MODELLING THE NEXUS BETWEEN ENERGY-ECONOMIC GROWTH USING THE LONG PANEL DATA ESTIMATIONS

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MODELLING THE NEXUS BETWEEN ENERGY-ECONOMIC GROWTH USING THE LONG PANEL DATA ESTIMATIONS

by

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LIST OF ABBREVIATIONS

ADF	Augmented Dickey-Fuller
AEEI	Autonomous energy efficiency index
AIC	Akaike information criterion
AMG	Augmented mean group
ARDL	Autoregressive distributed lag
CADF	Cross-sectionally Augmented Dickey-Fuller
CCE	Common correlated effects
CCEMG	Common correlated effects mean group
CCEP	Common correlated effects pooled
CD	Cross-sectional dependence
CIPS	Cross-sectionally augmented Im, Pesaran and Shin
CIS	Commonwealth of Independent States
CS-ARDL	Cross-sectionally augmented autoregressive distributed lag
CS-DL	Cross-sectionally augmented distributed lag
DCCE	Dynamic common correlated effects
DF	Dickey-Fuller
DFE	Dynamic fixed effect
DGP	Data generation process
DIFF-GMM	First-differenced generalised method of moments
DL	Distributed lag
DOLS	Dynamic ordinary least squares
EC	Energy consumption
ECM	Error correction model
ECT	Error correction term

EEI	Energy efficiency index
EJ	Exajoules
EKC	Environmental Kuznets Curve
FE	Fixed effects
FMOLS	Fully modified ordinary least squares
G20	Group of Twenty
GCC	Gulf Cooperation Council
GDP	Gross domestic product
GLS	Generalised least squares
GM-FMOLS	Group mean fully modified ordinary least squares
GMM	Generalised method of moments
HAC	Heteroscedasticity and autocorrelation-consistent
IID	Independently and identically distributed
IMF	International Monetary Fund
IPS	Im, Pesaran and Shin
ktoe	Kilotonnes of oil equivalent
LLC	Levin, Lin and Chu
LM	Lagrange multiplier
MAE	Mean absolute error
max.	Maximum
MDGs	Millennium Development Goals
MENA	Middle East and North Africa
min.	Minimum
MG	Mean group
MJ	Megajoules
NARDL	Nonlinear autoregressive distributed lag
obs.	Observations

OECD	Organisation for Economic Cooperation and Development
OLS	Ordinary least squares
PMG	Pooled mean group
POLS	Pooled ordinary least squares
PPP	Purchasing power parity
PURT	Panel unit root test
RE	Random effects
RMSE	Root mean square error
SDGs	Sustainable Development Goals
SER	Standard error of regression
SSR	Sum of squared residuals
std. dev.	Standard deviation
SYS-GMM	System generalised method of moments
TEC	Total primary energy consumption
TPES	Total primary energy supply
TWh	Terawatt-hours
VECM	Vector error correction model

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PEMODELAN HUBUNGAN ANTARA TENAGA-PERTUMBUHAN EKONOMI MENGGUNAKAN PENGANGGARAN DATA PANEL PANJANG

ABSTRAK

Hubungan antara tenaga dan pertumbuhan ekonomi telah dikaji selama beberapa dekad, tetapi kajian terdahulu telah melaporkan hasil-hasil yang tidak muktamad. Satu kemungkinan yang menyebabkan hasil-hasil heterogen sedemikian adalah jurang anggaran. Oleh itu, tesis ini menyumbang dari segi penemuan-penemuan empirikal dan kaedah-kaedah anggaran. Secara empirik, tesis ini mengkaji hubungan sebab-akibat dua hala antara penggunaan tenaga dan pertumbuhan ekonomi untuk dua kumpulan panel, iaitu ekonomi-ekonomi berpendapatan rendah dan sederhana rendah (Kumpulan 1) dan ekonomi-ekonomi berpendapatan tinggi (Kumpulan 2), sepanjang 1990–2019 dengan set data suku tahunan. Selain daripada objektif pertama, tesis ini bertujuan untuk menangani pelbagai isu anggaran berkaitan data panel panjang yang sering diabaikan oleh model-model panel konvensional, meliputi tidak pegun atau kointegrasi, heterogeniti cerun, pergantungan keratan rentas dan kesan dinamik. Selain itu, data ekonomi sentiasa mempamerkan kesan asimetri atau hubungan yang menyimpang daripada model-model linear yang menyekat hubungan tersebut menjadi linear. Untuk menyelesaikan masalah ini, penyelidikan ini menginovasikan pendekatan-pendekatan yang sedia ada dengan memperkenalkan anggaran-anggaran asimetri untuk mengkaji hubungan-hubungan antara penggunaan tenaga dan pertumbuhan ekonomi yang tidak linear atau asimetri. Penyelidikan ini juga bertujuan untuk mendedahkan model yang paling sesuai. Terdapat empat kumpulan anggaran model, iaitu penganggar-penganggar jenis kuasa dua terkecil biasa (OLS), model-

model lag teragih autoregresif panel (ARDL), kesan berkorelasi biasa (CCE) dalam model-model panel statik, dan CCE dalam model-model panel dinamik. Hasil kajian mendedahkan hubungan dua hala jangka panjang yang heterogen dan pergantungan keratan rentas, dan kesan-kesan asimetri dan dinamik adalah ketara. Model-model tidak linear dengan penganggar-penganggar CCEMG dan DCCE memberikan anggaran terbaik kepada hubungan antara penggunaan tenaga dan pertumbuhan ekonomi dalam kedua-dua kumpulan panel. Lebih-lebih lagi, negara-negara berpendapatan tinggi menikmati lebih banyak faedah daripada peningkatan penggunaan tenaga kerana peningkatan yang ketara dalam pertumbuhan ekonomi. Situasi ini menandakan penggunaan tenaga yang lebih cekap. Kejutan negatif terhadap penggunaan tenaga mempunyai pengaruh konstruktif yang agak besar terhadap pertumbuhan ekonomi berbanding dengan kejutan positifnya dalam jangka masa panjang. Hal ini menunjukkan kepentingan pemuliharaan tenaga. Tambahan pula, penggubal-penggubal dasar di negara-negara berpendapatan lebih rendah harus menguatkuasakan dasar-dasar kecekapan tenaga ke arah mencapai kecekapan ekonomi dan pertumbuhan yang mampan dalam jangka masa panjang.

MODELLING THE NEXUS BETWEEN ENERGY-ECONOMIC GROWTH USING THE LONG PANEL DATA ESTIMATIONS

ABSTRACT

The nexus between energy and economic growth has been examined for decades, but previous studies have reported inconclusive results. One possible reason for such heterogeneous results could be the estimation gaps. Hence, this thesis contributes in terms of empirical findings and estimation methods. Empirically, this thesis examines a two-way causal relationship between energy consumption and economic growth for two panel groups, i.e., low and lower-middle-income economies (Group 1) and high-income economies (Group 2), over 1990–2019 with quarterly datasets. Apart from the first objective, this thesis aims to address various estimation issues related to long panel data that conventional panel models frequently overlook, covering nonstationary or cointegration, slope heterogeneity, cross-sectional dependence and dynamic effect. Besides that, economic data always exhibit an asymmetric effect or relationship that deviates from linear models that restrict the association to being linear. To cater to this, this research innovates existing approaches by incorporating asymmetric estimates to examine nonlinear/asymmetric energy-growth relationships. This research also seeks to reveal the best fit of the models. There are four groups of model estimations, namely ordinary least squares (OLS)-type estimators, panel autoregressive distributed lag (ARDL) models, common correlated effects (CCE) in static panel models, and CCE in dynamic panel models. The results reveal a long-run bidirectional relationship that is heterogeneous and cross-sectionally dependent, and the asymmetric and dynamic effects are significant. The nonlinear models with CCEMG and DCCE estimators provide the best approximation to the

energy-growth relationship in both panel groups. Moreover, high-income nations enjoy more benefits from the rise in energy consumption because of a prominent upsurge in economic growth, signifying a more efficient use of energy. The negative shock to energy consumption has a relatively substantial constructive influence on economic growth compared to its positive shock in the long run, indicating the importance of energy conservation. Additionally, policymakers in lower-income countries should enforce energy efficiency policies towards achieving economic efficiency and sustainable growth in the long run.

CHAPTER 1

INTRODUCTION

1.1 Background of the Study

Energy plays an essential role in human lives and brings about sustainable development. Various tasks in our daily activities are impossible without the use of energy. On building a better quality of life besides combating the growing population worldwide, the world requires energy in increasing demand. The global energy demand is forecasted to grow by approximately 25 percent from 2014 to 2040, even though energy efficiency is improving significantly (Imperial Oil Limited, 2020). Energy production should accelerate to meet this increasing energy demand worldwide. All the energy sources such as renewables and non-renewables are necessary since the renewables alone could not support the growing energy demand (Moriarty & Honnery, 2016; Imperial Oil Limited, 2020).

In 2019, the growth in energy consumption was driven by energy sources from renewables and natural gas, with a total of 75% of the growth displacing coal from the energy mix. Consequently, the growth rate of carbon emissions in 2019 slowed down from the substantial rise in the previous year. Except for nuclear energy, the growth rate of all fuels was lower than their 10-year averages. By comparing the primary energy consumption across world regions, Asia Pacific has been the highest energy consumption region in the past two decades, whereas the African region consumed the least. Specifically, China was the greatest energy driver in the world, with more than three-quarters of net global growth, followed by India and Indonesia. By contrast, the United States and Germany experienced the largest declines (BP Statistical Review, 2020).

The world energy consumption is predicted to rise by approximately 50% from 2018 to 2050, as shown in Figure 1.1, with non-Organisation for Economic Cooperation and Development (OECD) countries constituting almost the whole portion of the growth. In particular, there will be about a 70% upsurge in energy consumption in non-OECD countries but merely a 15% growth in OECD countries. It is probably due to the increased access to energy, and the rapid growth of population and economy in the non-OECD countries. By contrast, the growth of energy consumption in OECD countries is relatively low, owing to improved energy efficiency, while only slight growth in energy-intensive industries (U.S. Energy Information Administration, 2019b).

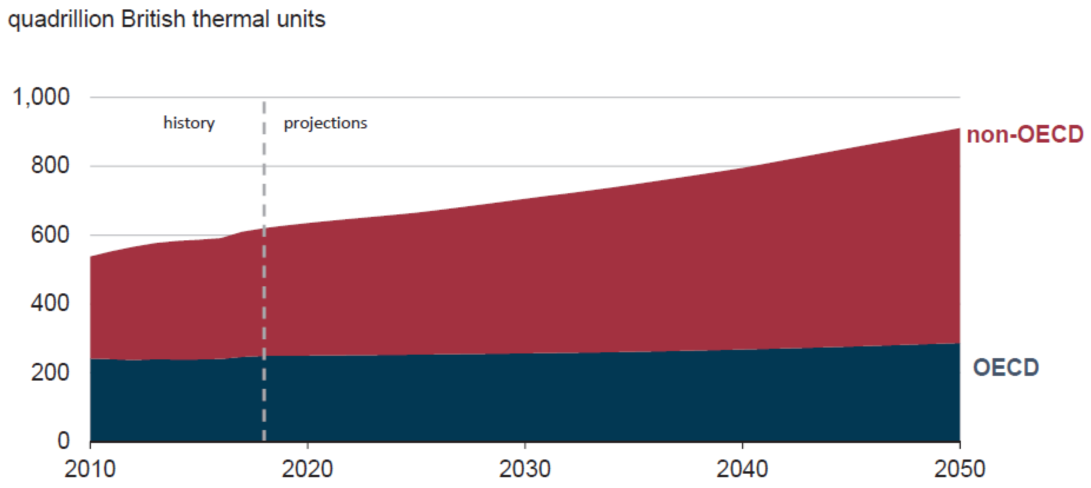

Figure 1.1 The growth projection of world energy consumption (Source: U.S. Energy Information Administration (2019b))

In reviewing the growth projection of non-OECD energy consumption across the world regions, Asia is the leading region to the noticeable energy consumption growth. For most of the past decades, the non-OECD Asian countries, namely China and India, have been the fastest-growing economies in the world, and these countries will remain to be the main contributors to the growth of world energy demand in the future. On the other hand, the non-OECD Europe and Eurasia region will have the smallest forecasted growth in energy consumption, which is just 11%. It is because of the declining population, especially in Russia, apart from the notable enhancements in energy efficiency in the region (U.S. Energy Information Administration, 2019b). Figure 1.2 shows the predicted growth of non-OECD energy consumption across the world regions.

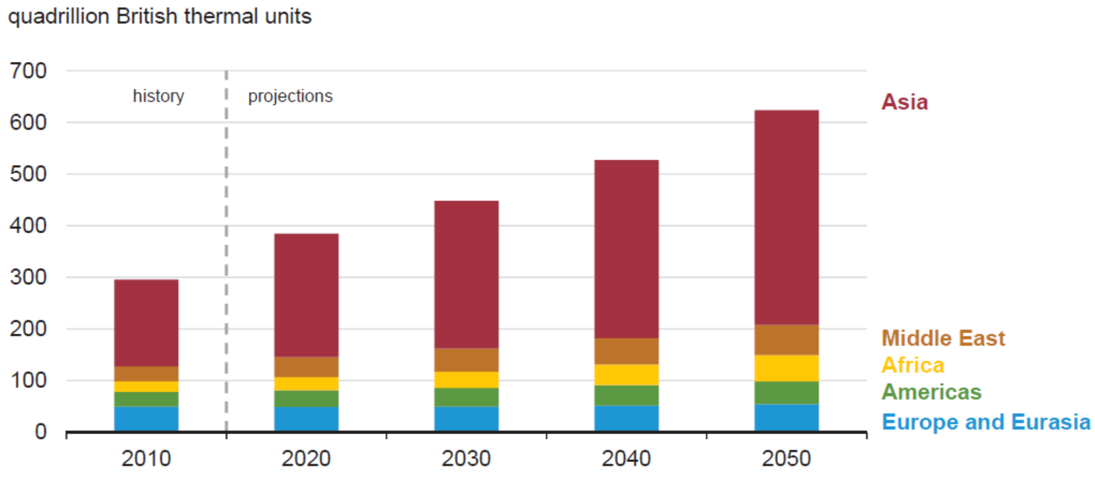

Figure 1.2 The growth projection of non-OECD energy consumption by region (Source: U.S. Energy Information Administration (2019b))

According to International Energy Agency (2019b), there are three main sectors, namely industrial, transport and residential sectors, consuming a relatively large amount of energy, which constitutes about 80% of the total world final energy consumption since 1990. In particular, the industrial sector uses energy for manufacturing, mining, construction and agriculture. Transportation is entirely dependent on energy to travel from one location to another. For the residential sector, daily activities such as lighting, cooking, watching television, operating electrical appliances, so on and so forth require the use of energy.

When studying the breakdown of primary energy consumption by source, it can be observed that petroleum and other liquids, coal and natural gas are the top three energy sources consumed by the world since decades ago, with 32%, 26% and 22%, respectively, of the total energy consumption in 2018. Nuclear and renewable (excludes biofuels) energy consumption took up the least, which were 5% and 15%, respectively, in 2018 (U.S. Energy Information Administration, 2019b). Figure 1.3 shows the line graphs and shares of the history and the projection of global primary energy consumption by source.

By referring to the projection part in Figure 1.3, the renewables (such as solar, wind, geothermal, biomass and hydropower) are forecasted to rise incredibly and become the largest share of energy sources in 2050, which driven by the growing electricity demand and the countries' policies. The petroleum (and other liquids) and coal are also projected to increase to meet the global energy demand. The coal consumption is predicted to drop until the 2030s because it is replaced by natural gas and renewables in the generation process of electricity in many world regions. Then, coal consumption is projected to increase in the 2040s to meet the increased industrial usage and electricity generation.

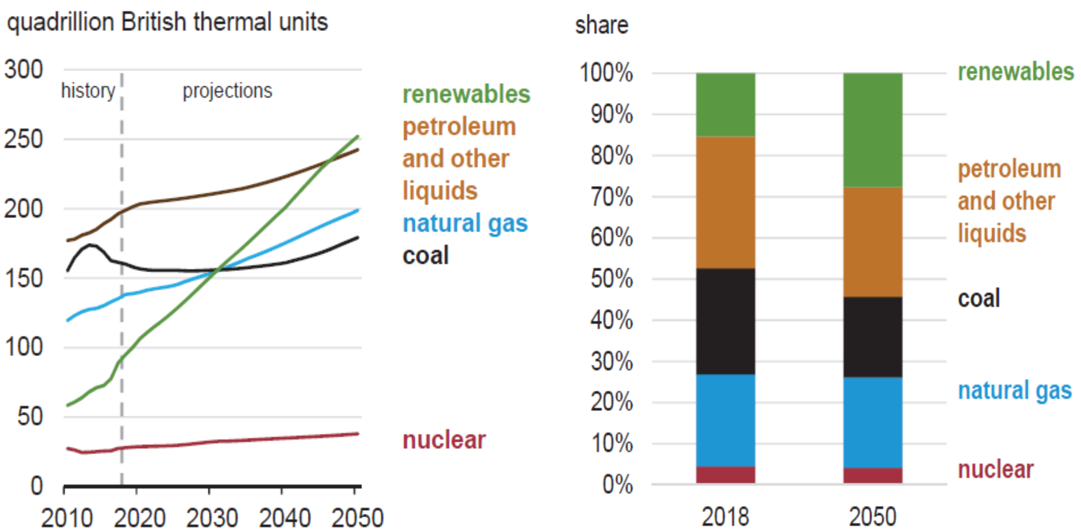

Figure 1.3 The world primary energy consumption growth projection by source (Source: U.S. Energy Information Administration (2019b))

Depending on the types of energy sources, some energy sources require a larger amount of energy input to produce the equal amount of output, owing to a different amount of energy will lose in the process of conversion. In general, higher quality of primary energy sources such as natural gas is more useful and productive than the lower quality, such as coal (Patterson, 1996). The primary energy consumption is the energy in their raw forms as inputs to the energy system, in which the inefficiencies are not taken into account when fossil fuels, the primary energy sources, are converted into the final energy product. Consequently, the final energy consumption is a better estimation of final energy demand, and hence, it is more appropriate for comparing the energy consumption by source (Ritchie & Roser, 2018).

As shown in Figure 1.4, there is a clearer understanding of the distinctions between total primary energy supply (TPES) and total final consumption. The TPES is the total amount of primary energy at the disposal of a country. It includes the energy that is extracted directly from natural resources, which is energy production and the imported energy, but excludes the exported energy. Conversely, the end use energy, commonly known as the total final consumption, is the energy directly consumed by the user. It includes natural gas, gasoline and electricity. As the primary energy usually could not be used directly, some energy conversion technologies are employed to convert TPES (energy input) to total final consumption (energy output). During this energy conversion process, some energy will be lost to the surrounding environment in the form of waste heat (Donev, 2020).

The amount of energy losses depends on the efficiency of the conversion systems and sources of energy used. For instance, transportation can almost fully utilise the primary energy sources due to very little energy is lost when crude oil transforms into fuels for transport such as gasoline, diesel and kerosene. Contrariwise, for electricity generation, the primary energy consumption is about three times the end use energy since the efficiency of most power plants is about 33%. However, it could not be denied that some end-use energy sources are also considered as TPES because the latter involves the composition of imports and exports. Specifically, the net secondary fuels and the net electricity traded turn into part of TPES (Donev, 2020).

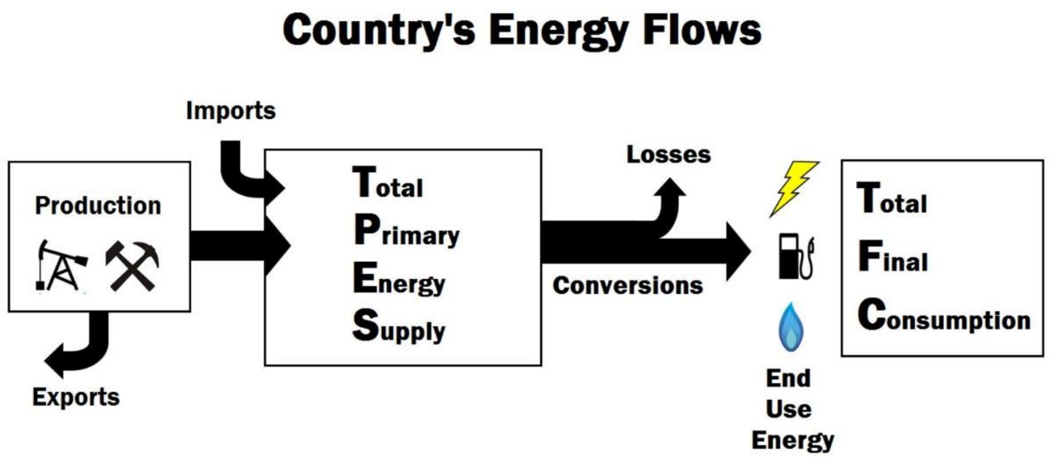

Figure 1.4 The flows of energy
(Source: Donev (2020))

The effect of energy on the economy as a whole is evident through many studies. Energy (or electricity) prices constitute an important part of the consumer price index, the common measure of inflation. Higher energy prices will increase inflation. As a result, energy consumption will decrease, ceteris paribus (Iyke, 2015). Besides that, the emission of waste heat from the conversion process of energy resources, especially the non-renewables, causing some environmental issues and global warming, which eventually will hamper economic growth.

While energy consumption stimulates the economic growth of a country, some studies reported that economic growth also leads to higher energy consumption. The main forms of energy consumed vary depending on the stage of economic development of the regions or countries, moving from biofuels, human and animal power, to the combination of traditional and modern fuels. For instance, wood is a choice of fuel for cooking, but it will be replaced with animal dung or agricultural residues when the wood is in short supply; the usage of kerosene or coal is more common in flourishing areas. The other example of the main energy end-uses is lighting. The use of electricity is less popular among poor households, and the inaccessible of electricity makes them use only candles or kerosene (Barnes & Floor, 1996).

Barnes and Floor (1996) claimed that per capita income levels are correlated explicitly with the increasing use of modern fuels. If the development process is continuing and the level of income is rising, then the projects to outspread the energy supplies could not be incredible. Over the years, the technological enhancements and drops in the cost of modern fuel supplies have been reducing the income level that can be fully shifted to the use of modern fuels. According to PwC (2020), due to the efforts of improving energy efficiency, the global economic growth increased faster than the global energy consumption for the past 25 years, which was from 1990 to 2015. This fact is shown in Figure 1.5, where the slope of the global gross domestic product (GDP) is steeper than the slope of the global energy consumption.

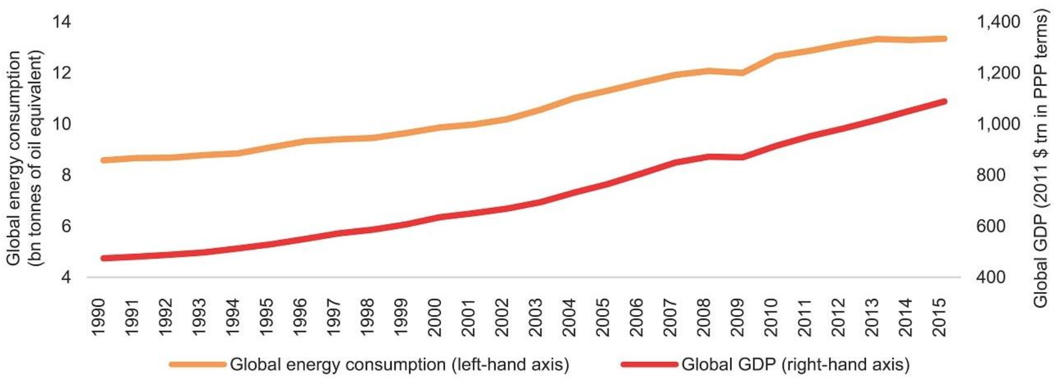

Figure 1.5 Global energy consumption and global GDP in 1990-2015
(Source: PwC (2020))

There are numerous empirical models for examining the linkage between energy consumption and economic growth. The available energy-growth literature can be classified into country-specific and panel-based studies. Many researchers studied the nexus using time-series approaches for a single country or a few individual nations. The time-series models include but are not limited to ordinary least squares (OLS), autoregressive distributed lag (ARDL) or nonlinear ARDL (NARDL), threshold autoregressive model, smooth transition vector autoregressive model, regression method with breakpoints and Markov-switching vector autoregressive (MS-VAR). For panel-based studies, there are innumerable modelling approaches, including fixed and random effects models, generalised method of moment (GMM), pooled OLS (POLS), fully modified OLS (FMOLS), dynamic OLS (DOLS), panel error correction model (ECM), panel vector error correction model (VECM), panel VAR, panel ARDL or panel NARDL, common correlated effects (CCE) model, panel threshold regression, panel smooth transition regression and panel quantile regression.

1.2 Problem Statement and Motivation of the Study

In investigating the direction of the causal relationship between energy and growth, i.e., whether energy consumption has an influential effect on economic growth or whether the contrary is true, the outcomes would affect policy decisions. However, a substantial number of past studies have given rise to inconclusive and conflicting results. No consensus has been achieved for country-specific and panel-based studies. In general, the growth hypothesis is documented as the most common finding in country-specific studies. Specifically, 43.8% of the existing country-specific studies discovered a one-way causal relationship running from energy consumption to economic growth (i.e., growth hypothesis), 27.2% for a one-way causal relationship running from economic growth to energy consumption (i.e., conservation hypothesis), 18.5% for a bidirectional causality between energy consumption and economic growth (i.e., feedback hypothesis), and 10.5% for no causal relationship (i.e., neutrality hypothesis) (Mutumba *et al.*, 2021).

In addition, the effects can be heterogeneous across industries and countries. Numerous studies examined the linkage between energy consumption and economic growth to compare across many different groups of countries, for instance, according to the income levels, levels of development of the countries and energy dependency. A study by Sarwar *et al.* (2017), who used the dataset for a panel of 210 countries as an example, proved mixed evidence for the linkage between oil price, electricity consumption and economic growth. Their findings varied across income levels, OECD/non-OECD, regional levels, renewable energy consumption levels and oil export/import groups. Several studies have conducted surveys of the earlier literature and provided discussions or remarks regarding the causal relationship between energy consumption and economic growth. They include but are not limited to Hajko (2017), Jakovac (2018) and Mutumba *et al.* (2021). Besides, Smyth and Narayan (2015) discussed the implications for energy economics research.

The topic of the energy-growth nexus is predominant and crucial because it is closely linked to global warming and greenhouse gas mitigation policies. Through these policies, carbon dioxide emissions can be reduced directly or indirectly by reducing energy consumption, which then diminishes carbon dioxide emissions (Hajko, 2017). Additionally, non-renewable energy sources are limited and will eventually run out since they cannot be replenished. Perceiving the shortcomings of utilising non-renewables, awareness of energy conservation and the energy transition from non-renewables to renewables has become more prevalent. Notwithstanding, the economic impacts due to these changes or transitions are unknown. Therefore, numerous researchers seek to identify the association between energy consumption and economic growth.

The United Nations Sustainable Development Goals (SDGs) 7 and 8 focus on energy and economic growth to ensure that everyone has access to affordable and clean energy and encourage sustainable and inclusive economic growth. The SDGs call for participation from all nations, rich or poor, to boost prosperity while safeguarding our planet (United Nations, 2023b). There are some concerns and targets to accomplish the goals. Achieving Goal 7 is crucial because all sectors require a well-established energy system. For Goal 8, sustainable economic growth will boost all progress and enhance living standards (United Nations, 2023a). Hence, this research is motivated to contribute in this direction by modelling the two-way relationship between energy consumption and economic growth for low and lower-middle-income economies as well as high-income economies.

In fact, since the 1950s, the relationship between energy and growth has been a debatable topic. Due to the social consequences related to this topic, a growing number of in-depth studies have been conducted with much larger datasets and more robust econometric methods (Baz *et al.*, 2019). From previous studies, some limitations could be observed, particularly in terms of modelling approaches, which lead to controversial outcomes in the energy-growth literature (Hajko, 2017; Mutumba *et al.*, 2021). Among those studies, there are several major weaknesses, with a few estimation issues encountered. The approaches to the energy-growth analysis adopted by past studies are mainly based on the linear relationship and ignorance of nonstationary or cointegration, slope heterogeneity, cross-sectional dependence and dynamic effect in the regression.

The assumption of linearity may not provide a good approximation in cases where the real relationship is nonlinear (Enders, 2015). In the real world, nonlinear relationships or asymmetric effects might exist due to changes in economic variables as a result of myriad factors, such as financial crises, the hit of sudden shocks, environmental changes, oil price fluctuations and changes in energy policies, which could cause structural shifts in energy usage patterns, leading to nonlinearities in the relationship (Smyth & Narayan, 2015). Besides, linear approaches could not uncover nonlinearities or asymmetric effects. Accordingly, limiting the relationship to be linear may produce inaccurate results, which could potentially generate inaccurate policy decisions (Enders, 2015).

On the other hand, globalisation and trade linkages have reduced the distance across the world's regions. The world is without borders. Therefore, the influences among trade partners or neighbours might lead to interdependence and influences among countries. According to Westerlund and Edgerton (2008), the cross-sectional dependence effect is foreseen to be prevalent and common practice in analysing macroeconomic and financial data due to substantial inter-economy connections. However, such an effect is always ignored in the model estimations. Again, neglecting the cross-sectional dependence effect might lead to inaccurate results if the effect is present.

Moreover, the standard panel data analysis adopted by some past studies in handling macro panels or panel time-series analysis is usually the pooled technique, which is very common in micro panels. Applying this technique implies that the slope parameter of the panel data regression will produce a homogeneous effect, i.e., identical estimated coefficients across all cross-sectional members. Nevertheless, the assumption of slope homogeneity is frequently rejected. It is because of the large time-series dimension in macro panels. Adopting the conventional pooled estimators if the true condition is heterogeneous will result in a significant possible bias (Baltagi, 2005).

Another estimation issue overlooked in previous studies is the use of stationary or first-differenced datasets. Even though differencing the series to obtain stationarity is a straightforward strategy for tackling spurious regression, it loses the information inherent in the long-run linkage. One of the advantages of nonstationary panel models is that they preserve the information and uniqueness of the data while also offering additional information with long-run effects in the presence of cointegrating relationships (Wooldridge, 2013; Birkel, 2014; Parker, 2020).

Furthermore, numerous literature studies only focused on static regression in investigating the relationship between energy consumption and economic growth. It indicates that those studies disregarded the dynamic effect. Nonetheless, numerous economic linkages are dynamic (Baltagi, 2005). The current condition may be influenced by the historical lag movements due to the delay effects. In some circumstances, the relationships comprise a set of endogenous variables that are conditional on a collection of exogenous variables supposed to be specified by economic theory. Thus, the economy is perceived as an integrated system from the perspective of economists (Hsiao, 2014).

This research seeks to fill the gaps from previous studies to examine the reasons behind the controversial findings from the energy-growth literature by applying estimation approaches that consider a few aspects, namely nonstationary or cointegration, slope heterogeneity, cross-sectional dependence and dynamic effect. In addition, nonlinearities or asymmetric effects will also be incorporated into the standard linear panel regression models. This thesis intends to demonstrate that taking into account these features will improve the accuracy of estimates, which has different economic implications.

1.3 Research Questions

The direction of the causal relationship between energy and growth is ambiguous, that is, whether the fact that energy consumption gives an influential effect on economic growth or the contrariwise is true. Despite the conduct of the numerous studies, the topic is still deplorable due to the inconclusive and conflicting results. The conventional approaches might lead to different conclusions, as the conventional methods do not have the estimation options such as nonlinearity, heterogeneous, cross-sectional dependence and dynamic effect.

Aiming to fill the gaps from previous studies, the main research problems identified include:

1. How does energy consumption affect economic growth and vice versa in low and lower-middle-income economies (Group 1) and high-income economies (Group 2)?
2. Do nonstationary or cointegration, slope heterogeneity, cross-sectional dependence and dynamic effect influence the estimation results of the energy-growth nexus?
3. Do the models show nonlinear/asymmetric relationships between the energy-growth nexus?
4. Which estimation approaches provide the best approximation to the relationships?

1.4 Research Objectives

In answering the above research questions, our objectives are as follows:

1. To model a two-way causal relationship between energy consumption and economic growth for two panel groups, i.e., low and lower-middle-income

economies (Group 1) and high-income economies (Group 2), by conducting nonstationary panel data regressions in the multivariate framework.

2. To study the estimation issues of the panel data models that are often overlooked by conventional panel approaches, namely nonstationary or cointegration, slope heterogeneity, cross-sectional dependence and dynamic effect.
3. To examine the nonlinear/asymmetric relationships by incorporating the asymmetric estimates (i.e., asymmetric energy consumption or economic growth variables) in the standard linear panel models and then compare their estimated results with those using linear panel models.
4. To reveal the best fit of the models based on the above panel regressions.

1.5 Scope of the Study

This thesis provides a flawless view of the nexus of energy-growth in the nonstationary panel models with the nonlinear/asymmetric estimates included. Based on the above objectives, the main focus is the nexus between total primary energy consumption (TEC) per capita (kilowatt-hours) and gross domestic product (GDP) per capita (constant 2015 US$). The TEC per capita and GDP per capita are more comparable across countries because they are adjusted for the population size of the countries. If these two variables are adopted without the per capita, the outcomes of the analysis might be different. Some countries have large population or high energy consumption level. More residents imply that higher income will be generated to the countries. Even countries in the same panel groups will produce too different GDP levels. The similar justification is also applied to energy consumption.

Apart from this, other variables that might contribute to the linkages are added as control variables, namely gross fixed capital formation (percent of GDP) and labour force participation rate (percent of total population ages 15–64). The labour force covers every individual age 15–64 who contributes to the creation of products and services. Only this group of people is considered, instead of the total labour force that includes all ages, because children or old people are more unlikely to generate beneficial outputs in general.

The targeted groups of countries are categorised by their income levels. In particular, two panel groups of countries are taken into consideration, i.e., low and lower-middle-income economies (Group 1) and high-income economies (Group 2). In other words, the countries with similar income levels, which are classified by the World Bank (2022b), are grouped in a panel for investigation instead of the individual country. This research applies the quarterly datasets with the time frame of 1990Q1–2019Q1, in which the frequency of data is converted from the annual datasets collected. The estimation methods adopted by this research are limited to long panel data estimations. The panel data approaches for short panels are not covered.

1.6 Methodology

The analysis starts with the preliminary tests, namely cross-sectional dependence (CD) tests, panel unit root tests and panel cointegration tests. The first two tests are to detect the presence of cross-sectional and time-series properties, respectively, while the latter is to test for the long-run relationship between the independent and dependent variables. The slope homogeneity test is also adopted to evidence the presence of heterogeneous effect in the slope parameters of the panel data regressions.

It is followed by four groups of model estimations. The first group is the ordinary least squares (OLS)-type estimators, consisting of fully modified OLS

(FMOLS) and dynamic OLS (DOLS) estimators. The second group is the panel autoregressive distributed lag (ARDL) model that includes mean group (MG), pooled mean group (PMG) and dynamic fixed effect (DFE) estimators. The third group is the common correlated effects (CCE) estimation in static panels, comprising common correlated effects mean group (CCEMG), common correlated effects pooled (CCEP) and augmented mean group (AMG). The fourth group of models is CCE in dynamic panels, namely dynamic common correlated effects (DCCE), cross-sectionally augmented distributed lag (CS-DL) and cross-sectionally augmented ARDL (CS-ARDL) models.

After obtaining the results for all estimators, one best model is chosen from each group of models by comparing the goodness of fit and forecast indicators. Yet, the selection of panel ARDL model is the exception. It is because the Hausman specification test is available to determine the appropriateness of restrictions imposed in the MG, PMG and DFE estimators. Subsequently, the results are compared across these four best models to reveal the best fit of models from the linear/symmetric and nonlinear/asymmetric regressions.

The regression function of the panel data model is as follows,

$$Y_{it} = f\,(X_{1it}, X_{2it}, X_{3it}),\ i = 1, 2, \ldots, N,\ t = 1, 2, \ldots, T,$$

where i and t indicate the cross-sectional and time-series dimensions, respectively, N is the number of countries and T is the number of time periods. Y_{it} represents the dependent variable, whereas the explanatory variables are denoted by X_{1it}, X_{2it} and X_{3it}. Since a two-way relationship between energy consumption and GDP is examined, the dependent variable can be represented by the GDP or energy consumption.

In addition, the modification of regressions is made by including the nonlinear/asymmetric elements through the data decomposition technique (i.e., positive and negative partial sum decompositions) of energy or GDP variables. The nonlinear/asymmetric function is as follows,

$$Y_{it} = f\,(X_{1it}^{+}, X_{1it}^{-}, X_{2it}, X_{3it}),$$

where X_{1it}^{+} and X_{1it}^{-} are the decomposed positive series and negative series of X_{1it}. The details of methodologies will be discussed in Chapter 4 (i.e., the Methodology chapter).

1.7 Significance of the Study

The purpose of this research is to study the two-way linear/symmetric and nonlinear/asymmetric relationships between energy consumption and economic growth for low and lower-middle-income economies as well as high-income economies by using long panel data estimations. The contribution of this research is twofold, which is in terms of estimation methods and empirical findings. Several features make this research different from previous studies. Panel data estimation issues, such as nonstationary or cointegration, slope heterogeneity, cross-sectional dependence and dynamic effect, which had always been ignored in panel regressions, are included in this research to permit clearer and more accurate results. Since different types of panel models are performed, this research delivers an overall picture by considering diverse estimation issues and model performances. Through modelling various types of model estimations in a single study, this thesis provides more robust findings than the available energy-growth studies.

Although a few recent studies have employed panel data models that consider most estimation issues in the energy-growth literature, those studies overlooked the potential nonlinear or asymmetric effects in the nexus. Rather than merely focusing on linear regression, this research applies a nonlinear/asymmetric approach to model the linkage between energy consumption and economic growth. In particular, the linear/symmetric variables (i.e., energy consumption and GDP) are decomposed into their respective positive and negative series via the partial sum decomposition technique, and then the asymmetric estimates are incorporated into the standard panel data regressions. This innovation in long panel data estimations, particularly the second-generation panel models, is the novelty of this thesis.

Moreover, this research reveals deeper and additional information on the energy-growth nexus in addition to delivering noteworthy empirical findings, particularly for low and lower-middle-income economies as well as high-income economies. The outcomes of this research are remarkable and significantly contribute to the energy-growth literature. The available literature with macro panels that applied the second-generation approaches, such as Kamah and Riti (2021) and Namahoro *et al.* (2021), only examined the symmetric net impact of energy consumption and economic growth. Accordingly, these studies failed to detect the effect prompted by asymmetric positive and negative shocks on explanatory variables. Through the asymmetric impacts of energy consumption or economic growth instead of their net effects, the findings are impactful to the authorities and policymakers in determining the type of energy policies to implement for the two panel groups. Policymakers could formulate or devise various strategies based on the outcomes of the asymmetric effects to determine whether limiting or encouraging energy usage is more beneficial to long-term economic growth and vice versa.

Furthermore, the topic of this thesis is very relevant to sustainable development. The world has been progressing towards sustainable development by adhering to the goals and targets set by the United Nations in the SDGs. Notwithstanding, the progress is not at a sufficient pace to accomplish the SDGs

(United Nations, 2023a). The conduct of this research could hopefully provide some new insights into a few goals of the SDGs.

1.8 Organisation of the Thesis

The thesis is divided into six chapters, including this introductory chapter. The following chapter, Chapter 2, narrates the literature review and background study. The definition, concept and relationship between a few energy indicators (i.e., energy consumption, energy intensity and energy efficiency) are explained clearly. The sources and classifications of energy are described. Then, there are some reviews of energy resources, consumption and transition trends. It is followed by theoretical frameworks and empirical reviews.

Next, Chapter 3 discusses the panel data analysis and some estimation issues. In this chapter, some concepts related to panel data analysis are enlightened, which include the comparison between micro (short) and macro (long) panels as well as the advantages and challenges of panel data. Also, the issues encountered in panel data analysis are stated with some clarifications. The classification of panel data models is listed, with a key focus on the nonstationary heterogeneous panel models. The other crucial feature in the panel data analysis, which is nonlinearity and asymmetric effects, is also described.

Chapter 4 describes the data and the methodology applied in this research. Under the data section, the two dimensions of panel data, i.e., the cross-sectional members and time-series units, are specified. The foremost aspect of constructing/decomposing data for obtaining asymmetric series is elucidated. The descriptive statistics and graphical representation of the series are also demonstrated.

It is followed by explanations of the estimation functions, procedures taken, and methodologies of preliminary tests and model estimations for this research.

Subsequently, Chapter 5 summarises and discusses the results. The results of preliminary tests are reported before the findings of model estimations. For the results of model estimations, explanations are first made based on the available variables or terms that appear in the full tables. Then, the preferred or best estimators within each group of estimation techniques are determined, and the estimated coefficients are interpreted. After that, the chosen estimators are compared across all four approaches employed, and then justifications are provided based on the interpretation of the results obtained as well as connections to related energy-growth literature.

Finally, Chapter 6 draws the conclusion, highlights the key contributions, and delivers the economic implications and policy recommendations. This chapter also describes the global challenges and actions taken, where a few goals from the 17 Sustainable Development Goals (SDGs) that can be linked to the topic of this thesis are emphasised. It is followed by the limitations of the study. At last, the chapter ends with some suggestions for future research.

CHAPTER 2

LITERATURE REVIEW AND BACKGROUND STUDY

2.1 Overview

In this chapter, the definitions and concepts of energy consumption are discussed, along with the relationship between energy consumption, energy efficiency and energy intensity. The category and classification of energy sources, related plots and statistics are explained accordingly. It is followed by the theoretical framework, which includes the theory of production and growth, the hypothesis of the energy-environmental Kuznets curve (energy-EKC), factors affecting the nexus between energy and growth, and the four hypotheses for the relationships between energy and gross domestic product (GDP). Then, empirical reviews are done and summarised according to the direction of causality (the four hypotheses) between energy and growth, heterogeneous effects (countries, sectors and periods), and linearity versus nonlinearity. The limitations that could be obtained from previous studies are also discussed.

2.2 Concept and Background Study

2.2.1 Energy consumption, energy intensity and energy efficiency

According to Patterson (1996), energy efficiency could not be measured quantitatively. Alternatively, a series of indicators, particularly thermodynamic, physical-thermodynamic, economic-thermodynamic and economic indicators, must be relied on to measure the changes in energy efficiency. Generally, energy efficiency is attained when less energy is used to generate an equivalent amount of beneficial output. Thus, the energy efficiency index (EEI) is introduced with a simple ratio, that is,

$$EEI = \frac{\text{useful output of a process}}{\text{energy input into a process}}\,.$$

The energy input into a process is also known as the energy consumption of the process. The 'useful output' of the process does not necessarily indicate the energy output. It could also be a product or other physical output (particularly, GDP), or it could be in terms of market prices. Energy efficiency sometimes involves reversing the numerator and denominator. For instance, the energy-GDP ratio is frequently used as the indicator of energy efficiency (Patterson, 1996).

Patterson (1996) also claimed that if the numerator and denominator of EEI are reversed, then it is the energy intensity ratio, that is,

$$\text{energy intensity} = \frac{\text{energy consumption}}{\text{output}}\,.$$

In other words, energy intensity is the ratio of energy consumption to economic (or physical) output, where the energy consumption could be the primary energy consumption or the final energy consumption (Ortiz & Sollinger, 2003; Samuelson, 2014). However, if energy intensity is required to indicate the regional energy efficiency, Samuelson (2014) argued that it is problematic to determine an appropriate definition for energy intensity. Using the IEA/Eurostat methodology to calculate the energy intensity based on primary energy, the energy intensity will increase (efficiency will decrease) if an economy uses more nuclear or geothermal energy instead of fossil fuel to generate electricity since the efficiency of fossil fuel plants is greater. Alternatively, computing energy intensity with final energy will provide clearer measures of end-user energy efficiency. Nevertheless, this approach will not reveal improvements in the efficiency of electricity generation. As a result, the author highlighted that different definitions of energy intensity applied could noticeably change the incentives.

In general, energy consumption, energy efficiency and energy intensity are closely related. According to Herring (1999), the debate on the inverse relationship between energy efficiency and energy consumption had spread since the early 1990s. Higher energy efficiency will lead to lower energy consumption. However, some economists debated that enhancing energy efficiency at the microeconomic level would facilitate higher energy consumption at the macroeconomic level. This is due to the ‘rebound’ or ‘takeback’ effect (Herring, 1999; 2006; Greening *et al.*, 2000). Higher energy efficiency would reduce the price of energy indirectly, causing its use to be more affordable, hence greater energy usage. This effect is named the Khazzoom-Brookes postulate (Herring, 1999; Saunders, 2000). Saunders (2000) discussed some significant insights regarding the rebound issue. One of the insights is an increase in fuel efficiency raises the desirability of fuel usage than other factors required for production. The gain in fuel efficiency also increases the overall economic output, therefore induces the consumption of fuel.

On the other hand, Howarth (1997) interrogated this rebound effect. He designed a model to prove that enhanced energy efficiency could not raise energy consumption except under empirically implausible assumptions. His model distinguished the energy uses and energy services in the activities of production with two assumptions, which are the domination of the costs of energy in the total cost of energy services, and the expenses on energy services make up a large portion of economic activities. Since both assumptions are not feasible, the author concluded that improvements in energy efficiency will reduce energy consumption in the long run.

The concept of energy intensity can be linked to the concept of energy efficiency. Energy intensity is a measure of the energy needed per unit of output, whereas energy efficiency increases when the output is delivered with less energy use.

Consequently, the energy intensity is often used as a proxy for energy efficiency in many literature studies. Despite that, the changes in energy intensity may not explain an increase in energy efficiency due to structural changes. A decrease in energy intensity implies energy conservation, but conservation is heavily depending on the level of energy efficiency. However, there is no significant difference between energy efficiency and energy intensity at a given level of technology (Adom, 2015).

In other words, when studying the energy performance of an economy, it is generally assumed that energy intensity and energy efficiency are similar energy indicators. However, this widespread assumption was denied by Proskuryakova and Kovalev (2015). They pointed out the discrepancies between the concept of energy intensity and energy efficiency. First, measuring the energy efficiency by using energy intensity does not explain what inefficient is since it does not provide any specific recommendation on the development of energy efficiency. Second, energy intensity does not specify any approximate range of the room for improving energy efficiency at a known technology level.

Expressed differently, higher energy intensity does not certainly show that there is room for improvements. Similarly, lower energy intensity attained does not stipulate the necessity to repeal energy efficiency incentives (Proskuryakova & Kovalev, 2015). In short, energy intensity and energy efficiency should be interpreted as two distinct and independent parameters, as mentioned by Proskuryakova and Kovalev (2015). They also claimed that the energy intensity indicator is still very useful for analysing energy factors in economic growth and the economic dependence on energy. Therefore, they concluded that the measure of energy intensity could reflect energy consumption but not energy efficiency.