modelling	No significant relationship between renewable energy and energy imports.
Xu et al. (2019)	31 countries 1996-2015	Panel FE	Imports reduce GDP per capita, but renewable energy reduces such negative effects for oil imports.
Vaona (2016)	26 countries periods vary by country	Panel system GMM	Renewable energy shows significant negative effect on import demand.
Gökgöz and Güvercin (2018)	28 EU countries 1992-2014	Panel FE, RE based on Hausman Test	Renewable energy shows significant negative effects for coal, oil and natural gas imports
Marques et al. (2018)	10 EU countries 1990-2014	Panel ARDL model	Solar and hydro energy showed negative effect on fossil fuel electricity production.
Naim and Matsumoto (2020)	1359 Trading Partners 1988-2017	Trade Gravity Panel model	Renewable energy reduces LNG imports. Higher significant outcomes occur for OECD countries while non-OECD countries show insignificant results

Appendix (III) Key statistics of variables for sample countries

Country	Coal Imports (PJ)		Oil Imports (PJ)		Natural Gas Imports (PJ)		Renewable Energy (PJ)		Non-renewable Energy (PJ)	
	2000	2019	2000	2019	2000	2019	2000	2019	2000	2019
Austria	128.34	115.24	520.13	638.58	222.78	492.48	277.66	414.04	133.30	87.96
Belgium	352.84	135.24	2215.31	2641.54	555.92	804.88	22.34	146.68	552.50	505.55
Czech Republic	43.45	123.41	359.88	496.03	313.29	328.93	67.50	194.47	1223.82	928.61
Finland	149.10	95.18	654.37	756.78	143.63	89.60	324.51	478.99	297.81	319.05
France	560.37	305.27	4711.33	3987.10	1526.49	2047.51	658.87	1035.50	4810.68	4456.20
Germany	930.34	1179.76	6232.58	5452.54	2557.53	3168.24	376.11	1850.70	5285.43	2520.09
Greece	33.90	8.51	979.86	1350.07	70.70	186.62	61.13	113.74	359.38	138.44
Ireland	71.05	8.72	397.98	372.84	103.73	101.18	9.84	56.60	80.54	114.42
Italy	553.81	275.80	4594.25	3374.27	1969.86	2436.83	401.81	1020.97	777.74	419.77
Japan	4091.61	4857.54	11410.72	7939.57	2657.16	3766.92	659.29	1031.73	3715.20	1054.51
South Korea	1638.60	3352.17	6298.54	7865.27	714.74	2017.79	30.58	277.00	1411.34	1745.71
Netherlands	340.20	278.73	4372.87	6238.19	522.30	1778.94	60.35	256.99	2388.09	1115.19
Portugal	166.13	64.08	730.58	688.41	85.38	221.05	157.40	224.36	3.65	21.82
Spain	558.79	231.73	3284.86	3688.15	647.56	1355.41	282.32	766.19	1035.85	661.69
Switzerland	7.80	3.35	533.55	469.31	101.88	122.61	181.36	219.98	317.60	326.69
United Kingdom	638.45	201.94	2957.08	3679.05	84.33	1678.04	94.78	706.74	11314.18	4386.45
United States	419.25	144.74	25124.07	19486.91	3675.22	2654.79	4266.93	7379.44	65503.83	89326.73

Country	Real GDP per capita (Constant 2015 US$)		Crude Oil Import Prices (2015 $/bbl)		GDP Share in Manufacturing (%)		Total energy consumption for freight/passenger transport (PJ)	
	2000	**2019**	**2000**	**2019**	**2000**	**2019**	**2000**	**2019**
Austria	38827.27	46650.99	29.39	64.52	18.21	16.54	225.24	282.43
Belgium	35660.45	43053.79	27.87	63.78	17.54	12.30	314.92	343.96
Czech Republic	12312.50	20202.15	26.59	64.39	23.38	22.62	170.81	278.36
Finland	37869.16	46116.53	28.13	63.58	24.15	14.41	162.96	174.71
France	33583.86	38896.69	28.18	64.98	14.48	10.01	1697.35	1685.21
Germany	34476.21	43311.63	28.09	64.43	20.55	19.44	2305.87	2353.72
Greece	18635.39	18996.19	26.95	62.02	9.49	7.99	271.10	252.21
Ireland	41606.32	75112.81	29.88	65.03	23.12	32.01	105.16	139.89
Italy	32337.90	32078.09	27.77	64.7	17.57	14.87	1647.37	1472.02
Japan	31430.63	36362.36	28.72	66.78	22.45	20.31	3603.08	2832.98
South Korea	16992.48	31674.31	28.22	65.4	26.45	25.22	1010.62	1416.89
Netherlands	40440.68	48424.25	27.59	63.96	13.35	10.77	385.24	411.06
Portugal	18787.47	21608.72	28.2	65.89	15.05	11.90	261.55	246.28
Spain	23928.67	28091.01	27.16	62.84	16.23	10.95	1269.96	1362.29
Switzerland	74013.06	88413.19	29.53	64.57	17.73	18.22	207.22	215.23
United Kingdom	39229.27	47750.88	28.45	65.58	13.34	8.88	1831.10	1656.11
United States	48689.03	60836.77	27.54	56.31	15.12	10.93	24307.48	26149.02

Appendix (IV) Correlation Matrix for Variables

	$LNCOAL_{it}$	$LNOIL_{it}$	$LNNATGAS_{it}$	$LNRE_{it}$	$LNNONRE_{it}$	$LNGDP_{it}$	$LNPRI_{it}$	$MANU_{it}$	$LNTRAN_{it}$
$LNCOAL_{it}$	1.0000								
$LNOIL_{it}$	0.7329	1.0000							
$LNNATGAS_{it}$	0.7972	0.8788	1.0000						
$LNRE_{it}$	0.3680	0.5864	0.6397	1.0000					
$LNNONRE_{it}$	0.4615	0.7623	0.6779	0.5281	1.0000				
$LNGDP_{it}$	-0.1471	0.0852	0.0389	0.2095	0.2290	1.0000			
$LNPRI_{it}$	-0.0222	-0.0285	0.0895	0.1407	-0.0547	0.0960	1.0000		
$MANU_{it}$	0.1650	-0.2021	-0.0543	-0.2544	-0.0995	0.0151	-0.1227	1.0000	
$LNTRAN_{it}$	0.6413	0.9018	0.8451	0.7551	0.7810	0.1054	-0.0235	-0.1698	1.0000

국문초록

The impact of renewable energy production on fossil fuel imports: Evidence from OECD countries

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이 연구는 국가의 자국 내 재생에너지 생산이 화석연료수입에 미치는 영향을 실증 분석하여 재생에너지가 화석연료수입을 감소시키는지 확인하고자 하였다. 이를 위해 OECD 국가 17개국의 20년 데이터(2000-2019)를 기반으로 자기회귀시차분포(ARDL) 모형을 이용하여 분석하였으며, 추정법은 그룹평균(MG), 통합그룹평균(PMG), 그리고 동적고정효과(DFE)를 이용하여 추정했다. 종속변수는 각각 석탄, 석유, 천연가스수입으로 세가지 모형을 추정하였으며, 독립변수는 자국 내 재생에너지 생산, 자국 내 비재생에너지 생산, 1인당 실질 국내총생산(GDP), 평균원유수입가격, GDP 내 제조업 비중, 화물 및 여객 수송 총 에너지 소비량으로 산정하였다.

분석을 진행하기에 앞서 횡단면 의존성 검정과 패널 단위근 검정을 실시하였다. 횡단면 의존성 검정을 실행한 결과, 모든 변수에서 횡단면 의존성이 나온 것으로 검정되어 이는 패널 단위근 검정을 할 때 이를 고려한 검정법을 이용해야 함을 나타낸다. 횡단면 의존성을 고려한 패널 단위근 검정에서는 몇몇 수준변수에서는 단위근이 있는 것으로 검정되었지만 이를 차분한 모든 변수에 대해서는 정상성이 있는 것으로 나타나 패널 ARDL 모형 사용의 적절성을 보여주었다.

하우스만 검정에 의하면 분석에 이용되었던 세가지 추정법 중에서 PMG 추정법이 가장 적절한 것으로 나타났다. 이를 토대로 PMG 추정법 분석결과를 살펴보면, 세 화석연료 모형 모두 오차수정항(ETC)이 음의 값으로 유의미하게 추정되었다. 이를 통해 공적분 관계를 확인할 수 있

고 변수들이 장기적 균형관계로 수렴되는 것을 확인할 수 있다.

재생에너지 생산은 석탄, 천연가스에 한해 수입 감소효과가 나타났으며, 장기계수에서 재생에너지 생산이 1% 증가함에 따라 석탄수입은 약 0.34%, 천연가스수입은 약 0.1% 감소하는 것으로 추정되었다. 자국 내 비재생에너지 생산의 경우, 장기계수에서 1% 증가함에 따라 천연가스 수입이 약 0.26% 감소하는 것으로 나타났다.

1인당 실질 GDP 변수의 경우, 단기계수에서 1인당 실질 GDP가 1% 증가함에 따라 석탄수입은 약 3.48% 증가하는 것으로 추정되었으나, 장기계수에서는 오히려 약 2.2% 감소하는 것으로 추정되었으며, 석유 또한 장기계수에는 약 1.09% 감소한다고 추정되었다. 반면에 천연가스의 경우 장기적으로 1인당 실질 GDP 1% 증가에 따라 약 0.82% 증가하는 것으로 추정되어 석탄, 석유수입과는 상반된 결과를 보여주었다.

평균원유수입가격에 대해서는 해당 변수가 1% 증가함에 따라 장기에는 석탄수입이 0.22% 증가, 단기에는 천연가스수입이 약 0.09% 증가하는 것으로 추정되어 이러한 결과는 세 화석연료 사이의 대체관계를 보여주었다. 그러나 장기에는 반대로 천연가스수입이 약 0.06% 감소하는 것으로 추정되었다.

GDP 내 제조업 비중의 경우, GDP 내 제조업 비중이 1% 증가함에 따라 석탄, 석유수입은 각각 장기에 약 3.31%, 4.94% 증가하는 것으로 나타난 반면에, 천연가스수입은 약 5.22% 감소하는 것으로 추정되었다. 또한 수송부문 에너지 소비의 경우, 수송부문 에너지 소비 1% 증가가 단기에는 천연가스수입 약 1.01% 증가로, 장기에는 석유수입 약 0.85% 증가로 이어졌다.

이러한 분석결과를 통해, 재생에너지 생산의 증가는 석탄수입과 천연가스수입을 대체하여 해외수입의존도를 줄일 수 있으며, 이를 통해 에너지 안보에 기여할 수 있는 것으로 기대된다. 반면에 1인당 실질 GDP에 대한 추정결과를 통해 OECD 국가들이 경제가 성장함에 따라 기후변화대응 등을 이유로 재생에너지와 관계없이 석탄 및 석유수입을 줄이려는 경향을 확인할 수 있으며, 반대로 천연가스는 전환기 연료 역할로서

아직은 수입이 증가하는 것을 확인할 수 있다. 또한 제조업 및 수송부문이 화석연료 수입에 유의미한 영향을 미쳐, 해당 부문에서의 에너지 효율성 증대를 통한 에너지 소비 감소 및 재생에너지로의 전환 정책이 필요한 것을 통해, 탄소중립 목표와 에너지 안보 목표가 부분적으로 일맥상통하다는 것을 시사점으로 도출할 수 있다.