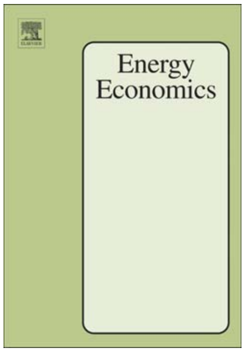

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Economic Growth, Fossil Fuel and Non-Fossil Consumption: A Pooled Mean Group Analysis using Proxies for Capital

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Abstract

This study employs a Pooled Mean Group estimator to examine the nexus between economic growth and fossil and non-fossil fuel consumption for 53 countries between 1990 and 2012. The global sample was divided into four categories: developed exporters, developed importers, developing exporters and developing importers. The purpose of these categories was to observe whether factors unique to these countries influence the relationship between energy consumption and economic growth. With the exception of developing importers, evidence of bi-directional causality between fossil fuel consumption and real GDP across all subsamples is observed. This leads to the conclusion that efforts to directly conserve fossil fuels may harm economic growth. In terms of non-fossil fuel use, the results are more diverse. Bi-directional causality between non-fossil fuel use and real GDP is found in the long and short run for developed importers; bi-directional causality only in the long run for developed exporters; negative long-run causality from real GDP to non-fossil fuels for developing exporters; and long-run causality from non-fossil fuel use to real GDP for developing importers. These results lead to the conclusion that other factors have been responsible for the progress seen in non-fossil fuel use. Thus it is concluded that economic growth on its own is insufficient to promote clean energy development. There is a need for policy makers to create an environment conducive to renewable energy investment.

Keywords: Economic growth, Fossil fuel consumption, Non-fossil fuel consumption, Granger causality, Pool mean group estimation

JEL Codes: C01 C33 013 Q43

Growth, Fossil Fuel and Non-Fossil Consumption: A Pooled Mean Group Analysis using Proxies for Capital

1. Introduction

The recent United Nations Climate Change Conference in Paris resulted in a commitment to limit warming to well below 2°C above pre-industrial levels and pursue efforts to limit the global temperature increase to 1.5°C (UNFCCC, 2015). Whilst the agreement demonstrates countries' willingness to combat climate change, the implementation of the promised policies will nevertheless pose significant challenges. Primary among them is the trade off between mitigating climate change while maintaining economic growth. This is of particular significance for developing countries, who will be among the largest contributors to future increases in greenhouse gas (GHG) emissions. Based on current trends, non-OECD emissions are projected to exceed OECD emissions by 127% by 2040 (EIA, 2013). Therefore, it is vital that emerging countries manage their development more sustainably in comparison to countries that developed in previous generations. Unruh (2000, 2002, 2006) has even described a "carbon lock-in" phenomenon, whereby countries with energy systems based on fossil fuels find it difficult to transition to alternative energy once energy infrastructure and policies are set in place.

Figure 1 shows per capita carbon dioxide emissions for the countries in this study, categorised according to their level of development and importer or exporter status. It can be seen that in the case of developed countries, carbon dioxide (CO_2) emissions, at least on a per capita basis, slightly decreased between 1990 and 2012, possibly reflecting the ongoing change in the composition of these economies, as well as increases in energy efficiency and non-fossil use. On the other hand, per capita emissions for developing countries are still increasing. Unless this trend can be halted or reversed, the trajectory for global warming will be significantly steeper.

[Figure 1]

The threats from climate change are well documented and GHG emissions mainly from fossil fuel consumption are a leading cause of this phenomenon. Furthermore, developing countries are considered most vulnerable to these risks because of their dependence on agriculture, the most climate-sensitive production sector. Moreover, developing countries are least able to adapt to climate change due to a combination of underdeveloped infrastructure, weak social safety nets and low personal savings for disaster recovery (Ward and Shively, 2012). The World Health Organisation (WHO) projects 250,000 additional deaths per year from climate change between 2030 and 2050 (WHO, 2015).

At the same time though, it is important to acknowledge the contributions of energy consumption to economic development. To the extent that energy use increases economic growth, raises incomes, raises education levels, and improves health and infrastructure, the responsible use of energy can be a positive force for achieving development goals such as poverty reduction. This reasoning, of course, assumes that energy consumption causes economic growth, and therefore efforts to conserve energy would restrain incomes. Figure 2 shows a clear correlation between energy use and GDP per capita, but causality is less obvious. It could instead be the case that causality runs in the other direction, with incomes being the main driver of energy use. Alternatively, the relationship could be bi-directional or there could be no relationship whatsoever.

[Figure 2]

Understanding these dynamics is one of the main objectives of the energy-income nexus literature. Recent developments in the literature have been characterized by conflicting results, with no clear consensus on the nature of the causality. Different forms of causality have been observed depending on the countries investigated, the timeframe considered, the variables included and the econometric approach employed This in itself is not completely unreasonable, as the relationship between energy and growth is likely to differ across time and across countries. To contribute to the existing analysis, this study disaggregates energy consumption into fossil and non-fossil fuel sources and divides a global sample of 53 countries into four subsamples: developed exporters, developed importers, developing exports and developing importers. The purpose of this disaggregation is to ascertain what role the level of development and energy importer/exporter status plays in the relationship between energy and income, and also whether these findings differ with respect to the two alternate energy sources – fossil and non-fossil fuels.

In addressing climate change, policymakers are increasingly aware that a ‘one-size-fits-all’ approach is not always appropriate. Instead, it is more desirable for countries to contribute to the global emissions reduction effort according to their strengths and weaknesses. This will depend on resource endowments, geographical characteristics and the prominence of particular industries in a given economy. This line of reasoning was reflected in the most recent round of UN climate change negotiations, where countries were called upon to publish Intended Nationally Determined Contributions (INDCs), in which countries specify what role they will play in reaching the global temperature target. INDCs foster transparency and disclosure and encourage other nations to increase their efforts, while signalling to businesses and consumers how they can modify their actions accordingly (World Resources Institute, 2015). Given the focus on tailoring energy and environment policies to specific countries, this paper makes a contribution to the policy debate by outlining how countries in each of the four subsamples could respond to climate change without unnecessarily hampering their economic prospects.

Several important phenomena in the global economy are of relevance to the energy-income nexus. As evidenced by Figure 3, the services sector accounts for a larger share of GDP in developed nations than in developing nations, but over time this share has increased for all countries. A consequence of this structural transformation is that the industrial and agricultural sectors, which are considered to be more energy-intensive, now play a smaller role in the economies under investigation. It is instructive to note that many of the developed countries in this study (both net energy importers and exporters) have managed to decrease their use of fossil fuels, even though they have registered steady increases in GDP.

[Figure 3]

Table 1 shows that average annual fossil fuel consumption growth has been 0.08% for developed importers. Whilst it is imperative not to confuse correlation with causality, it seems that the once obviously positive relationship between fossil fuels and GDP has been weakening, even reversing for a sizeable share of developed countries. Tests of causality between these variables will have important policy implications for the developed world, and will also act as a future guide for developing countries.

[Table 1]

Another important development has been the rapidly increasing adoption of renewable energy. This has been facilitated by greater environmental awareness, technological innovations, decreases in cost, increases in scale and assistance from governments in the form of subsidies and tax credits. On average, annual growth in non-fossil fuel consumption from 1990-2012 has been 3.6%. In this study we conduct causality tests to determine whether this uptake in non-fossil fuels has any implications for economic growth, whether the increase in non-fossil fuels is a result of higher incomes or whether the adoption of renewables is somehow attributable to other factors.

The distinction between energy importers and exporters will also be informative in this study. Table 1 also shows how importers and exporters differ in their energy mix. Between 1990 and 2012, the share of energy consumption from fossil fuels has increased by three percentage points globally. The disaggregation into the four subsamples serves to explain this progression. In developed nations, irrespective of importer/exporter status, the non-fossil fuel share of energy consumption has increased because growth in the consumption of non-fossil fuels has significantly outpaced fossil fuel growth. However, based on the countries included in the analysis, fossil fuels played a larger role in the energy mix of exporters when compared to importers. By convention, importers are deemed to be more oriented towards non-fossil fuels, not simply because of energy security concerns and a scarcity of hydrocarbons, but also because their economies are structured towards less energy intensive industries and a broader energy mix.

On the other hand, the share of non-fossil fuels in the energy mix of developing countries has unfortunately decreased. This may seem puzzling. For developing exporters, growth in fossil fuels has exceeded non-fossil fuel growth as can be expected. Meanwhile for developing importers, average growth in non-fossil fuel consumption has been an impressive 5.5% but this has likely been off a very low base. The probable implication is that despite the progress made in the non-fossil fuel domain, fossil fuels have still been required to meet the ever growing energy needs of developing nations, and the abundance of energy makes this much more feasible for exporters. It is interesting to note that the energy mix is almost identical for developed importers and developing exporters. The causality tests will reveal whether importers and exporters indeed differ in their approach to non-fossil fuels. Another rationale for the disaggregation into fossil and non-fossil fuels in this analysis is to investigate opportunities for substitutability between the two energy sources. This is of particular importance for policy makers as they manage the transition towards cleaner sources of energy.

This paper contributes to the existing literature in a number of ways. Firstly, we employ a Pooled Mean Group (PMG) estimator[1] which is only beginning to be explored in published energy-income nexus research. The PMG estimator allows for cross-sectional heterogeneity through its short-run parameters and enables short- and long-run causality inferences to be drawn, irrespective of whether the included variables are I(1) or I(0). Secondly, we adopt improved measures of human and physical capital, whereas previous studies have relied on gross capital formation and total labor force. This has been achieved by incorporating average years of schooling as a measure for labor force education and by accumulating gross capital formation according to the perpetual inventory method. Thirdly, although emphasis is beginning to be placed on the role of development and income levels in the energy-growth nexus, not much attention has been paid to discerning between net exporters and importers of energy. Finally, we have made an effort to include countries often omitted from previous studies, particularly Eastern European countries for which certain data before 1990 can be scarce.

The remainder of the paper is organised as follows. Section 2 reviews the existing literature, section 3 outlines the methodology, section 4 presents and discusses the results, while section 5 concludes with a discussion of the policy implications and avenues for future research.

2. Literature Review

Findings in the energy-income nexus generally fall under four hypotheses: growth, conservation, feedback and neutrality. The growth hypothesis involves causality from energy consumption to economic growth. An implication of the growth hypothesis is that efforts to reduce energy consumption will harm economic growth. The conservation hypothesis involves causality from economic growth to energy consumption. In this instance, efforts to reduce energy consumption will not have a detrimental impact on economic growth. The feedback hypothesis is supported when

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[1] Motivation for the PMG estimator as well as a description of its properties is provided in the Methodology.

bi-directional causality is observed, and the neutrality hypothesis assumes that there is no causality in either direction.

The pioneering study in this area was by Kraft and Kraft (1978), who found evidence of unidirectional causality running from income to energy consumption. Akarca and Long (1980) criticized this result, arguing that the inclusion of the 1973-1974 period (dominated by the OPEC oil crisis) had an unreasonable effect on the results – instead they put forward evidence of neutrality. These early studies usually employed either Granger or Sims causality. However, a criticism of this early literature has been the assumption of stationarity (Constantini and Martini, 2010), which may have led to spurious results. The development of unit root tests and the work of Engle and Granger (1987) in the area of cointegration enabled future research to ascertain the order of integration for the included variables and apply error correction modelling to draw conclusions concerning causality. Despite this econometric progress, findings remained mixed and were sensitive to the sample selection (whether through time frame or the choice of countries), the econometric approach, and the variables included in the analysis.

The use of panel vector error-correction modelling (VECM) commenced around 2005. Panel data offers several advantages over pure time-series data. Panel data mitigates the limited size of relevant time series data, enabling cross-section and time dimensions to be combined. This allows for higher degrees of freedom and greater statistical power of unit root tests, which suffer from low power. Heterogeneity is also accounted for, and the panel structure reduces the risk of collinearity between the regressors. Analysis incorporating panel data was made possible by the development of tailored panel unit root and cointegration tests.

Early studies to use this econometric approach include: Lee (2005), Al-Iriani (2006) and Mahadevan and Asafu-Adjaye (2007). Lee (2005) discovered causality running from energy to GDP for 18 developing countries in a trivariate model incorporating gross capital formation, while Al-Iriani (2006) observed causality from GDP to energy consumption for the six countries of the Gulf Cooperation Council. Mahadevan and Asafu-Adjaye (2007) incorporated prices into their analysis and arranged the included countries according to level of development and net energy trade balance. In the short run, bi-directional causality was found for all categories except developing importers, for which the finding was unidirectional causality from energy to GDP. In the long run, the bi-directional causality continued for developed exporters, and importers exhibited causality only from energy to GDP.

Many studies have focused on a particular region or category of countries. Hossain (2011) observed causality from GDP to energy consumption for nine newly industrialised countries. Ozcan (2013) analysed data 12 Middle East countries between 1990 and 2008, and detected causality from economic growth to energy consumption. Cowan et al. (2014) analysed the causality between electricity consumption and economic growth and CO_2 emissions in the BRICS countries (Brazil, Russia, India, China and South Africa) with the finding of feedback for Russia, conservation for South Africa and neutrality for Brazil, India and China.

Apergis and Payne (2009) examined six Central American countries and found bi-directional causality between energy consumption and economic growth in the short run, but the long-run causality was consistent with the conservation hypothesis. For seven South American nations, Yoo and Kwak (2010) observed causality from electricity consumption to growth for Argentina, Brazil, Chile, Colombia and Ecuador; a feedback effect for Venezuela; and neutrality for Peru. Wang et al. (2011) investigated causality for 28 provinces in China, with evidence supporting the feedback hypothesis in the short run and the conservation hypothesis in the long run. The diversity of these findings reinforces the notion that policies must be tailored to the circumstances of a given economy.

Another avenue of research has been the disaggregation of energy consumption into different energy sources. This has been motivated in large part not only by the issue of climate change, but also by concerns for energy security. Using data from 1949-2006 for real GDP, renewable and non-renewable energy consumption in the US, Payne (2009) found evidence of neutrality. When considering the impact of renewable energy in Europe, Menegaki (2011) also found evidence in support of the neutrality hypothesis. For a panel of twenty OECD countries from 1985-2005, the findings of Apergis and Payne (2010) supported the feedback hypothesis for real GDP and renewables in both the long and short run. Extending the analysis to both renewable and non-renewable energy sources, Apergis and Payne (2012) considered a panel of 80 countries and once again observed bi-directional long- and short-run causality between economic growth and both sources of energy.

Apergis et al. (2010) compared nuclear energy and renewable energy in their impact on CO_2 emissions. Whilst there was evidence of bi-directional causality between renewables and economic growth, renewables were not effective in reducing CO2, possibly due to a lack of investment or lack of storage technology which means fossil-fuel backups are still required. Nuclear energy, on the other hand, was found to decrease emissions, but the causality with growth was less straightforward. GDP led to increases in nuclear power, but the causality in the other direction was negative. Potential reasons offered for this finding were high capital costs and the cost of disposing radioactive waste. Two recent papers investigating the relationship between renewable energy consumption and economic growth are by Inglesi-Lotz (2016) and Alper and Oguz (2016). Inglesi-Lotz (2016) analysed the relationship for 34 OECD countries and found that a 1% increase of renewable energy consumption will increase real GDP by 0.105%. Alper and Oguz (2016) also anlaysed the relationship for eight new EU members, finding causality to run from renewable energy to real GDP for Bulgaria, real GDP to renewable energy for the Czech republic and neutrality for the remaining countries.

Salim and Rafiq (2012) studied six major emerging economies (Brazil, China, India, Indonesia, the Philippines and Turkey) deemed to be “proactively accelerating” renewable energy uptake. In the long run, renewable energy was driven by income and pollution in Brazil, China, India and Indonesia, but income was the only significant factor for Turkey and the Philippines. In the short run, Brazil, China, Turkey and the Philippines each aligned with the feedback hypothesis, while India and Indonesia exhibited causality only from income to renewables. Ohler and Fetters (2014) decomposed renewable energy into five of its main sources: biomass, geothermal, hydroelectric, solar, waste and wind. Positive bi-directional causality was observed for hydroelectric and waste energy; negative bi-directional causality was observed for geothermal and wind energy; unidirectional causality was found from GDP to solar energy; increases in GDP increased biomass, but biomass decreased GDP.

The persistence of inconclusive results in the literature has prompted researchers to pursue other factors that may explain the variations in causality. For example, Constantini and Martini (2010) evaluated the causality between energy consumption and economic growth for different end-use sectors of OECD and non-OECD nations. The direction of the causality was found to differ substantially between the industry, services, transportation and residential sectors, and in some cases differed within a sector depending on whether a country was OECD or non-OECD. In a similar study involving renewable and non-renewable energy in the US, Bowden and Payne (2010) discover no causality between real GDP and commercial and industrial renewable energy consumption; bi-directional causality between real GDP and commercial and residential non-renewable energy consumption; and unidirectional causality from residential renewable and industrial non-renewable energy consumption to real GDP. The implications for policymakers are that energy policies must be tailored to different sectors as well as countries.

More recently, Karanfil and Li (2015) incorporated urbanization and net electricity imports into an analysis of 160 countries, concluding that the “electricity-growth nexus is highly sensitive to regional differences, countries' income levels, urbanization rates and electricity dependency”. The authors constructed subsamples according to OECD membership, levels of income and geography, finding evidence in support of the conservation hypothesis for East Asia and the Pacific, the Middle East and North Africa, and countries in the Middle East and North Africa, and lower-middle income countries. North America, Sub-Saharan Africa and countries in the upper middle income bracket exhibited neutrality, while bi-directional causality was found for South Asia, Europe and Central Asia, Latin America and the Caribbean, and high and low income countries. Apergis and Payne (2011) also separated 88 countries according to income. Their evidence supports the feedback hypothesis between electricity use and GDP for high and upper middle income panels; the growth hypothesis in the short run for lower middle income countries but the feedback hypothesis in the long run; and the growth hypothesis for low income countries. The studies discussed above are summarized in Appendix Table A.1.

It is important to note that this paper proposes a slightly different disaggregation of energy consumption. Here we distinguish between fossil fuels and non-fossil fuels, rather than renewables and non-renewables. If the purpose of energy policy analysis is to mitigate pollution, then it can be argued that the fossil fuel split is a more informative categorisation because this sorts energy sources according to their level of emissions.

For example, nuclear energy is not classified as a renewable, however, as a non-fossil fuel, it stands to offer certain benefits. Adamantiades and Kessides (2009) state that “nuclear power plants currently save some 10 percent of total CO_2 emissions from world energy use” and “emissions of CO_2 would be some 2.5 billion tonnes higher per year” without the use of nuclear energy. In fact, with regard to GHG emissions, nuclear energy is on par with most renewable energy sources, and is actually cleaner than solar energy production. Whilst the 2011 Fukushima Daiichi nuclear disaster in Japan would have increased the negative public perception of nuclear energy, it is still likely to form an integral element of the future global energy mix with over 60 projects currently under construction in 15 countries and extension programs underway to improve existing plants (World Nuclear Association, 2015).

Earlier studies were either bivariate or trivariate in nature. More recently, research has progressed into multivariate analysis. For example, Payne (2009), Apergis and Payne (2010, 2011, 2012) and Ohler and Fetters (2014) have included measures of both capital formation and labor force, in an attempt to emulate a production function framework. This paper improves on these studies by generating more representative proxies. Years of schooling and estimates of the return to education are added to labor force data to derive a measure of human capital. Meanwhile, the perpetual inventory method and estimates of depreciation and GDP growth are used to create a measure of physical capital. This provides an estimate of the physical capital stock rather than gross capital formation, which is in essence a measure of investment.

3. Methodology

3.1 Data Description and Sources

Annual data on 53 countries (see Appendix Table A.2) from 1990 to 2012 were collected from the World Bank, the U.S. Energy Information Administration (EIA) and the Barro-Lee Educational Attainment Dataset. Data on real GDP (constant 2005 USD), real gross capital formation (GKF) (constant 2005 USD) and total labor force were obtained from the World Bank's World Development Indicators (WDI), while information on fossil and non-fossil fuel consumption (both measured in trillions of British thermal units) was acquired from the EIA. Fossil fuel consumption was calculated as the sum of petroleum, coal and natural gas consumption. The EIA does not publish data on non-fossil fuels, so this was derived as total energy consumption less fossil fuel consumption. In order to generate the human capital proxy, average years of total schooling for the population aged 25 was obtained from the Educational Attainment Dataset. The range of data required on education and capital formation restricts the number of countries available for analysis, but nevertheless these 53 countries accounted for 84.6% of world energy consumption in 2012.

To complement the energy statistics already presented in the Introduction, the indicators in Table 2 provide further justification for the panel data approach, given the apparent heterogeneity in this global dataset. The average GDP growth rate between 1990 and 2012 for the 53 countries as a whole was 3.5%. As would be expected, developed exporters and importers reported the lowest growth rates of 2.2% and 2.1%, respectively, while the GDP growth rate was highest in developing importers, at 5.0%. GDP per capita in 2012 was highest for developed exporters ($38,618). It is interesting to note that this was 41% higher than the average GDP per capita for developed importers. The obvious caveat here is that these figures do not necessarily represent differences between importers and exporters in general, rather they serve to highlight some of the characteristics of the countries under investigation.

Average labor force was highest for developing importers, although this is likely to be heavily influenced by China and India, who both belong to this subsample. There is also a clear contrast between developed and developing nations with respect to labor force growth. This reinforces the fact that countries at a later stage of development typically experience lower population and therefore labor force growth, particularly due to ageing populations. Schooling was slightly higher for developed exporters than for developed importers, but the difference was larger for developing importers and exporters. Understandably the growth rate in schooling over the sample period was higher for developing nations, as most of the developed nations included in this study already possessed relatively high average years of schooling by 1990.

[Table 2]

In addition to testing for heterogeneity across countries, testing for heterogeneity across time is also warranted. The Common Correlated Effects Mean Group (CCEMG) estimator presented in this paper allows for country-specific time trends and indicates for each sample how many of the individual time trends are statistically significant. There is evidence that a substantial proportion of the time trends are significant, which strengthens the case for heterogeneity across time. The results for each sample can be found in the Appendix.

3.2 Theoretical framework

This paper adopts an augmented neoclassical production function framework of the following form:

$$Y_{it} = f(K_{it}, H_{it}, FE_{it}, NFE_{it}) \tag{1}$$

where $i = 1, \dots, N$ are the cross-section units observed over $t = 1, \dots, T$ periods; Y_{it} is real GDP; K_{it} represents the physical capital stock; H_{it} is the human capital stock; FE_{it} depicts total fossil fuel consumption; and NFE_{it} depicts total non-fossil fuel consumption. Y_{it}, FE_{it} and NFE_{it} are obtained directly from the database, but K_{it} and H_{it} need to be approximated. One concept that will prove useful in interpreting this paper's results is the diminishing marginal product of each production factor. This implies that holding all else equal, as the use of one input increases, its productivity decreases. This mindset will help to understand the dynamics in the energy-income nexus for the countries under investigation.

Previous studies have used real gross capital formation (GKF) or real gross fixed capital formation (GFKF) as a proxy for physical capital, but this by definition implies working with investment rather than the actual stock of physical capital. This study attempts to measure the physical capital stock for each economy. This is achieved by accumulating GKF, assuming a constant depreciation rate and using the simplified perpetual inventory method (OECD, 2009). Here, physical capital stock in year t equals investment in year t plus the accumulated and depreciated stock of physical capital in year t-1. That is,

$$K_t = I_t + (1-\delta)K_{t-1} \tag{2}$$

where δ is the fixed physical capital depreciation rate, which is set at 4% using the aggregate depreciation rate estimated in Berlemann and Wesselhöft (2014). We calculate a weighted average based on the depreciation rates of residential, private non-residential, and government fixed assets of 22 OECD countries. The 4% value used here is the median for the period 1980-2010, which aligns with the time period covered in this paper. Next, we approximate the benchmark physical capital stock, K_0. We assume that it is the sum of depreciated previous investments and current investment. That is,

$$K_0 = I_0 + (1-\delta)I_{0-1} + (1-\delta)^2 I_{0-2} + (1-\delta)^3 I_{0-3} + \cdots \tag{3}$$

Next, we assume that the growth rate of the volume of investment is equal to the long-run real GDP growth, g, which implies that $I_0 = (1+g)I_{0-1}$. Substituting this into Equation (3) gives:

$$K_0 = I_0\left[1 + \left(\frac{1-\delta}{1+g}\right) + \left(\frac{1-\delta}{1+g}\right)^2 + \left(\frac{1-\delta}{1+g}\right)^3 + \cdots\right] \tag{4}$$

It can be shown that the physical capital stock benchmark may be approximated as:

$$K_0 = \frac{1+g}{g+\delta} \tag{5}$$

Therefore, given the estimated physical capital stock benchmark, the depreciation rate and the long-run real GDP growth, we are able to compute a proxy for physical capital stock for each country. For human capital we use $H_{it} = L_{it}h_{it}$ as a proxy, where $h_{it} = e^{rs_{it}}$. L_{it} depicts the total labor force, s_{it} is the average years of schooling and r is the return to education which is set at 10% based on Pritchett (2001).

The motivation for incorporating physical and human capital into the model is twofold. Firstly, these variables attempt to address the omitted variable bias that has possibly affected earlier studies. Mankiw et al. (1992) stressed the importance of physical and human capital within a production function framework. They showed that investment and population growth rates are influenced by human capital. Therefore, when these variables are left out of the production function, they form part of the error term, which leads to biased estimation. Moreover, non-causality is another source of bias when relevant variables are omitted (Lutkepohl, 1982).

Secondly, the addition of human capital not only helps to produce unbiased estimates, but it also allows us to test for complementarities, causal relationships other than the energy-income nexus, such as the causal relationship between clean energy use and human capital. For instance, finding short-run causality from human capital to clean energy could lend support to the view that enhancing education could promote awareness about environmental issues. The availability of schooling and capital formation data restricts the number of admissible countries in this sample, so instead the emphasis is on countries that are likely to have a significant impact on the energy landscape in future years and whose decisions on energy mix could shape global efforts against climate change.

3.3 Panel Unit Root Tests

Before conducting any estimations, a selection of panel unit root tests were implemented to ascertain the order of integration. This achieves two objectives: firstly to avoid the spurious consequences of non-stationarity and secondly to investigate the potential for cointegrating relationships. A wide range of panel unit root tests have been established in the literature, owing to their higher power when compared to conventional unit root tests. These tests differ largely on whether they control for cross-sectional dependence and whether they allow for common roots or individual roots. Tests proposed by Im et al. (2003) (hereafter IPS) and Pesaran (2007) allow for individual roots. Tests that control for cross-sectional dependence include Bai and Ng (2001, 2004), Pesaran (2007), Phillips and Sul (2003) and Moon and Perron (2004).

Given the heterogeneity for the 53 countries observed in this paper, only unit root tests that assumed individual roots were considered. However, due to the finding of cross-sectional dependence, only the test proposed by Peseran (2007) is presented here.[2] The Pesaran (2007) procedure is a modification of the IPS (2003) approach. In the IPS procedure an ADF (Augmented Dickey Fuller) regression is estimated for each cross-section as follows:

$$\Delta y_{it} = \rho_i y_{it-1} + \sum_{j=1}^{p_i} \beta_{ij} \Delta y_{it-j} + X'_{it}\delta_i + \varepsilon_{it} \qquad (6)$$

where i = 1, …, N indicate the countries observed over t = 1, …,T years; p_i denotes the number of included lags, which is permitted to vary across countries; ρ_i represents the autoregressive coefficients; X_{it} denotes any exogenous variables, including any fixed effects and individual trends. Under the null hypothesis, every series in the panel has a unit root, while under the alternative hypothesis, at least one of the individual series is stationary. Expressed formally: $H_{1:} \begin{cases} \rho_i = 0 & i = 1, \dots, N_1 \\ \rho_i < 0 & i = N_1, \dots, N \end{cases}$

This is in contrast to common root tests where it is assumed that the autoregressive coefficients are homogenous for all cross sections (i.e. $\rho_i = \rho\ \forall i$). The IPS test statistics,$\bar{t}$, is computed as the average of individual ADF test statistics, $\bar{t} = \frac{1}{N}\sum_{i=1}^{N} t_{\rho_i}$. Im et al. prove that the $\bar{t}$ statistic is normally distributed under the null hypothesis. Critical values are available from IPS (2003) and are also provided in most statistical packages.

Pesaran's (2007) approach addresses the issue of cross-sectional dependence. He proposes that ADF regressions should be further augmented with cross-section averages of lagged levels and first differences of individual series. This leads to CIPS (cross-sectionally augmented IPS) test statistics.

3.5 Cross-Section Independence

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[2] The results for the first generation unit root tests are available upon request.

An important assumption to consider is that of cross-sectional independence. In an increasingly interconnected world, cross-sectional dependence can occur through spatial or spillover effects or as a result of unobservable common factors. It is important to test for cross-sectional dependence, as certain unit root tests are not necessarily robust to this assumption. To this end, a procedure proposed by Pesaran (2004) is implemented to check for instances of cross-sectional dependence.

Consider the panel data model specified in Equation (6). The null hypothesis is cross-sectional independence, which means $H_0\colon \rho_{it} = \rho_{jt} = Corr\left(e_{it}, e_{jt}\right) = 0\ \forall t \wedge \forall i \neq j$ against the alternative hypothesis of cross-sectional dependence, $H_1\colon Corr\left(e_{it}, e_{jt}\right) \neq 0$ for some $i \neq j$, where the e_{it} are the estimated residuals of the regression estimated in the previous sub-section. Pesaran (2004) proposes a test based on the average of the pairwise correlation of the residuals:

$$CD = \sqrt{\frac{2T}{N(N-1)}}\left(\sum_{i=1}^{N-1}\sum_{j=i+1}^{N}\hat{\rho}_{ij}\right) \tag{9}$$

where $\hat{\rho}_{ij} = \sum_{t=1}^{T} e_{it}e_{jt} / \left(\sum_{t=1}^{T} e_{it}\right)^{1/2}\left(\sum_{t=1}^{T} e_{jt}\right)^{1/2}$. Listed in Table 3 are the tests of cross-sectional independence for the global sample and each of the four subsamples. The null hypothesis of cross-sectional independence is rejected for the global sample, developed importers and developing importers, while no evidence of cross-sectional dependence is found for developed or developing exporters. These findings endorse the selection of unit root tests presented, which includes tests that control for cross-sectional dependence.

[Table 3]

3.6 The Pooled Mean Group (PMG) Estimator

This study employs an econometric method that is only beginning to be explored in the energy-income nexus literature: the PMG Estimator[3] proposed by Pesaran et al. (1999). When working with panel data, econometric approaches can be separated into

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[3] Previous applications of the PMG estimator in other research areas include Okada and Samreth (2011) and Martinez-Zarzoso and Bengochea-Morancho (2004) for an Environmental Kuznets Curve; Bangake and Eggoh (2012) for capital mobility in Africa; and Bassanini and Scarpetta (2002) for human capital.

two distinct categories. Firstly, individual heterogeneity can be accommodated by estimating individual equations for each cross section and averaging the parameter estimates. This is achieved by the Mean Group (MG) estimator proposed by Pesaran et al. (1995), which can be shown to be a consistent but not necessarily efficient estimator of the average heterogeneous parameters. Alternatively, the cross sections can be pooled with the use of a dynamic fixed effects or other similar model. This approach allows for different intercepts but requires that slope parameters be identical for all cross-sections, which can be a highly restrictive assumption.

The PMG estimator seeks to find a balance between these two competing approaches, by capitalising on the merits of both methods. Short-run coefficients are permitted to vary across countries (akin to the MG estimator) while long-run coefficients are required to be homogenous for all cross sections (akin to the fixed effects estimator). There are several advantages of the PMG estimator in comparison to other methodologies. For example, the PMG estimator can be used regardless of whether the variables are I(0) or I(1), and long- and short-run causality inferences can be drawn even if the presence of cointegration is not formally detected. Furthermore, if variables are in logarithms then the long-run coefficients can be interpreted as elasticities. Consider the following ARDL (1,1,1,1,1) equation:

$$y_{it} = \lambda_i y_{i,t-1} + \sum_{j=0}^{1} \delta_{ij}' X_{i,t-j} + \mu_i + \varepsilon_{it} \tag{10}$$

where $X_{i,t-j}$ is an $n \times k$ vector of the logarithms of the explanatory variables (*k*, *h*, *fe*, *nfe*), δ_{ij} is a $k \times 1$ coefficient vector and μ_i accounts for country-specific effects. Equation (10) can be rearranged into an error correction model of the following form:

$$\Delta y_{it} = \phi_{1,i}\left(y_{i,t-1} - \theta_{1,i}' X_{i,t-1}\right) + \delta_{1,i}^{*\prime} \Delta X_{it} + \mu_i + \varepsilon_{it} \tag{11.1}$$

Where $\phi_{1,i} = -(1 - \lambda_i)$ and $\theta_{1,ji} = \frac{\sum_{j=0}^{1} \delta_{ij}}{1 - \lambda_i}$

In a similar manner, the remaining equations can be expressed as follows:

$$\Delta k_{it} = \phi_{2,i}\left(k_{i,t-1} - \theta_{2,i}' X_{i,t-1}\right) + \delta_{2,i}^{*\prime} \Delta X_{it} + \mu_i + \varepsilon_{it} \tag{11.2}$$

$$\Delta h_{it} = \phi_{3,i}\left(h_{i,t-1} - \theta_{3,i}' X_{i,t-1}\right) + \delta_{3,i}^{*\prime} \Delta X_{it} + \mu_i + \varepsilon_{it} \tag{11.3}$$

$$\Delta fe_{it} = \phi_{4,i}\left(fe_{i,t-1} - \theta_{4,i}' X_{i,t-1}\right) + \delta_{4,i}^{*\prime} \Delta X_{it} + \mu_i + \varepsilon_{it} \tag{11.4}$$

$$\Delta nfe_{it} = \phi_{5,i}\left(nfe_{i,t-1} - \theta_{5,i}{}'X_{i,t-1}\right) + \delta^{*\prime}_{5,i}\Delta X_{it} + \mu_i + \varepsilon_{it} \tag{11.5}$$

where, in each instance, X_{it} is an $n \times k$ vector of the remaining explanatory variables. The δ^{*}s denote short-run coefficients. Significance of these coefficients indicates short-run causality from the associated explanatory variable to the dependent variable. The θs denote long-run coefficients. The significance of these coefficients would indicate that the associated variable forms a long-run relationship with the dependent variable, and if the associated error correction term is both negative and significant, then it is also a source of long-run causality. The ϕs represent error correction terms (ECTs). The inverse of the absolute value of these coefficients provides a speed of adjustment estimate.

At this point it is worthwhile to define Granger causality. A variable X Granger-causes another variable Y if the prediction error of the current Y decreases by using past values of X in addition to past values of Y.

An important diagnostic test that must be conducted is a Hausman-type poolability test, which verifies whether the pooling of long-run coefficients is appropriate. Formally, this test has the null hypothesis H_0: $\theta_i = \theta \; \forall \, i$ against the alternative that these coefficients are not common for all cross sections. Following the traditional Hausman test methodology, the MG estimator is consistent under both hypotheses. On occasional instances in this study, the null hypothesis of poolability is rejected, and in these cases the MG estimator is employed, but in general the PMG estimator is a valid approach.

4. Results

4.1 Panel Unit Root Tests

Table 4 displays the results for the panel unit root tests. Although there are some discrepancies, the overall evidence points to the included variables being integrated of order one.[4] This ambiguity under certain specifications lends support to the use of the PMG estimator.

[Table 4]

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[4] As a robustness check, we also implemented a modified version of Clemente et al.'s (1998) unit root test (not reported here but available upon request) incorporating a structural break for single time series within the panels.

4.2 PMG Estimation Results

Table 5 outlines the main findings of the study. A more detailed analysis follows.

[Table 5]

4.2.1 Results for Global Sample

Table 6 reports the results for the global sample with the long-run coefficients in Equation (11.1) displaying the elasticity of GDP with the respect to the various inputs in the production function. All variables except non-fossil fuel consumption are significant. A 1% increase in physical capital *ceteris paribus* leads to a 0.61% increase in real GDP; a 1% increase in human capital leads to a 0.31% increase in GDP; and a 1% increase in fossil fuel consumption leads to a 0.15% increase in GDP. Although the elasticity for non-fossil fuel energy is not significant, the decomposition into subsamples will demonstrate that this value is heavily influenced by developing exporters; non-fossil fuel consumption is a significant factor for all other categories.

[Table 6]

With regard to the energy-income nexus, there is evidence of bi-directional causality between fossil fuel consumption and real GDP in both the short and long run as well as evidence of short run causality running from non-fossil fuel use to real GDP. The ECTs for real GDP, fossil fuels and non-fossil fuels are highly significant correspond to speeds of adjustment of 3.57, 5.56 and 1.85 years, respectively, indicating that each variable responds quite swiftly to deviations from long-run equilibrium. Substitutability between fossil and non-fossil fuels is evident in both the short and long run, as represented by the negative coefficients for fossil and non-fossil fuels in Equations (11.4) and (11.5).

The inclusion of physical and human capital are important contributions of this study in order to mitigate omitted variable bias as well as to investigate complementarities. The significance of these variables, predominantly as long-run elasticity coefficients and less frequently as short-run coefficients, suggests that they are important in explaining economic growth and changes in energy consumption. Complementarities are indeed evident between both forms of capital and both sources of energy. Notably, increases in both forms of capital lead to decreases in fossil fuel use. This negative relationship implies that these variables can be considered as substitutes in the production function. In other words, countries with more human and physical capital may require fewer inputs of fossil fuels, as new infrastructure may promote greater energy efficiency. This negative relationship persists in the subsamples analysis reported below. On the other hand, physical capital was found to increase non-fossil fuel adoption: new infrastructure and other additions to the capital stock are likely to be more compatible with more modern energy sources.

4.2.2 Results for Developed Exporters

[Table 7]

Table 7 contains the findings for developed exporters. In terms of the energy income nexus, there is bi-directional causality between real GDP and fossil fuel consumption in both the short and long run. There is also bi-directional causality between real GDP and non-fossil fuel consumption in the long run, but not in the short run. The ECTs for real GDP, fossil fuel consumption and non-fossil fuel consumption correspond to speeds of adjustment of 4.35, 1.03 and 1.75 years, respectively. This demonstrates that each of these variables respond swiftly to deviations from long-run equilibrium. Short- and long-run substitutability between the two energy sources is evident through Equations (11.4) and (11.5), in which the necessary coefficients are negative. With regard to physical and human capital, human capital does not appear to be a source of short run causality while physical capital is a significant factor only for real GDP. Instead, these variables tend to be more relevant in the long run, as is clear from the significant elasticity values. The elasticity values for energy demonstrate that increases in fossil fuels appear to more beneficial to growth than non-fossil fuels. For example, a 1% in fossil fuel use leads to a 0.23% increase in real GDP, while a 1% increase in non-fossil fuels use leads only to a 0.10% increase in real GDP.

These results provide important guidance to policy formulation. Firstly, the bi-directional causality between real GDP and non-fossil fuels in the long run is promising. It reveals that economic growth is responsible for increasing uptake in non-fossil fuels, and in return this uptake contributes to long-run growth prospects. Despite this, the absence of such a relationship in the short run means that policymakers must extend efforts to promote non-fossil fuel use, by continuing programs of subsidies, rebates, tax credits, regulation, energy standards and public-private partnerships. The causality from fossil fuels to real GDP signals that outright energy conservation is not the most viable course of action. Rather, measures targeted at efficiency and promoting greater non-fossil fuel use are likely to be less harmful to economic growth, until such a time when a more substantial transition fossil to non-fossil fuels becomes feasible.

4.2.3 Results for Developed Importers

Table 8 displays the results for developed importers. As for developed exporters, bi-directional causality is observed between fossil fuels and real GDP. In contrast to developed exporters though, bi-directional causality between real GDP and non-fossil fuels is observed not only in the long run, but also in the short run. In addition, Equation 11.5 presents evidence of short-run substitutability. Interestingly, there is no indication of long-run substitutability but it could be argued that as non-fossil fuels comprise a larger share of the energy mix, opportunities for substitutability may be less available in the long run, and as such, decreases in fossil fuel consumption lead to increases in non-fossil fuel consumption only in the short run. The ECTs for real GDP, fossil fuel and non-fossil fuel consumption correspond to speeds of adjustment of 2, 2.9 and 2.7 years, respectively. This indicates that each of these variables respond quite quickly to deviations from long-run equilibrium.

[Table 8]

The magnitudes of the elasticity coefficients are also a useful means of comparison with developed exporters. The elasticities of real GDP with respect to fossil and non-fossil fuel energy are both lower (0.178% and 0.003%, respectively). Compared to developed exporters, a lower elasticity for non-fossil fuels could suggest a lower marginal product, as non-fossil fuels already constitute a larger share of importers' energy mix. As was the case for developed exporters, human and physical capital are clearly important control variables in the long run, although they are only occasionally significant as short run coefficients.

A number of policy implications can be drawn from these findings. Firstly, there is clear evidence, in both the short and long run, that increases in real GDP lead to increases in non-fossil fuel use, and furthermore increased non-fossil use drives real GDP. This does not mean that governments do not have a role to play in promoting sustainable energy, but rather that their policies will be implemented in economic settings more conducive to non-fossil fuel consumption. At the same time though, a bi-directional relationship also exists for fossil fuels, which implies that efforts to conserve fossil fuels may potentially harm economic growth. To address this challenge, policies can be targeted at energy efficiency and promoting further adoption of non-fossil fuels.

4.2.4 PMG Estimator Results for Developing Exporters

The findings for developing exporters are displayed in Table 9. There is evidence of bi-directional causality between fossil fuel consumption and real GDP in both the short and long run. However, the relationship between non-fossil fuel consumption and real GDP is less comprehensive: causality is observed only in the long run from real GDP to non-fossil fuels, and furthermore this relationship is negative. Instead it appears that increases in non-fossil use have been driven by additions to the physical capital stock, as well as decreases in fossil fuels through their substitutable relationship, which is also confined to the long run.

[Table 9]

The elasticity of GDP with respect to fossil fuels (0.23%) is virtually identical to the value for developed exporters, while the elasticity with respect to non-fossil fuels is insignificant. The ECT for real GDP corresponds to a speed of adjustment of 2.56 years, while for fossil and non-fossil fuels the speeds of adjustment are both 1.32 years, highlighting that all these variables respond swiftly to deviations from long-run equilibrium. Human and physical capital are once again important sources of causality in the long run. At the 10% level of significance, increases in physical capital lead to increased non-fossil fuel adoption in the short run. Meanwhile, short-run increases in human capital are found to significantly cause decreases in fossil fuel use. This could imply that countries with higher levels of education are more inclined to address fossil fuel dependency.

For policymakers, it is clear that more action needs to be taken to encourage growth in non-fossil fuel energy use. As was outlined in the Introduction, fossil fuel growth has outpaced non-fossil growth in these nations between 1990-2012 and this trend must be reversed to prevent emissions reaching the levels of their developed counterparts. Because economic growth has been shown not to increase non-fossil fuel consumption, governments will be required to continue and extend subsidies, tax credits, regulation and public sector investment in order to foster more non-fossil fuel use.

4.2.5 Results for Developing Importers

The results for developing importers are presented in Table 10. Once again short- and long-run bi-directional causality between fossil fuel use and real GDP can be observed, but with one exception. The elasticity of fossil fuel energy with respect to real GDP is substantially negative. This is an unexpected finding and an inspection of the energy data is in order. For instance, the real GDP of China was 8.7 times larger in 2012 than it was in 1990, yet fossil fuel consumption was only 3.7 times higher by the end of the sample period. Meanwhile in Vietnam, fossil fuel use increased almost eightfold, yet real GDP was only 4.4 times higher in 2012 compared to 1990. This is of course a very basic analysis, but it illustrates that for the timeframe under investigation, economic growth has not always been accompanied by growth in fossil fuels of a similar magnitude. Subsidies could also be a contributing factor.

[Table 10]

With regard to non-fossil fuels, there is no evidence of substitutability between fossil and non-fossil fuels. However, there is long-run causality running from non-fossil fuels to real GDP. Also in the long run, additions to the physical capital stock cause increases in both sources of energy, although the effect on fossil fuels was almost three times larger than the effect on non-fossil fuels. Meanwhile, long-run increases in human capital had a negative effect on fossil fuels. The elasticity of real GDP with respect to fossil fuels is 0.11% and the elasticity with respect to non-fossil fuels is 0.03%. The value for fossil fuels is the lowest of all the subsamples, while the value for fossil fuels is similar to the result for developed importers. All ECTs are statistically significant and have the expected signs.

The persistent finding of causality from fossil fuel consumption to real GDP along with the lack of causality from real GDP to non-fossil fuels has implications for policy. As for each of the other subsamples, direct fossil fuel conservations measures would most likely hamper economic growth, and with regard to non-fossil fuels, increases in income alone will not be sufficient to sustain the current 5.5% annual average economic growth rate.

Given the finding of cross-sectional dependence for some of our samples, the CCEMG estimator proposed by Pesaran (2006) was also estimated. Although minor changes were observed in some coefficient estimates, importantly these variations do not affect the main findings and policy implications of the paper. The estimation results are reported in Appendix Tables A3-A7. As a further robustness check and as a means of comparison with previous studies, a Panel VECM was also estimated.[5] Despite differences in individual coefficient estimates, the results were generally consistent with those of the PMG estimation.

5. Conclusions

The purpose of this study was to investigate the relationship between economic growth, fossil and non-fossil fuel consumption for 53 countries between 1990 and 2012. These countries were analysed as a global sample and then within four subsamples: developed exporters, developed importers, developing exporters and developing importers. This enabled conclusions to be drawn on the role of level of development and net energy trade balance in determining the energy-income nexus. An important contribution is the introduction of improved proxies for human and physical capital, by incorporating years of education into labor force data, and by accumulating gross capital formation using the perpetual inventory method. In order to infer the short- and long-run causal dynamics, the Pooled Mean Group (PMG) estimator was employed. The benefits of this approach are that the model can be estimated irrespective of whether the variables are I(0) or I(1). In addition, the use of the PMG estimator does not explicitly rely on the detection of cointegration.

For developed exporters, there was evidence of bi-directional causality between fossil fuel consumption and real GDP in both the short and long run, while there was bi-directional causality between non-fossil fuel consumption and real GDP only in the long run. In the case of developed importers, there was bi-directional causality between real GDP and fossil and non-fossil fuels in both the long and short run. The results for developing exporters revealed short- and long-run bi-directional causality between fossil fuel use and real GDP, but for non-fossil fuels, there was negative long-run unidirectional causality from real GDP to non-fossil fuel use. Finally for

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[5] The results are available from the authors upon request.

developing importers, there was once again bi-directional causality between real GDP and fossil fuels, but the causality from real GDP to fossil fuels in the long run was negative. On the other hand, non-fossil fuel consumption was found to increase real GDP in the long run. For all the subsamples, substitutability between fossil and non-fossil fuels was observed with the exception of developing importers. Human capital and physical capital were found to be relevant explanatory variables affecting the growth-energy consumption relationship, thereby justifying their inclusion in the model. Additionally, these findings were found to be robust to the use of a Panel VECM estimator.

These findings have a number of important implications for energy policy. Firstly, the relationship between fossil fuel consumption and economic growth is virtually uniform across all categories. Moreover, short and long causality has been observed from fossil fuels to real GDP, which implies that direct fossil fuel conservation measures may be harmful to economic growth, regardless of whether a country is a net importer or exporter of energy and regardless of a country's stage of development. As a result, climate change policies should be targeted at raising energy efficiency and encouraging the development of non-fossil fuel energy, until fossil fuel use can be reduced without hampering growth.

The differences between the subsamples were stark when considering non-fossil fuel use. In general the contrasts between developed and developing countries were more prominent than those between net energy importers and exporters. For developed countries there was generally a feedback relationship between real GDP and non-fossil fuels, especially in the long run in the case of developed exporters. This implies that increases in income lead to a greater consumption of non-fossil fuel energy, and in turn this uptake has reached a point where there are benefits for the broader economy. However, this was not the case for developing countries. For developing exporters, long-run increases in income lead to decreases in non-fossil fuel use, while for developing importers non-fossil fuel use appears to be beneficial for economic prosperity only in the long run.

These findings imply that other factors have been responsible for the progress in non-fossil fuel use achieved to date. These include government-led initiatives as well as environmental awareness and a desire for increased energy security. The key message from this analysis is that economic growth on its own is insufficient to promote a clean energy transition. There is the need for policymakers create an environment conducive to renewable energy investment. This could be achieved through a combination of appropriate institutions, subsidies, tax credits, and clean energy initiatives. Already there are promising signs. Morocco, one of the developing importers in this study, has embarked on a public-private partnership project to build the world's largest concentrated solar plant, with the capacity to power 1.1 million homes by 2018 (Climate Investment Funds, 2015). It will reduce the country's dependence on fossil fuel imports and help increase the country's share of renewable energy in electricity generation to 42% by 2020.

This paper offers a number of avenues for future research. Firstly, although the improved proxies for human and physical capital were important contributions to the model, they could be improved in future work. It was implicitly assumed that the return to education is constant, however, it may indeed differ at the primary, secondary and tertiary levels. Therefore incorporating a proxy that accounts for the quality and/or level of education would be useful. Also, another determinant of human capital is health standards. Thus introducing a measure of health would provide a more realistic representation of labor force productivity. Extensions to the physical capital proxy are also warranted. This could be done by extending the definition of capital to include natural resources, although it could be argued that the distinction made between exporters and importers in this study, which reflects their relative resource abundance is a step in this direction.

Energy subsidies are an important determinant of energy consumption that have not been addressed in this study. An assessment of which countries subsidise energy, and to what extent, would further inform our understanding of the energy-growth nexus. Countries could foreseeably be categorised according to their subsidy regimes to see how this affects the relationship between fossil fuel use and growth. Finally, the production function framework adopted in this study could enable the estimation of a Solow residual. This measure of total factor productivity would enable inferences to be drawn on how technology impacts the energy-growth nexus.

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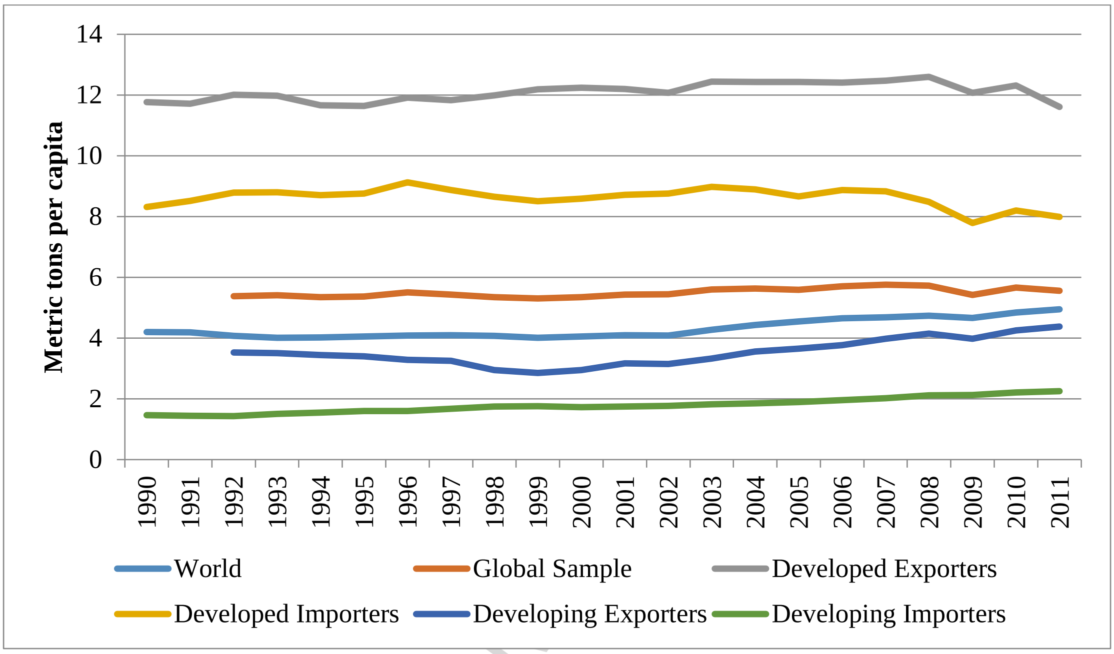
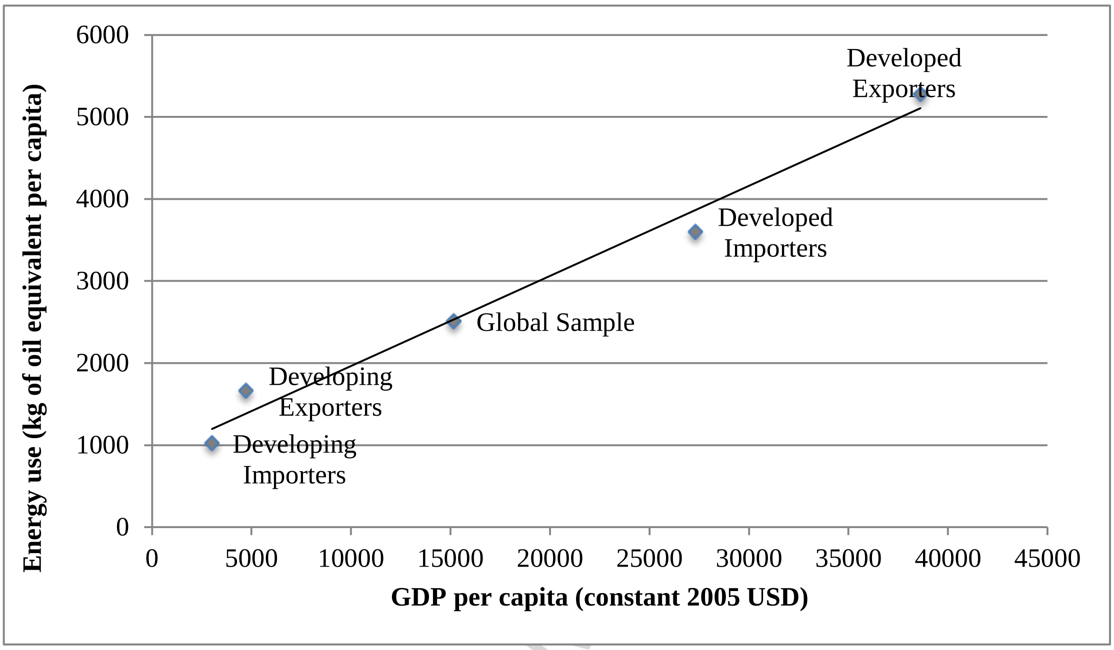
Figure 1
CO_2 emissions (metric tons per capita), 1990-2012



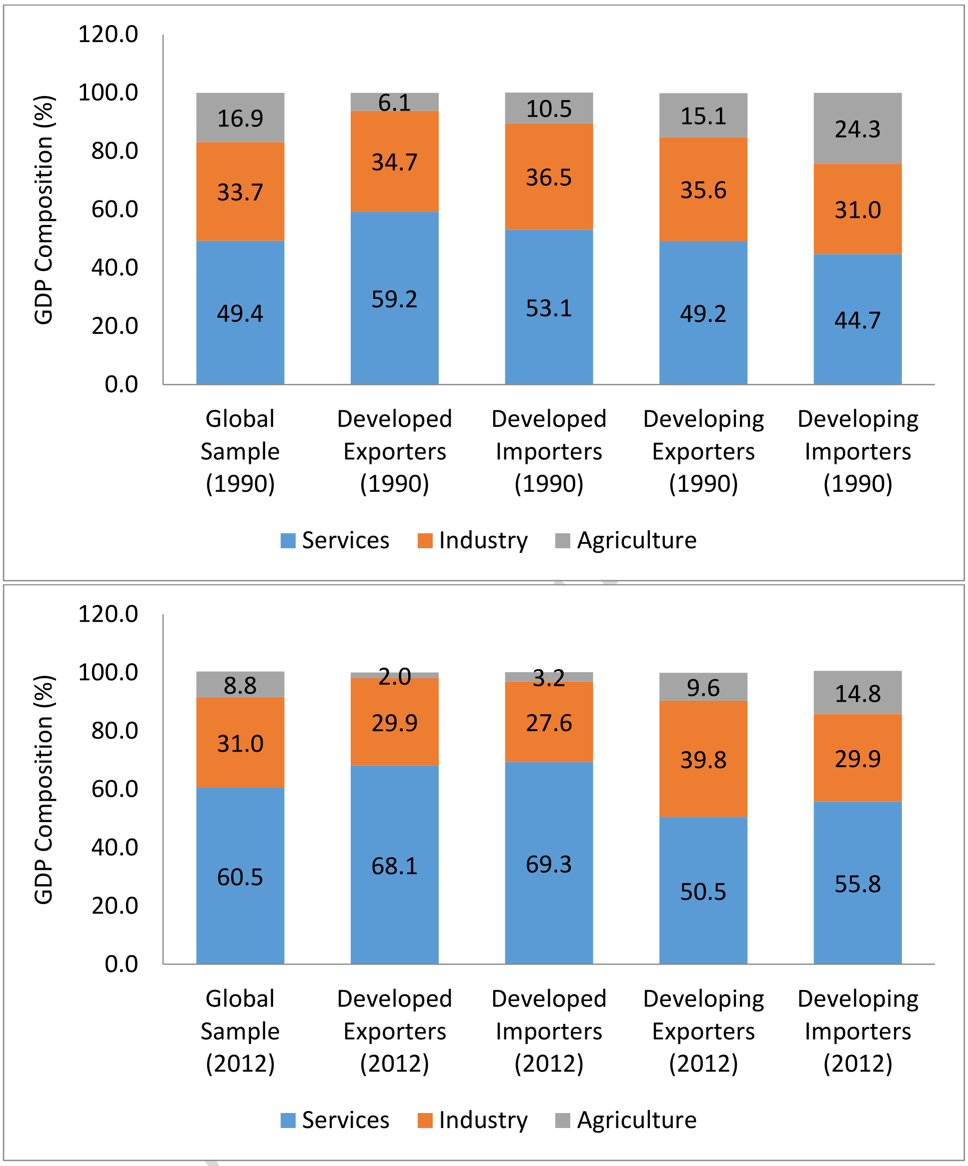
Source: World Bank (2015)
Note: Values represent the average of all the countries within the given category. Data were incomplete for Developing Exporters in 1990 and 1992.

Figure 2
Correlation between energy use and GDP per capita



Source: World Bank (2015)

Figure 3
GDP composition by sector, 1990 and 2012



Source: World Bank (2015)

Table 1
Energy consumption data, 1990-2012

Indicator	Global Sample	Developed Exporters	Developed Importers	Developing Exporters	Developing Importers
Annual Energy Consumption Growth Rate (%)	2.53	0.55	0.43	3.11	4.60
Annual Fossil Fuel Consumption Growth Rate (%)	2.41	0.62	0.08	3.39	4.43
Annual Non-Fossil Fuel Consumption Growth Rate	3.62	1.43	3.02	2.28	5.45
Fossil Fuel Share, 1990 (%)	67.8	83.4	81.3	66.3	50.8
Non-Fossil Fuel Share, 1990 (%)	32.2	16.6	18.7	33.7	49.2
Fossil Fuel Share, 2012 (%)	70.8	82.1	74.4	74.2	61.9
Non-Fossil Fuel Share, 2012 (%)	29.2	17.9	25.6	25.8	38.1

Sources: World Bank (2015), EIA (2015)

Table 2
Summary statistics for sample countries, 1990-2012

Variable	Global Sample	Developed Exporters	Developed Importers	Developing Exporters	Developing Importers
GDP Growth Rate (1990-2012)	3.51%	2.16%	2.10%	3.67%	5.04%
GDP Per Capita (2012)	$15,151	$38,618	$27,295	$4,710	$3,009
Physical Capital Growth Rate (1990-2012)	6.29%	4.56%	5.18%	5.74%	8.03%
Physical Capital per capita (2012)	$97,161	$233,462	$188,506	$28,164	$13,127
Labor force (average, 2012)	49,486,038	25,406,287	27,662,615	29,187,601	85,409,091
Labor force growth rate (1990-2012)	1.59%	0.92%	0.50%	2.24%	2.39%
Schooling (2010)	9.00	11.96	11.21	8.33	6.58
Schooling Growth rate (1990-2012)	1.81%	0.91%	1.31%	2.28%	2.26%

Sources: World Bank (2015), Barro-Lee Educational Attainment Dataset (2010)

Table 3
Pesaran (2004) Test for cross sectional dependence

Sample Type	Test Statistic	Probability Value
Global Sample	9.400	0.0000
Developed Exporters	-0.467	0.6405
Developed Importers	2.515	0.0119
Developing Exporters	-1.276	0.2019
Developing Importers	8.227	0.0000

Table 4

Unit root test results based on Pesaran (2007)

	Global Sample		Developed Exporters		Developed Importers		Developing Exporters		Developing Importers	
Var.	With Trend	Without Trend	With Trend	Without Trend	With Trend	Without Trend	With Trend	Without Trend	With Trend	Without Trend
y	2.603	-0.818	0.671	1.580	2.502	1.141	-0.106	-1.829**	-0.913	0.804
Δy	-0.229	-2.092***	-1.804**	0.076	-1.588*	-2.351***	-1.103	-3.429***	-1.968**	-2.150**
k	9.379	-0.144	0.064	2.336	3.313	0.462	1.916	-0.753	1.794	-0.012
Δk	-1.004	-1.910**	-0.677	-0.416	-2.076**	-2.197**	-3.008***	-2.741***	-3.744***	-2.104**
h	5.927	-0.332	0.512	-2.240**	2.793	-0.034	2.651	-0.302	-0.868	0.307
Δh	-0.762	-4.334***	0.887	-2.052**	-0.776	-2.623***	2.844	0.071	0.018	-2.744***
fe	2.890	-0.897	-0.359	0.226	1.980	1.339	0.504	2.358	1.129	-0.024
Δfe	-5.018***	-6.383***	-2.238**	-2.167**	-3.968***	-4.552***	-1.56*	-2.811***	-3.341***	-4.875***
nfe	0.724	-0.241	-1.297*	-1.700**	2.007	-0.003	3.176	1.152	-0.639	-0.777
Δnfe	-1.578*	-4.180***	-0.094	-2.530***	-4.589***	-6.126***	-0.682	-1.710**	-1.428*	-3.642***

*** Indicates significance at the 1% level; ** indicates significance at the 5% level and * indicates significance at the 10% level.
Lag lengths were determined by the Schwarz Information Criterion (SIC).

Table 5
Summary of results

Sample Type	Short-run causality	Long-run causality	Substitutability
Global Sample	Feedback, Growth Y ↔ FE Y ← NFE	Feedback, Neutrality Y ↔ FE Y ≠ NFE	Short-run and Long-run
Developed Exporters	Feedback, Neutrality Y ↔ FE Y ≠ NFE	Feedback Y ↔ FE Y ↔ NFE	Short-run and Long-run
Developed Importers	Feedback Y ↔ FE Y ↔ NFE	Feedback Y ↔ FE Y ↔ NFE	Short-run
Developing Exporters	Feedback, Neutrality Y ↔ FE Y ≠ NFE	Feedback, Conservation Y ↔ FE Y → NFE *(negative)*	Long-run
Developing Importers	Feedback, Neutrality Y ↔ FE Y ≠ NFE	Feedback, Growth Y ↔ FE *(effect from GDP to fossil fuels is negative)* Y ← NFE	None

Table 6

Results for the global sample

Dependent Variable	y (eq. 11.1)	k (eq. 11.2)	h (eq. 11.3)	fe (eq. 11.4)	nfe (eq. 11.5)
Long-run coefficients					
y		1.20***	0.18***	0.49***	0.09
k	0.61***		0.43***	-0.17***	0.37***
h	0.31***	0.24***		-0.51***	0.17
fe	0.15***	-0.06***	0.13***		-0.13**
nfe	0.00	-0.01	-0.01	-0.01	
ECT	-0.28***	-0.07***	-0.08***	-0.18***	-0.54***
Short-run coefficients					
Δy		0.15***	0.02	0.70***	0.14
Δk	1.95***		0.04	-0.17	-0.27
Δh	-0.31	0.10		0.00	-2.46
Δfe	0.20***	0.01	0.01		-0.54***
Δnfe	0.01**	0.00	-0.01	-0.05***	
Hausman Test Stat.	1.06	0.18	4.24	3.62	2.46
Hausman Test P-value	0.90	1.00	0.37	0.46	0.65

*** Indicates significance at the 1% level; ** indicates significance at the 5% level and
* indicates significance at the 10% level.

Table 7

Results for developed exporters

Dependent Variable	y (eq. 11.1)	k (eq. 11.2)	h (eq. 11.3)	fe (eq. 11.4)	nfe (eq. 11.5)
Long-run coefficients					
y		4.53***	0.54	1.35***	0.44***
k	0.76***		-0.15	-0.34	-0.17*
h	-0.46***	-3.64**		-0.66	0.14
fe	0.23**	-1.16***	-0.67		-0.41***
nfe	0.10***	-0.41***	-0.25*	-0.22	
ECT	-0.23**	-0.02***	-0.39***	-0.97***	-0.57**
Short-run coefficients					
Δy		0.09***	0.09	0.93***	0.11
Δk	1.77*		-0.76	-3.33	-3.33
Δh	0.10	-0.08		-0.37	-0.32
Δfe	0.22**	-0.01*	0.01		-0.59***
Δnfe	0.01	0.00	0.00	-0.16***	
Hausman Test Stat.	0.97	0.86	-16.85	9.96	2.27
Hausman Test P-value	0.91	0.93	NA	0.04	0.69

*** Indicates significance at the 1% level; ** indicates significance at the 5% level and
* indicates significance at the 10% level.

Table 8
Results for developed importers

Dependent Variable	y (eq. 11.1)	k (eq. 11.2)	h (eq. 11.3)	fe (eq. 11.4)	nfe (eq. 11.5)
Long-run coefficients					
y		1.21***	1.32	0.33***	0.33***
k	0.69***		-0.35	-0.13***	-0.08
h	-0.16***	0.24***		-0.54***	0.17
fe	0.18***	-0.01	-0.23		0.10
nfe	0.00***	-0.01	-0.49	0.02*	
ECT	-0.50***	-0.06***	-0.36***	-0.34***	-0.37***
Short-run coefficients					
Δy		0.17***	0.03	0.90***	1.39***
Δk	3.14***		0.12	0.18	-2.61
Δh	-0.10	-0.01		-0.25	1.77
Δfe	0.22***	-0.01	0.01		-0.91**
Δnfe	0.02*	-0.01	0.01	-0.06	
Hausman Test Stat.	0.58	0.29	-159.08	5.4	1.82
Hausman Test P-value	0.97	0.99	NA	0.25	0.77

*** Indicates significance at the 1% level; ** indicates significance at the 5% level and
* indicates significance at the 10% level.

Table 9
Results for developing exporters

Dependent Variable	y (eq. 11.1)	k (eq. 11.2)	h (eq. 11.3)	fe (eq. 11.4)	nfe (eq. 11.5)
Long-run coefficients					
y		2.13***	0.65*	1.22***	-0.83***
k	0.36***		-0.34	0.85	1.31***
h	0.53***	-0.93***		-0.95	-0.40
fe	0.23***	-0.43***	0.77		-0.46***
nfe	0.00	0.03	0.04	-0.04	
ECT	-0.39***	-0.06***	-0.11	-0.76***	-0.76***
Short-run coefficients					
Δy		0.17***	0.13	1.10***	0.15
Δk	1.36		-0.55	-0.79	7.24*
Δh	-0.34	0.04		-2.01**	-4.61
Δfe	0.22***	-0.01	-0.04		-0.70
Δnfe	0.00	0.00	0.00	-0.03	
Hausman Test Stat.	0.32	0.83	12.38	14.11	6.22
Hausman Test P-value	0.99	0.93	0.01	0.01	0.18

*** Indicates significance at the 1% level; ** indicates significance at the 5% level and
* indicates significance at the 10% level.

Table 10

Results for developing importers

Dependent Variable	y (eq. 11.1)	k (eq. 11.2)	h (eq. 11.3)	fe (eq. 11.4)	nfe (eq. 11.5)
Long run coefficients					
y		1.24***	-0.46**	-0.81***	-0.06
k	0.24***		0.75***	1.34***	0.46***
h	0.53***	0.22***		-0.64***	0.15
fe	0.11***	-0.11***	0.22		-0.05
nfe	0.03***	0.00	-0.04	0.09***	
ECT	-0.25***	-0.07***	-0.28***	-0.32***	-0.69***
Short run coefficients					
Δy		0.17***	-0.03	0.54***	-0.89
Δk	1.11**		0.13	0.12	1.00
Δh	-0.59	0.17		-0.01	-6.45**
Δfe	0.11***	0.01	0.01		-0.27
Δnfe	0.01	0.00	0.00	-0.02	
Hausman Test Stat.	2.60	1.30	-49.57	3.87	4.35
Hausman Test P-value	0.63	0.86	NA	0.42	0.36

*** Indicates significance at the 1% level; ** indicates significance at the 5% level and
* indicates significance at the 10% level.

Highlights

- We examine the nexus between real GDP, fossil and non-fossil fuel use
- The global sample was divided into four categories: developed exporters, developed importers, developing exporters and developing importers
- Bidirectional causality is found between fossil fuel use and real GDP for most of the subsamples
- We conclude that efforts to directly conserve fossil fuels may harm economic growth