Renewable energy consumption and economic growth nexus: evidence from a threshold model

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Abstract

The existing literature on renewable energy consumption and economic growth nexus produces mixed results as the effect of renewable energy consumption on economic growth can be either positive, negative or not significant. This paper examines the causal link between renewable energy use and economic growth by employing a threshold model using a 103-country sample in the 1995 to 2015 period. We find that the relationship between renewable energy consumption and economic growth depends on the amount of renewable energy used. Our results demonstrate that the effect of renewable energy consumption on economic growth is positive and significant if and only if developing countries or non-OECD countries surpass a certain threshold of renewable energy consumption. However, if developing countries use renewable energy below a given threshold level, the effect of renewable energy consumption on economic growth is negative. However, we also find that renewable energy consumption has no significant effect on economic growth in developed countries and a positive and significant effect on economic growth in OECD countries. The findings of this paper suggest that for developing countries to realize positive economic growth from their investment to renewable energy, they need to surpass a certain threshold of renewable energy consumption.

JEL Classification: C24; O13; Q2; Q43

Keywords: Renewable energy consumption; Economic Growth; Threshold; Non-linear effects; Panel data; OECD countries

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1. Introduction

Renewable energy sources have gained growing importance in the world energy consumption portfolio over recent years due to the increasingly negative consequences of climate change, volatile energy prices, and favorable government policies towards renewable energy use. The IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation suggests that historical increases in greenhouse gas (GHG) emissions have resulted from the provision of energy services and that increases in renewable energy not only mitigate the effects of climate change (see e.g., Shafiei and Salim, 2014; Balsalobre-Lorente et al., 2018; Inglesi-Lotz and Dogan, 2018; Belaïd and Zrelli, 2019 among many others that demonstrated that the increases in renewable energy consumption leads to lower Co2 emissions) but also could contribute to a number of crucial sustainable development goals such as social and economic development, energy access, energy security and reduction of environmental and health impacts (Edenhofer et al., 2011). Due to the wider benefits of renewable energy use, the share of renewables in meeting global energy demand is expected to grow by one-fifth in the next five years to reach 12.4% in 2023 based on the International Energy Agency (2018) projections.

With the increased use of renewable energy, there has been an extensive amount of literature that examined the relationship between renewable energy consumption and economic growth. There is a stream of literature that found no causal relationship between energy consumption and economic growth, also known as the neutrality hypothesis (neutrality hypothesis is supported by Menegaki (2011) for 27 European countries, Omri et al. (2015) for Brazil, Finland, and Switzerland; Chang et al. (2015) for Canada, Italy and the USA, Bulut and Muratoglu (2018) for Turkey, among others). On the other hand, another stream of literature found that renewable energy consumption increases economic growth (e.g., positive effect of renewable energy consumption on economic growth is supported by Bhattacharya et al. (2016) and Bhattacharya et al. (2017) for large set of countries, Chang et al. (2015) for Germany and Japan, Inglesi-Lotz (2016) for the OECD countries, Magnani and Vaona (2013) for Italian regions, Ozturk and Bilgili (2015) for 51 Sub-Saharan African countries, among many others). The third stream of literature demonstrates that increases in renewable energy consumption lead to negative economic growth due to high investment costs (see e.g., negative effect of renewable energy consumption on economic growth is identified by Ocal and Aslan (2013) for Turkey; Marques and Fuinhas (2012) for 24 European countries; Bhattacharya et al. (2016) for India, Ukraine, the US and Israel). Hence it seems that there is no agreement in the literature about the effect of renewable energy consumption on economic growth. This paper aims to provide a convincing argument about why the existing literature has found mixed and contradicting results. The use of the panel threshold model, where the effect of renewable energy consumption on economic growth may differ depending on the renewable energy consumption threshold, provides an explanation of why the results vary when a different set of countries are considered in the analysis. In other words, the panel threshold model allows us to test whether the relationship between renewable energy consumption and economic growth varies if a given country consumes renewable energy above or below the threshold. Below we will provide a detailed discussion on why we expect to find a threshold that is determinant on the effect of renewable energy consumption's effect on economic growth.

There have been arguments in the literature that the storage capacity for renewable energy sources is relatively low compared to that of fossil-based fuels, something that may lead to energy supply problems during the high peak demand periods (Heal, 2009; Forsberg, 2009; Apergis et al., 2010). Furthermore, switching from traditional non-renewable resources of energy production to technology-based renewable sources requires large up-front investments, which may affect the economic growth negatively (Marques and Fuinhas, 2012; Ocal and Aslan, 2013). Furthermore, Marques and Fuinhas (2012) argue that costs of development of renewable energy sources are provided by public policies which may raise the final cost of energy, assuming that regulators include these costs in the final price of electricity. For instance, Astariz and Iglesias (2015) reviewed cost estimates for ten electricity generation technologies and suggested that the most cost-effective technology is pulverized fuel, where the production cost of an energy unit of non-renewable energy sources was cheaper than that of renewable energy sources. In sum, due to the above-mentioned mechanisms, increases in renewable energy sources could lead to negative effects on economic growth.

Even though initial investment costs of deployment of renewable energy sources are high compared to non-renewable, there has been a major decline in costs for solar and wind technologies over the last few years (see, e.g., IRENA, 2019), which would lead to lower costs of renewable energy generation. Similarly, Rubin et al. (2015) review empirical learning rates that have been reported for a broad spectrum of electric power generation technologies and suggest that learning rates from power plant technologies using fossil fuels were lower in magnitude than those for renewable energy technologies. Therefore, the average cost of renewable energy generation is likely to fall with the increased use of renewable energy. Schilling and Esmundo (2009) show that the generation of electricity per kWh has been increasing at an increasing rate with the increases in R&D investment in renewable energy technologies suggesting that the costs of renewable energy have been decreasing at an increasing rate when the renewable energy investment was higher. Hence, countries that use relatively higher renewable energy are likely to face increasingly lower rates of costs of renewable energy consumption.

Based on the above literature, we expect that if countries use relatively lower levels of renewable energy, then the relative cost of using renewable energy compared to fossil fuels may be higher and hence the renewable energy consumption or growth of renewable energy consumption may not lead to a significant effect (or even may have a negative effect) on economic growth for these countries. However, for countries that consume relatively higher levels of renewable energy, the use of renewable energy and growth of renewable energy consumption may affect economic growth positively as the cost of renewable energy could be relatively lower than that of non-renewable energy. To test this argument, we use renewable energy consumption as a threshold variable and examine whether there exists a threshold level of renewable energy with the use of panel threshold models where the effect of renewable energy consumption or growth of renewable energy consumption on economic growth differs below and above a renewable energy consumption threshold.

This study contributes to the existing body of research in various ways. First, many existing studies used various panel estimation methods such as panel co-integration, panel dynamic least squares, fully modified least squares, and panel vector error correction methods to examine the causal link between renewable energy consumption and economic growth. However, to our knowledge, only a small body of literature examined the potential non-linear relationship between renewable energy consumption and economic growth. This study uses a panel sample splitting methodology to test whether there exists a renewable energy consumption threshold level, where the effect of renewable energy consumption on economic growth would differ above and below this level. Second, most of the existing literature that examined the relationship between renewable energy consumption and economic growth using unit root and cointegration tests adopted the assumption of cross-sectional independence. However, it is common for macro-level data to violate this assumption hence resulting in low power and size distortions for the tests that assume cross-section independence (Pesaran, 2015)[1]. Therefore, our study uses recently developed panel data methods that take cross-sectional dependence into account. Thirdly, given the existing studies found that the relationship between renewable energy consumption and economic growth varies based on the set of countries used, we also examine whether the findings obtained with the threshold model for the whole set of countries are different when using different subsets of countries such as OECD, non-OECD, developed and developing countries.

The rest of the paper is organized as follows. Section 2 provides a literature review that examines the relationship between renewable energy consumption and economic growth. Section 3 develops the theoretical threshold model, while section 4 discusses the data set. Section 5 provides the empirical results and robustness analysis, and finally, section 6 concludes and offers some policy discussion.

2. Literature review

There has been an increasing stand of literature that examines the relationship between renewable energy consumption and economic growth (see Table 1 summary of the relevant literature examining the relationship between renewable energy consumption and economic growth). This literature mainly tests four potential hypotheses: (1) the feedback hypothesis (i.e., the hypothesis that suggests that there is a bidirectional causation between renewable energy consumption and economic growth); (2) the growth hypothesis (i.e., the hypothesis that suggests that there is a one-way causation from renewable energy consumption to economic growth); 3)

[1] There are only few studies that considered the potential cross-section dependence when examining the link between energy consumption and economic growth (see e.g., Cowan et al., 2014; Osman et al., 2016; Belaïd and Zrelli, 2019).

the conservative hypothesis (i.e., the hypothesis that suggests that there is a one-way causation from economic growth to renewable energy consumption); 4) the neutrality (i.e., the hypothesis that suggests that there is no causational link between renewable energy consumption and economic growth).

<Insert Table 1 approximately here>

Based on the country and period coverage, research in the area relies on different methodologies to examine the relationship between renewable energy consumption and economic growth. Most of the papers in the literature use panel data methodologies such as panel cointegration tests, Granger causality, dynamic or vector error correction methods to examine the relationship between renewable energy consumption and economic growth (Apergis and Danuletiu, 2014; Apergis and Payne, 2010; Apergis and Payne, 2011; Apergis and Payne, 2012; Bhattacharya et al., 2016; Bulut and Muratoglu, 2018; Chang et al., 2015; Inglesi-Lotz, 2016; Kahia et al., 2017; Koçak and Şarkgüneşi, 2017; Lin and Mubarek, 2014; Ozturk and Bilgili, 2015; Pao et al., 2014; Salim et al., 2014; Salim and Rafiq, 2012) where most of this literature employed fully modified ordinary least square (FMOLS) and dynamic ordinary least square (DOLS) to estimate the long-run elasticities. Another popular methodology in this relationship has been the use of linear autoregressive distributed lag (ARDL) approach to cointegration developed by Pesaran et al. (2001) and non-linear ARDL developed by Shin et al. (2014) (see, e.g., Tugcu et al. (2012) and Tugcu and Topcu (2018) for the use of linear and non-linear ARDL methods in examining the relationship between renewable energy and economic growth). Finally, another panel methodology has been the generalized methods of moments (GMM), which can tackle potential endogeneity problems (Bhattacharya et al., 2017; Magnani and Vaona, 2013; Omri et al., 2015; Narayan and Doytch, 2017).

Depending on the methodology and sample of countries, all four hypotheses have been verified empirically. For instance, when the entire panel data set is used, the majority of the findings either support the feedback hypothesis (Apergis and Danuletiu, 2014; Apergis and Payne, 2010; Apergis and Payne, 2011; Apergis and Payne, 2012; Chang et al., 2015; Kahia et al., 2017; Narayan and Doytch, 2017; Pao et al., 2014; Salim et al., 2014; Salim and Rafiq, 2012) or the growth hypothesis (Bhattacharya et al., 2016; Bhattacharya et al., 2017; Inglesi-Lotz, 2016; Magnani and Vaona, 2013; Ozturk and Bilgili, 2015; Pao et al., 2014) with the exception of findings of Menegaki (2011) which supports the neutrality hypothesis for the European countries. However, when the relationship between renewable energy and economic growth is analyzed for specific countries, different hypotheses are supported when different set of countries are used in the analysis, and all four-hypotheses are verified for some (Chang et al., 2015; Koçak and Şarkgüneşi, 2017; Omri et al., 2015; Tugcu and Topcu, 2018; Tugcu et al., 2012).

It is noticeable that the findings from the literature are mixed depending on the method used and country coverage. However, one commonality of the literature is that most of the studies in this strand of literature examine a linear relationship between renewable energy consumption and economic growth with few exceptions. For instance, Chang et al. (2009) used the panel threshold regression method proposed by Hansen (1999) and found that countries characterized by high economic growth are able to respond to high energy prices with increases in renewable energy consumption, but no direct causal link was found between economic growth and renewable energy consumption for low-economic growth countries. On the other hand, in a recent study, by using nonlinear ARDL approach developed by Shin et al. (2014) and the asymmetric causality procedure proposed by Hatemi-J (2012), Tugcu and Topcu (2018) find that long-run results provide strong support for an asymmetric relationship between energy consumption and economic growth, and recommend that future studies should use an empirical methodology that can examine this asymmetric linkage between renewable energy consumption and economic growth. In this paper, in the line of Tugcu and Topcu (2018) findings, we will examine the potential non-linear relationship between renewable energy and economic growth based on the use of input variable where the effect of renewable energy on economic growth may vary depending on the levels of renewable energy, labor, and capital used in the production function.

In the next section, we present our model specification. We follow a GMM estimation approach similar to that used by Magnani and Vaona (2013), Bhattacharya et al. (2017) and Narayan and Doytch (2017). However, different from the above papers, our panel threshold model can allow us to test whether there exists a threshold of renewable energy consumption where the effect of renewable energy consumption on economic growth is different above and below this threshold.

3. Threshold model specification

In this study, we aim to investigate the relationship between growth and renewable energy. To construct the econometric model, we assume that the production in the economy for country *i* at time *t*, Y_{it}, is given by the following production function:

$$Y_{it} = f(K_{it}, L_{it}, REC_{it}, NREC_{it}) \quad (1)$$

where subscripts $i = 1, \ldots, N$ represents the country and $t = 1, \ldots, T$ indexes the time. Y_{it} denotes economic growth. K_{it}, L_{it}, REC_{it} and $, NREC_{it}$ are the capital, labour and renewable energy consumption and non-renewable energy consumption for country *i* at time *t*, respectively. Hence, the long-run equilibrium is of the following form:

$$lnY_{it} = \rho_{0i} + \rho_{1i}lnK_{it} + \rho_{2i}lnL_{it} + \rho_{3i}lnREC_{it} + \rho_{4i}lnNREC_{it} + \varepsilon_{it} \qquad (2)$$

where ρ_{0i} is an unobserved country fixed effect, and ε_{it} is an i.i.d error term.

In the presence of panel cointegration, the dynamic panel error correction model is given by the following equation:

$$\Delta lnY_{it} = \alpha_i + \sum_{l=1}^{L} \beta_{1,i,l}\, \Delta lnY_{it-l} + \sum_{l=0}^{L} \beta_{2,i,l}\, \Delta lnK_{it-l} + \sum_{l=0}^{L} \beta_{3,i,l}\, \Delta lnL_{it-l} + \sum_{l=0}^{L} \beta_{4,i,l}\, \Delta lnREC_{it-l} + \sum_{l=0}^{L} \beta_{5,i,l}\, \Delta lnNREC_{it-l} + \beta_{5,i}(lnY_{it-1} - \rho_{0i} - \rho_{1i}lnK_{it-1} - \rho_{2i}lnL_{it-1} - \rho_{3i}lnREC_{it-1} - \rho_{4i}lnNREC_{it-1}) + \varepsilon_{it} \qquad (3)$$

where Δ denotes the first-difference and L is the length of lags chosen by AIC.

To estimate model (3) in one step, we can examine the following expression by multiplying the error correction terms out

$$\Delta lnY_{it} = \beta_{0,i} + \sum_{l=1}^{L} \beta_{1,i,l}\, \Delta lnY_{it-l} + \sum_{l=0}^{L} \beta_{2,i,l}\, \Delta lnK_{it-l} + \sum_{l=0}^{L} \beta_{3,i,l}\, \Delta lnL_{it-l} + \sum_{l=0}^{L} \beta_{4,i,l}\, \Delta lnREC_{it-l} + \sum_{l=0}^{L} \beta_{5,i,l}\, \Delta lnNREC_{it-l} + \beta_{5,i}\, lnY_{it-1} - \beta_{5,i}\rho_{1i}lnK_{it-1} - \beta_{5,i}\rho_{2i}lnL_{it-1} - \beta_{5,i}\rho_{3i}lnREC_{it-1} - \beta_{5,i}\rho_{4i}lnNREC_{it-1} + \varepsilon_{it} \qquad (4)$$

It is worth noticing that the one-step estimation results of the constant and each error correction coefficients of (4) are composite terms of long-run adjustment rate, long-run coefficients, and the country-specific fixed effects.

To examine the potential non-linear relationship between production inputs and economic growth, we employ a dynamic panel error correction threshold regression model, which is a sample split form of the model (4) and can be expressed as follows:

$$\Delta lnY_{it} = \beta_{0,i} + \beta_1^T X_{it} + \varepsilon_{it}, \qquad q_{it} \le \gamma \qquad (5)$$

$$\Delta lnY_{it} = \beta_{0,i} + \beta_2^T X_{it} + \varepsilon_{it}, \qquad q_{it} > \gamma \qquad (6)$$

where X_{it} is a d_x by 1 vector containing all the regressors of the model (4), q_{it} is the threshold variable, and γ is the threshold level. Therefore, model (4) can be regarded as a special case of the threshold model with either $q_{it} \leq \gamma$ or $q_{it} > \gamma$ for all $i = 1, \ldots, N$ and $t = 1, \ldots, T$.

For the compactness, (5) and (6) can be integrated as a single form as follows:

$$\Delta\, lnY_{it} = \alpha_i + \beta_2^T X_{it} + \delta^T X_{it} I(q_{it} \leq \gamma) + \varepsilon_{it} \qquad (7)$$

where $I(\cdot)$ is the indicator function representing the sample splitting, and $\delta = \beta_1 - \beta_2$. Hence, the indicator function in the non-linear specification defined in Eq. (7) describes the sample split by only one threshold level.

Considering the previous evidence of bidirectional causality between renewable and non-renewable energy consumption and economic growth in both the short- and long-run (e.g., Apergis and Payne (2012)), we employ a first-difference (FD) GMM method of Seo and Shin (2016) to estimate model (7). Alternatively, one may use other threshold regression methods (e.g., Hansen (2000), Caner and Hansen (2004), Kremer et al. (2013), and Kourtellous et al. (2016)). Yet, the FD-GMM method of Seo and Shin (2016) studies a dynamic threshold panel model and allows the endogeneity in both regressors and threshold variables whereas other methods either rely on the exogenous threshold variable or not applying for the dynamic panel.

In the spirit of Arellano and Bond (1991), we consider the following moment conditions to estimate (4) and (7)

$$E(\Delta\varepsilon_{it}\, lnY_{it-r}) = 0;\; E(\Delta\varepsilon_{it}\, lnK_{it-r}) = 0;\; E(\Delta\varepsilon_{it}\, lnL_{it-r}) = 0;\; E(\Delta\varepsilon_{it}\, lnREC_{it-r}) = 0;\; E(\Delta\varepsilon_{it}\, lnNREC_{it-r}) = 0 \;\text{ where } r = 5, \ldots, t-1 \;\text{ and } t = 6, \ldots, T \qquad (8)$$

Finally, to test the presence of a threshold effect, we use a sup-Wald test proposed by Seo and Shin (2016). Following Hansen (1996), the critical values are generated by a bootstrap method.

4. Data

To investigate the potential differing effects of renewable energy consumption on economic growth above (below) a given renewable energy consumption, we use renewable energy consumption (REC) as the threshold variable. We use the log difference of GDP in billions of constant 2010 U.S. dollars for economic growth, gross fixed capital formation in billions of constant 2010 U.S. dollars for capital (K), total labor force in millions (L), and total renewable and non-renewable electricity consumption defined in millions of kilowatt-hours for renewable energy consumption (REC and NREC, respectively). Annual data for 103 countries from 1990 until 2015 were obtained from the International Energy Agency and the World Development Indicators of the World Bank (see Appendix Table A1 for the list of countries used in this paper). All the variables chosen for this analysis are similar to the ones used by Apergis and Payne (2010), Wolde-Rufael and Menyah (2010), Apergis and Payne (2011), Apergis and Payne (2012), Lin and Moubarak (2014), Omri et al. (2015), Bhattacharya et al. (2016), Inglesi-Lotz (2016). The use of similar variables employed in the literature allows us to compare our findings with those that used linear estimation methods.

Table 2 presents the descriptive statistics for the whole sample, OECD and non-OECD countries. On average, OECD countries have higher levels of GDP, labor, capital, and renewable and non-renewable energy consumption, but non-OECD countries have experienced higher levels of GDP growth.

<Insert Table 2 approximately here>

Table 3 presents the correlation matrix among production input variables (labor, capital, renewable energy, and non-renewable energy) and output variable (GDP) where all the input variables are positively and significantly correlated with aggregate production. In all samples, output has the highest correlation with capital. Similarly, most input variables are also positively and significantly correlated with one another as they tend to be used in production. However, there are some exceptions. For example, non-renewable energy and renewable energy consumption in OECD countries are negatively correlated, highlighting the fact that non-renewable energy is replaced with renewable one at an aggregate level (see Fig. 2 below). However, for non-OECD countries, the correlation coefficients of non-renewable energy consumption with labor and renewable energy consumption are close to zero. Finally, among inputs, we find that the correlation coefficient between capital and labor is the highest for the OECD countries, whereas the correlation coefficient between renewable energy consumption and labor is the highest for non-OECD countries.

<Insert Table 3 approximately here>

We observe that over the study period, total renewable energy consumption has been increasing for OECD, non-OECD countries, and all countries in our sample (Fig. 1). Fig. 1 provides the aggregate renewable energy used by all countries in the sample, however, on average, the renewable energy used per OECD-country is relatively higher than that of non-OECD countries (see Table 2 for the descriptive statistics). We also see a different picture when we look at renewable energy consumption as a percentage of total energy consumption for a different sample of countries (Fig. 2). In that case, we see that the percentage of renewable energy consumption in OECD countries has increased over time, but the opposite is true for the non-OECD countries. In other words, even though there has been an increase in the use of renewable energy in non-OECD countries, its share in the total energy consumption has been declining. In the next section, we will examine the effect of the increased use of total renewable energy consumption on economic growth for both OECD and non-OECD countries, and test whether there is any non-linear relationship between input variables and economic growth.

<Insert Fig. 1 and Fig. 2 approximately here>

5. Empirical analysis

We examine the long-run equilibrium relationship among economic growth, renewable energy consumption, non-renewable energy consumption, capital, and labour by using second-generation panel cointegration methods, linear GMM and threshold estimation methods. Considering the objectives of this study, we first examine for possible cross-sectional dependence in the data, and if present, we use unit root tests that account for it. After examining the cross-sectional dependence, we then move to the first- and second-generation panel cointegration tests to examine the long-run equilibrium relationship among variables. After performing a battery of panel unit root and panel cointegration tests to infer the degree of integration of the variables in our model (2), we then provide the results obtained with the linear GMM estimation technique and the results with the threshold estimation method. Finally, this section concludes with a set of robustness analyses where we carry out a similar set of analyses with the use of different samples of countries.

5.1. Cross-sectional dependence and unit root tests

The early literature on unit root and cointegration tests was based on the assumption of cross-sectional independence (Pesaran, 2015). However, it is common for macro-level data to violate this assumption, something that will result in low power and size distortions for tests that assume cross-section independence. Similar to few studies that considered the potential cross-section dependence when examining the link between energy consumption and economic growth (see e.g., Cowan et al., 2014; Osman et al., 2016; Belaïd and Zrelli, 2019), before proceeding to unit root and cointegration tests, we first check the presence of cross-sectional dependence by using the cross-section dependence test of Pesaran (2004).

Table 4 presents the results for the cross-section dependence test of Pesaran (2004). Those results suggest that the null hypothesis of cross-sectional independence is strongly rejected for all the variables considered (i.e., ln(GDP), ln(K), ln(L), ln(REC), and ln(NREC)) at the 1% significance level for three set of samples (i.e., all, OECD countries, and non-OECD countries). The results suggest that all of the variables are cross-sectionally correlated irrespective of the sample of countries used.

<Insert Table 4 approximately here>

Given the fact that the variables are cross-sectionally dependent, it is inappropriate to use the first generation of panel unit root tests that are based on the cross-sectional independence assumption (see e.g., Maddala and Wu, 1999; Choi, 2001; Levin et al., 2002; Im et al., 2003), since they would suffer from size distortions and the ignorance of cross-section dependence (Pesaran, 2015). Therefore, to account for the presence of cross-sectional dependence in the variables, we use the cross-sectionally augmented Im-Pesaran-Shin (CIPS) unit root test proposed by Pesaran (2007)[2]. Table 5 presents the CIPS unit root test results. When we use the levels of the variables, we fail to reject the null hypothesis of the unit root at the 5% significance level for all samples used. However, the null hypothesis of non-stationarity can be rejected at the 1% significance level for all of the variables with the exception of non-renewable energy consumption for the non-OECD and OECD countries (which were significant at the 5% and 10% level, respectively) when we obtain the first-order differences of the variables used. Hence, based

[2] Another test is also proposed by Breitung and Das (2005) but this test does not apply to this study's application area as the cross-section dimension (N) in our application is greater the time-series dimension (T) but this test requires T to be greater or equal to N.

on the results, we find that the variables are non-stationary in levels and stationary in first differences.

<Insert Table 5 approximately here>

5.2.Panel cointegration tests

Given the existence of cross-sectional dependence in all samples for all variables, the co-integration tests of Pedroni (1999, 2004) are invalid. Hence, to check whether there exists a long-term relationship between the variables, we use the cointegration tests proposed by Westerlund (2007). Since the cointegration test proposed by Westerlund (2007) allows for heterogeneity and is developed to deal with cross-sectionally dependent data (Persyn and Westerlund, 2008), as is the case for the data used in this paper, using this cointegration test is appropriate for this study. Table 6 gives the results of the panel cointegration test proposed by Westerlund (2007). Four sets of co-integration tests are conducted, where the group mean tests (Gt and Ga) examine the alternative hypothesis that at least one unit is cointegrated, while the panel tests (Pt and Pa) consider the alternative hypothesis that the panel is cointegrated (Persyn and Westerlund, 2008). Almost all four test statistics reject the null of no cointegration at the 10% level for all countries and non-OECD sample and panel tests reject the no cointegration at the 5% level for the OECD sample. Overall, the tests confirm the existence of a cointegration relationship between variables, suggesting that there exists a long-run cointegration between the variables considered in the model.

<Insert Table 6 approximately here>

5.3.Results with linear GMM and threshold estimation methods

Given the presence of a cointegration relationship, model (4) and model (7) are estimated to determine the long-run linear and non-linear relationships, respectively. Table 7 presents the results from the linear specifications (i.e., estimations based on the first difference generalized methods of moments (FD-GMM) method) when we use the whole sample, OECD and non-OECD countries. Our main variables of interest in this analysis are the growth of renewable energy ($\Delta LnREC_{it}$) and lagged renewable energy use ($LnREC_{it-1}$), whereas the remaining variables are mainly considered as control variables. We find that growth in renewable energy consumption significantly improves the economic growth in OECD countries at the 1% level but is not significant for the whole sample and non-OECD countries. On the other hand, even though the lagged level of renewable energy is not significant for the whole sample, we find that the lagged renewable energy is statistically significant for the OECD and non-OECD countries separately, suggesting that use of renewable energy leads to higher economic growth when countries are split into two. With the other lagged input variables, both labour and capital are significantly and positively associated with economic growth for all sample sizes, whereas the lagged non-renewable energy is not significant. Lagged income is negative and significant in all regressions highlighting the convergence among the economies. On the other hand, the lagged growth rate is significant only for the non-OECD countries suggesting that relatively fast-growing countries tend to grow faster in the following periods.

<Insert Table 7 approximately here>

However, the economic returns to renewable energy use may be different based on the level of renewable energy used. Hence, we test for this type of non-linearity and estimate the nonlinear specification (model (7)) using renewable energy consumption as a threshold variable. Table 8 reports the results when we use renewable energy as a threshold variable, where we strongly reject the null hypothesis of a linear model (i.e., $\delta = 0$) for the whole sample and non-OECD countries. For the OECD countries, we fail to reject the null hypothesis of the linear model. Hence the results for the OECD countries are not reported. The findings with respect to the OECD countries are consistent with the positive and linear relationship found between renewable energy consumption and economic growth by Apergis and Payne (2010) and Inglesi-Lotz (2016) for the OECD countries. Hence, the growth of renewable energy consumption in OECD countries leads to positive economic growth, and the effect of the growth of renewable energy consumption on economic growth does not change based on the amount of renewable energy consumed by the OECD countries (i.e., the relationship is linear). However, we obtain a significant threshold of renewable energy consumption level when all countries and non-OECD countries are used in the analysis (see the p-values reported in Table 8 where the null hypothesis of the linear relationship is rejected at the 1% level). The findings with the threshold model suggest that the growth of renewable energy consumption (i.e., $\Delta lnREC_{it}$) significantly and positively affects economic growth if and only if countries use a renewable energy above a given threshold level (i.e., when ln(REC) is above 9.5058 and 9.5926 for the whole sample and non-OECD countries, respectively). If countries use renewable energy below these threshold levels, the effect of the growth of renewable energy consumption on economic growth is insignificant, which is similar to the findings obtained from the linear estimations. Similarly, the linear model suggests that lagged renewable energy is significant for the OECD and non-OECD countries. With the threshold model, lagged renewable energy has a significant and positive effect on economic growth for the whole sample and for non-OECD countries that utilize renewable energy above the thresholds. Furthermore, both coefficients of lagged renewable energy consumption are relatively larger than the ones obtained with the linear model. Our findings highlight the fact that studies that supported the neutrality hypothesis (e.g., Menegaki (2011) for 27 European countries, Omri et al. (2015) for Brazil, Finland, and Switzerland; Chang et al.

(2015) for Canada, Italy and the USA, Bulut and Muratoglu (2018) for Turkey, among others) may have reached this conclusion due to the linear estimation methods that they used and if countries surpass a certain threshold of renewable energy consumption, the effect of this variable on economic growth would be positive and significant. As a result, not considering the potential non-linear effects may lead to misleading outcomes as the coefficients obtained with the linear estimation methods for all and non-OECD countries are not significant.

<Insert Table 8 approximately here>

These findings have important policy implications. If policymakers would have relied only on linear model estimates, then they would have concluded that growth in renewable energy consumption is positively and significantly associated with economic growth in OECD countries only. However, our findings with the threshold model unveil another story. Both the lagged renewable energy consumption level and growth of renewable energy consumption are positively and significantly associated with economic growth for the non-OECD and the whole sample of countries as long as these countries use renewable energy above a given threshold.

Beyond the effect of renewable energy consumption on economic growth, there are also other important findings highlighting the complementary effect of inputs on each other. For instance, with the linear models, the growth of capital (ΔLnK_{it}) has a differing effect on economic growth for different sets of countries (see Table 7). However, this effect is significantly larger if countries surpass the threshold of renewable energy consumption levels (see the coefficients obtained for ΔLnK_{it} with the linear model and threshold models in Tables 7 and 8, respectively). On the other hand, labour growth (ΔLnL_{it}) has no significant effect on economic growth for non-OECD countries (see Table 7), but it has a significant effect on economic growth if countries use lower levels of renewable energy (see Table 8). In other words, the level of renewable energy consumption not only determines the effect of renewable energy consumption on economic growth but also plays an important role in the effect of other input variables on economic growth.

5.4.Robustness analysis

In our empirical analysis section, we divided countries into two groups (i.e., OECD and non-OECD countries), but both the OECD and non-OECD countries consist of developed and developing countries. Therefore, in this section, we carry out additional robustness analysis to examine whether the relationship between economic growth and input variables differ when the whole sample of countries are split into two groups based on their level of economic development (i.e., developed and developing countries)[3].

Similar to the previous subsections, we checked for the presence of cross-sectional dependence by using the cross-section dependence test of Pesaran (2004). The results suggest that the null hypothesis of cross-sectional independence is strongly rejected for all the variables considered at the 1% significance level for both samples of countries (see Appendix Table A2 for the cross-sectional dependence test results). When we examine the levels of the variables, we fail to reject the null hypothesis of the unit root at the 10% significance level for all samples used but the null hypothesis of non-stationarity can be rejected at the 10% significance level for all of the variables when we use first differences (see Appendix Table A3 for the CIPS unit root test results when developing and developed country samples are used). Hence, based on the results, we find that the variables are non-stationary in the levels and stationary in the first-order differences for the developing and developed country samples. Finally, when we use the cointegration tests proposed by Westerlund (2007), one of the four test statistics rejects the null

[3] Developed countries are chosen based on the high-income country classification of the World Bank (see Table A1 for the list of developed and developing countries).

of no cointegration at the 10% level for developing and developed countries suggesting that there exists a long-run cointegration between the variables considered in the model.

Based on the initial set of results, to compare the findings based on the linear estimations and estimations with the threshold model, we carried out estimations based on Eq. (4) and (7), respectively, and the results obtained with the linear and threshold estimations are reported in Tables 9 and 10, respectively. We find that the growth of renewable energy consumption is not a significant determinant of economic growth when linear estimation methods are used both for developed and developing countries. However, when we use the threshold estimation methods, we reject the linearity hypothesis at the 5% and 1% level for developed and developing country samples, respectively (see the p-value of SupWald test in Table 10). With the developed countries sample, we find that the findings are in line with the linear estimation methods where the effect of the growth of renewable energy growth on economic growth is not significant. In other words, irrespective of the linear or threshold models used, the renewable energy growth does not affect economic growth significantly, which is in line with the findings of the Menegaki (2011) for 27 European countries, Omri et al. (2015) for Finland, and Switzerland; Chang et al. (2015) for Canada, Italy and the USA. The potential explanation of this insignificant effect could be the fact that costs of developing renewable energy sources are created by public policies which may raise the final cost of energy, assuming that regulators include these costs in the final price of electricity (Marques and Fuinhas, 2012). On the other hand, we find that the growth of renewable energy consumption negatively and significantly affects the economic growth if countries use renewable energy below the threshold level (i.e., $\ln(REC) < 9.6054$), but the effect of growth of renewable energy consumption on economic growth is positive and significant if countries use renewable energy above the threshold level (i.e., $\ln(REC) > 9.6054$). This finding provides an explanation of why some of the literature obtained a negative effect for some countries (e.g., Ocal and Aslan, 2013; Marques and Fuinhas, 2012; Bhattacharya et al., 2016). If countries use renewable energy below the threshold level, they experience lower economic growth due to high up-front investment costs and capacity storage problems of renewable energy sources. However, if developing countries reach a threshold of renewable energy consumption, then they start to benefit from decreased costs of renewable energy consumption, and the effect of the growth of renewable energy consumption on economic growth becomes significant. In other words, our analysis provides an explanation of why two different strands of literature found contradicting results (i.e., the literature that found a positive and negative effect of renewable energy on economic growth).

<Insert Tables 9 and 10 approximately here>

6. Conclusions and policy implications

Recently, traditional energy sources (petrol, coal and natural gas) are being replaced with renewable energy sources. In this context, this paper empirically examines whether there is any non-linear relationship between renewable energy consumption and economic growth when we employ a threshold model and use renewable energy consumption as the threshold variable. The linear models only identify a positive relationship between renewable energy and economic growth for OECD countries. Linear models suggest that there is no significant effect of the growth of renewable energy growth on economic growth for non-OECD and developing countries. However, with the threshold models, non-OECD and developing countries would benefit significantly from investing in renewable energy sources as long as their use of renewable energy surpasses a certain threshold. For developing countries, the growth of renewable energy has a negative effect on economic growth if they use relatively lower levels of renewable energy. Our findings highlight that developing countries that use relatively lower levels of renewable energy are not doomed to suffer from negative economic growth if they increase their renewable energy consumption as they can start enjoying the economic benefits of renewable energy growth after surpassing a certain threshold of renewable energy. In other words, the negative effect of renewable energy usage at initial levels could be compensated in the long term when these countries start using higher levels of renewable energy.

The recent literature highlighted the importance of better governance (Cadoret and Padovano, 2016) and energy market liberalization (Nicolli and Vona, 2019) for renewable energy deployment. Our results may further motivate such direction given the importance of renewable energy consumption for economic growth with the increased levels of renewable energy consumption even though the initial investments may have a negative effect on economic growth for developing countries.

There are various avenues for future research based on the limitations and findings of this paper.

First, we consider the country-level effects of aggregate renewable energy consumption on economic growth without disentangling the effects of renewable energy use in different sectors. It is possible that the effect of renewable energy use on economic growth differs across different sectors, and a future study examining this effect would make for a worthwhile investigation.

Second, we investigate the threshold level of renewable energy consumption when panel data set is used, and a future study may use time series threshold models to examine potential thresholds for a given country (region).

Third, our analysis relies on yearly data, but the responses to the energy prices to use (or not to use) renewable energy may take place in shorter time periods. A future study examining the short-term responses of industries and countries to energy prices and their decision with respect to renewable energy consumption, and the effect of these decisions on firm productivity or country performance would be a worthwhile venue.

Fourth, in this paper, we investigate the effect of renewable energy consumption on economic growth, but a future study could examine whether there exist threshold levels for some factors such as oil prices, GDP per capita, Co2 emissions where the effect of socio-economic variables on renewable energy consumption would differ below and above these threshold levels.

Finally, we currently consider the aggregate levels of renewable energy consumption. Given that the costs of renewable energy generation are different based on different sources, it is possible that the effect of renewable energy consumption on economic growth may be different depending on the alternative renewable energy sources used to generate energy. A future study examining the effect of alternative renewable energy consumption on economic growth may identify sources of renewable energy generation that are economically more beneficial to a set of countries.

<Insert Tables A1, A2, A3 and A4 approximately here>

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Table 1. List of literature examining the relationship between renewable energy consumption and economic growth between 2010 and 2019

Research	Sample	Time frame	Methodology	Findings
Apergis and Danuletiu (2014)	80 countries	1990-2012	Panel cointegration; dynamic error correction	REC ↔ Y
Apergis and Payne (2010)	OECD countries	1985–2005	Panel cointegration; Vector error correction	REC ↔ Y
Apergis and Payne (2011)	6 Central American countries	1980–2006	Heterogeneous panel cointegration test	REC ↔ Y
Apergis and Payne (2012)	80 countries	1990-2007	Panel cointegration; Vector error correction	REC ↔ Y
Bhattacharya et al. (2016)	38 countries	1991-2012	Heterogeneous panel cointegration test; FMOLS, DOLS,	REC → Y
Bhattacharya et al. (2017)	85 countries	1991-2012	System GMM FMOLS	REC → Y
Belaïd and Zrelli (2019)	9 Mediterranean countries	1980-2014	Pooled Mean Group (PMG) estimator & ARDL	REC ↔ Y
Bulut and Muratoglu (2018)	Turkey	1990-2015	Panel Granger causality tests	Y ≠ REC
Chang et al. (2015)	G7 countries	1990-2013	Panel Granger causality	REC ↔ Y (whole panel) Y ≠ REC (Canada, Italy, USA) Y → REC (France, UK) REC → Y (Germany, Japan)
Inglesi-Lotz (2016)	30 OECD countries	1990-2010	Panel cointegration	REC → Y
Inglesi-Lotz and Dogan (2018)	Top 10 electricity generator countries in the Sub-Saharan Africa	1980-2011	Group-mean DOLS estimator	Y → REC

Kahia et al. (2017)	11 MENA countries	1980-2012	Panel Granger causality tests; vector error correction	REC ↔ Y
Koçak and Şarkgüneşi (2017)	9 Balkan and Blacksea countries	1990-2012	panel cointegration; heterogeneous panel causality	REC → Y (5 countries) REC ↔ Y (3 countries) Y ≠ REC (Turkey)
Lin and Mubarek (2014)	China	1977-2011	Cointegration tests; Granger causality	REC ↔ Y
Magnani and Vaona (2013)	Italian regions	1997-2007	System GMM	REC → Y
Menegaki (2011)	27 European countries	1997-2007	Random effect model Dynamic error correction	Y ≠ REC
Menyah and Wolde-Rufael (2010)	US	1960–2007	Granger causality tests	Y → REC
Narayan and Doytch (2017)	89 countries	1971-2011	GMM methods Fixed effects (FE)	REC ↔ Y
Omri et al. (2015)	17 countries	1990-2011	Simultaneous equations GMM	REC ↔ Y (6 countries) REC → Y (5 countries) Y → REC (3 countries) Y ≠ REC (3 countries)
Ozturk and Bilgili (2015)	51 Sub-Sahara African countries	1980-2009	Panel cointegration, Homogeneous and Heterogeneous DOLS	REC → Y
Pao et al. (2014)	Mexico, Indonesia, South Korea, and Turkey	1990-2010	Panel co-integration tests	REC → Y (long run) REC ↔ Y (short-run)
Salim et al. (2014)	29 OECD countries		Panel cointegration Granger causality	REC ↔ Y (short-run)
Salim and Rafiq (2012)	Brazil, China, India, Indonesia, Philippines, Turkey	1981-2006	FMOLS, DOLS, Granger causality	REC ↔ Y

Tugcu and Topcu (2018)	G7 countries	1980-2014	Non-linear ARDL; Asymmetric causality procedure proposed by Hatemi-J (2012)	Asymmetric & symmetric causation All 4-hypotheses are observed in different countries.
Tugcu et al. (2012)	G7 countries	1980-2009	ARDL; Causality tests	All 4-hypotheses are observed in different countries.

Table 2. Descriptive Statistics for Different Groups of Countries

All Countries

Variables	Mean	Std. Dev.	Maximum	Minimum	Observations
Growth	0.0386	0.0564	1.4997	-0.5025	2678
ln(GDP)	3.9882	2.2483	9.7215	-1.5391	2678
ln(Labour)	1.5956	1.6726	6.6683	-2.7830	2678
ln(REC)	9.8793	2.0843	15.2860	2.4539	2678
ln(Capital)	23.1505	2.3354	28.9915	17.0078	2678
ln(NREC)	3.8869	0.8319	4.6051	0.5284	2678

OECD Countries

Variables	Mean	Std. Dev.	Maximum	Minimum	Observations
Growth	0.0256	0.0296	0.2556	-0.0913	702
ln(GDP)	6.3858	1.2731	9.7215	3.2257	702
ln(Labour)	2.1377	1.3776	5.0804	-1.8326	702
ln(REC)	11.3050	1.5222	14.7352	6.2790	702
ln(Capital)	25.6064	1.2876	28.8489	22.5036	702
ln(NREC)	4.4222	0.1955	4.6007	3.6538	702

Non-OECD Countries

Variables	Mean	Std. Dev.	Maximum	Minimum	Observations
Growth	0.0432	0.0626	1.4997	-0.5025	1976
ln(GDP)	3.1365	1.8727	9.0947	-1.5391	1976
ln(Labour)	1.4030	1.7253	6.6683	-2.7830	1976
ln(REC)	9.3728	2.0216	15.2860	2.4539	1976
ln(Capital)	22.2779	1.9745	28.9915	17.0078	1976
ln(NREC)	3.6967	0.8868	4.6051	0.5284	1976

This table provides descriptive statistics for variables within different groups of countries. Growth is GDP growth. ln(GDP), ln(Labour), ln (Capital), ln(REC) and ln(NREC) are the logarithms of aggregate GDP, L, K, REC and NREC as defined in data section respectively.

Table 3. Correlation Matrix for Different Groups of Countries

All Countries

Variables	Ln(GDP)	ln(Capital)	ln(Labour)	ln(REC)	Ln(NREC)
Ln(GDP)	1.0000***				
	(0.0000)				
ln(Capital)	0.9871***	1.0000***			
	(0.0000)	(0.0000)			
ln(Labour)	0.7315***	0.7053***	1.0000***		
	(0.0000)	(0.0000)	(0.0000)		
ln(REC)	0.7456***	0.7241***	0.7860***	1.0000***	
	(0.0000)	(0.0000)	(0.0000)	(0.0000)	
ln(NREC)	0.5683***	0.5869***	0.0919***	0.2054***	1.0000***
	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0000)

OECD Countries

Variables	Ln(GDP)	ln(Capital)	ln(Labour)	ln(REC)	ln(NREC)
Ln(GDP)	1.0000***				
	(0.0000)				
ln(Capital)	0.9924***	1.0000***			
	(0.0000)	(0.0000)			
ln(Labour)	0.9215***	0.9231***	1.0000***		
	(0.0000)	(0.0000)	(0.0000)		
ln(REC)	0.6885***	0.6800***	0.6843***	1.0000***	
	(0.0000)	(0.0000)	(0.0000)	(0.0000)	
ln(NREC)	0.2831***	0.2843***	0.3013***	-0.3577***	1.0000***
	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0000)

Non-OECD Countries

Variables	Ln(GDP)	ln(Capital)	ln(Labour)	ln(REC)	Ln(NREC)
Ln(GDP)	1.0000***				
	(0.0000)				
ln(Capital)	0.9766***	1.0000***			
	(0.0000)	(0.0000)			
ln(Labour)	0.7827***	0.7372***	1.0000***		
	(0.0000)	(0.0000)	(0.0000)		
ln(REC)	0.6908***	0.6558***	0.8121***	1.0000***	
	(0.0000)	(0.0000)	(0.0000)	(0.0000)	
ln(NREC)	0.4802***	0.5064***	0.0031	0.0853***	1.0000***
	(0.0000)	(0.0000)	(0.8913)	(0.0001)	(0.0000)

*** significantly different from zero at the 1% level. This table provides a correlation matrix for variables within different groups of countries. ln(GDP), ln(Labour), ln(Capital), ln(REC) and ln(NREC) are logarithms of aggregate GDP, L, K, REC and NREC as defined in the data section.

Table 4. The cross-section dependence test results.

	All		OECD		Non-OECD	
	Statistic	P-value	Statistic	P-value	Statistic	P-value
Ln(GDP)	332.65***	0.000	244.49***	0.000	90.758***	0.000
Ln(K)	220.65***	0.000	174.43***	0.000	52.358***	0.000
Ln(L)	315.11***	0.000	234.74***	0.000	78.877***	0.000
Ln(REC)	183.14***	0.000	119.13***	0.000	66.546***	0.000
Ln(NREC)	28.847***	0.000	67.186***	0.000	31.145***	0.000

*** significantly different from zero at the 1% level, **, significantly different from zero at the 5% level, *, significantly different from zero at the 10 % level. This table provides the results of the cross-sectional dependence test of Pesaran (2004). Under the null hypothesis of cross-sectional independence, the statistic is distributed as a two-tailed standard normal.

Table 5. Panel unit root tests.

	All				OECD				Non-OECD			
	Statistic	10%	5%	1%	Statistic	10%	5%	1%	Statistic	10%	5%	1%
Level												
Ln(GDP)	-1.9827	-2.49	-2.54	-2.63	-2.2572	-2.58	-2.66	-2.81	-2.1319	-2.51	-2.56	-2.66
Ln(K)	-2.2124	-2.49	-2.54	-2.63	-2.3486	-2.58	-2.66	-2.81	-2.4592	-2.51	-2.56	-2.66
Ln(L)	-1.7351	-2.49	-2.54	-2.63	-1.8795	-2.58	-2.66	-2.81	-1.7018	-2.51	-2.56	-2.66
Ln(REC)	-2.0881	-2.49	-2.54	-2.63	-2.3423	-2.58	-2.66	-2.81	-2.0345	-2.51	-2.56	-2.66
Ln(NREC)	-1.9103	-2.49	-2.54	-2.63	-1.9318	-2.58	-2.66	-2.81	-2.0846	-2.51	-2.56	-2.66
First difference												
DLn(GDP)	-3.391***	-2.49	-2.55	-2.65	-2.892***	-2.58	-2.67	-2.83	-3.824***	-2.51	-2.57	-2.7
DLn(K)	-3.165***	-2.49	-2.55	-2.65	-2.597*	-2.58	-2.67	-2.83	-2.575**	-2.51	-2.57	-2.7
DLn(L)	-3.368***	-2.49	-2.55	-2.65	-4.065***	-2.58	-2.67	-2.83	-3.05***	-2.51	-2.57	-2.7
DLn(REC)	-4.429***	-2.49	-2.55	-2.65	-4.742***	-2.58	-2.67	-2.83	-4.491***	-2.51	-2.57	-2.7
DLn(NREC)	-3.075***	-2.49	-2.55	-2.65	-2.742**	-2.58	-2.67	-2.83	-2.527*	-2.51	-2.57	-2.7

*** significantly different from zero at the 1% level, **, significantly different from zero at the 5% level, *, significantly different from zero at the 10 % level..This table provides the results of the CIPS test of Pesaran (2007). We include a constant and trend and two lags. 10%, 5%, 1% are the critical values at 10%, 5%, and 1% level.

Table 6. Panel cointegration tests.

	Statistics			
	G_τ	G_α	P_τ	P_α
All	-2.225*	-7.288	-16.752***	-5.966***
	(0.081)	(0.485)	(0.000)	(0.00)
Non OECD	-3.086***	-8.833	-22.482***	-8.608*
	(0.000)	(0.222)	(0.000)	(0.071)
OECD	-2.053	-7.033	-8.353***	-4.386**

*** significantly different from zero at the 1% level, **, significantly different from zero at the 5% level, *, significantly different from zero at the 10 % level. This table provides the results of the panel cointegration test of Westerlund (2007). The test regression are fitted with a constant and trend term. We use three lags and leads. The kernel bandwidth is the closest integer that equals to $4\left(\frac{T}{100}\right)^{\frac{2}{9}}$. The null hypothesis assumes that there is no co-integration. The numbers in parentheses are the bootstrap p-values, which are robust in the presence of the cross-sectional dependence.

Table 7. Linear Dynamic Panel Error Correction Regression Results

Variables	All	OECD	Non-OECD
ΔLnY_{it-1}	0.0744	-0.0961	0.1316*
	(0.1867)	(0.1099)	(0.0591)
ΔLnK_{it}	0.2323***	0.3401***	0.1457***
	(0.0000)	(0.0000)	(0.0000)
ΔLnL_{it}	0.5796**	0.6084***	-0.2415
	(0.0438)	(0.0000)	(0.4278)
$\Delta LnREC_{it}$	0.0114	0.0364***	0.0012
	(0.5426)	(0.0055)	(0.9411)
$\Delta LnNREC_{it}$	0.0275	0.1201*	0.0588*
	(0.4898)	(0.0907)	(0.0802)
LnY_{it-1}	-0.7993***	-0.6828***	-0.6058***
	(0.0000)	(0.0000)	(0.0000)
LnK_{it-1}	0.1871***	0.2307***	0.1762***
	(0.0000)	(0.0000)	(0.0000)
LnL_{it-1}	1.0806***	0.7783***	0.5975***
	(0.0000)	(0.0000)	(0.0000)
$LnREC_{it-1}$	0.0091	0.0452***	0.0465*
	(0.7407)	(0.0028)	(0.0890)
$LnNREC_{it-1}$	0.0101	0.1468	0.0494
	(0.8121)	(0.1468)	(0.2041)
Observations	2060	540	1520

*** significantly different from zero at the 1% level, **, significantly different from zero at the 5% level, *, significantly different from zero at the 10 % level. This table provides estimations of the model (4) using FD-GMM method. The regression analysis also includes lagged growth rates of input variables but not reported. The moment conditions used are listed in (8). The lag length is one. P-values are provided in brackets.

Table 8. Non-linear Dynamic Panel Error Correction Regression Results when REC is used as a threshold variable

Countries	All		Non-OECD	
Threshold	9.5058***		9.5926***	
	Low	High	Low	High
ΔLnY_{it-1}	0.1561*	-0.0569	0.1143	-0.0349
	(0.0970)	(0.6623)	(0.3212)	(0.8642)
ΔLnK_{it}	0.1382***	0.2503***	0.0604	0.1922***
	(0.0004)	(0.0000)	(0.1278)	(0.0001)
ΔLnL_{it}	1.0107	0.5169	1.7972**	-0.7692
	(0.1518)	(0.3188)	(0.0059)	(0.2627)
$\Delta LnREC_{it}$	-0.0457	0.1508**	-0.0236	0.3133**
	(0.1147)	(0.0139)	(0.3243)	(0.0024)
$\Delta LnNREC_{it}$	-0.0307	0.0868	0.0580	-0.1322
	(0.6303)	(0.4960)	(0.3518)	(0.3873)
LnY_{it-1}	-0.7404***	-0.6600***	-0.7228***	-0.5300***
	(0.0000)	(0.0000)	(0.0000)	(0.0001)
LnK_{it-1}	0.2025***	0.1215**	0.1871***	0.0927
	(0.0000)	(0.0171)	(0.0004)	(0.1633)
LnL_{it-1}	0.8402***	0.8614***	0.7117***	0.6011***
	(0.0000)	(0.0000)	(0.0013)	(0.0056)
$LnREC_{it-1}$	-0.0437	0.0970*	0.0546	0.2208**
	(0.2823)	(0.0517)	(0.1685)	(0.0301)
$LnNREC_{it-1}$	0.0432	0.1059	0.0477	0.06#26
	(0.4581)	(0.1106)	(0.4810)	(0.4808)
SupWald *P* value	0.0000		0.0000	
SupWald	60.16		43.45	
Observations	2060		1520	

*** significantly different from zero at the 1% level, **, significantly different from zero at the 5% level, *, significantly different from zero at the 10 % level. This table provides estimations of the model (7) using FD-GMM method. The regression analysis also includes lagged growth rates of input variables but not reported. The moment conditions used are listed in (8). The lag length is one. P-values are provided in brackets. The threshold value that is found to be significant is reported in "threshold" for respective sample analysis.

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Table 9. Linear Dynamic Panel Error Correction Regression Results with developed and developing countries

Variables	Developed	Developing
ΔLnY_{it-1}	-0.0126	0.0370
	(0.7636)	(0.5912)
ΔLnK_{it}	0.2025***	0.1379***
	(0.0000)	(0.0000)
ΔLnL_{it}	0.4289**	-0.4098
	(0.0316)	(0.2078)
$\Delta LnREC_{it}$	-0.0006	0.0205
	(0.9519)	(0.3583)
$\Delta LnNREC_{it}$	-0.0146	0.0583*
	(0.8516)	(0.0840)
LnY_{it-1}	-0.7034***	-0.5255***
	(0.0000)	(0.0000)
LnK_{it-1}	0.1444***	0.1374***
	(0.0000)	(0.0005)
LnL_{it-1}	1.0731***	0.5254***
	(0.0000)	(0.0000)
$LnREC_{it-1}$	0.0071	0.0901**
	(0.6743)	(0.0171)
$LnNREC_{it-1}$	0.1643	0.0168
	(0.1464)	(0.6686)
Observations	580	1480

*** significantly different from zero at the 1% level, **, significantly different from zero at the 5% level, *, significantly different from zero at the 10 % level. This table provides estimations of the model (4) using FD-GMM method. The regression analysis also includes lagged growth rates of input variables but not reported. The moment conditions used are listed in (8). The lag length is one. P-values are provided in brackets.

Table 10. Non-linear Dynamic Panel Error Correction Regression Results for developed and developing country samples when REC is used as a threshold variable

Countries	Developed		Developing	
Threshold	10.0815**		9.6054***	
	Low	High	Low	High
ΔLnY_{it-1}	0.0412	-0.4144***	-0.0954	-0.2543*
	(0.6263)	(0.0008)	(0.3889)	(0.0705)
ΔLnK_{it}	0.1259***	0.4231***	0.0279	0.1801***
	(0.0000)	(0.0000)	(0.5128)	(0.0000)
ΔLnL_{it}	0.5363	0.3783	0.4379	-0.3465
	(0.1061)	(0.3000)	(0.3920)	(0.5970)
$\Delta LnREC_{it}$	-0.0218	-0.0547	-0.0537*	0.2122***
	(0.1160)	(0.2345)	(0.0849)	(0.0086)
$\Delta LnNREC_{it}$	-0.2168**	-0.0077	0.0267	0.0776
	(0.0414)	(0.9572)	(0.6235)	(0.5232)
LnY_{it-1}	-0.6926***	-0.4101***	-0.4650***	-0.4434***
	(0.0000)	(0.0003)	(0.0000)	(0.0000)
LnK_{it-1}	0.0776***	0.1170**	0.1436***	0.1204**
	(0.0023)	(0.0197)	(0.0058)	(0.0442)
LnL_{it-1}	0.7907***	0.5125***	0.4216***	0.3808**
	(0.0000)	(0.0036)	(0.0046)	(0.0105)
$LnREC_{it-1}$	0.0115	-0.0042	0.0819	0.1097
	(0.6237)	(0.8741)	(0.1553)	(0.1931)
$LnNREC_{it-1}$	0.3049*	-0.1032	-0.0012	0.0724
	(0.0815)	(0.4867)	(0.9837)	(0.3587)
SupWald *P* value	0.0302		0.0050	
SupWald	31.6888		55.8608	
Observations	580		1480	

*** significantly different from zero at the 1% level, **, significantly different from zero at the 5% level, *, significantly different from zero at the 10 % level. This table provides estimations of the model (7) using FD-GMM method. The regression analysis also includes lagged growth rates of input variables but not reported. The moment conditions used are listed in (8). The lag length is one. P-values are provided in brackets. The threshold value that is found to be significant is reported in "threshold" for respective sample analysis.

Appendix Table A1: List of countries

Country	OECD	Developed	Country	OECD	Developed
Albania			Ireland	x	X
Algeria			Israel	x	X
Argentina			Italy	x	X
Australia	X	X	Jamaica		
Austria	X	X	Japan	X	X
Bangladesh			Jordan		
Barbados			Kenya		
Belgium	X	X	Korea, Rep.	X	X
Belize			Lebanon		
Benin			Luxembourg	X	X
Bhutan			Macao SAR, China		X
Bolivia			Madagascar		
Botswana			Malawi		
Brazil			Malaysia		
Bulgaria			Mali		
Burkina Faso			Mauritania		
Burundi			Mauritius		
Cameroon			Mexico	X	
Canada	X	X	Mongolia		
Central African Republic			Morocco		
Chad			Mozambique		
Chile	X		Nepal		
China			Netherlands	X	X
Colombia			New Zealand	x	X
Congo, Rep.			Nigeria		
Costa Rica			Norway	X	X
Cote d'Ivoire			Pakistan		
Cuba			Panama		
Cyprus		X	Peru		
Denmark	X	X	Philippines		
Dominican Republic			Portugal	X	X
Ecuador			Rwanda		
Egypt, Arab Rep.			Saudi Arabia		
El Salvador			Senegal		
Equatorial Guinea			Singapore		X
Eswatini			South Africa		
Finland	X	X	Spain	X	X
France	X	X	Sri Lanka		
Gabon			Sudan		
Gambia			Sweden	X	X
Germany	X	X	Switzerland	x	X
Ghana			Tanzania		
Greece	X	X	Thailand		
Guatemala			Togo		
Guinea			Tunisia		
Guinea-Bissau			Turkey	X	
Guyana			Uganda		
Honduras			United Kingdom	X	X
Hong Kong SAR, China		X	United States	x	X
India			Uruguay		
Indonesia			Zimbabwe		
Iran, Islamic Rep.					

Table A2. Cross-section dependence test for developing and developed country samples.

	Developing		Developed	
	Statistic	P-value	Statistic	P-value
Ln(GDP)	237.88***	0.0000	96.99***	0.0000
Ln(K)	174.51***	0.0000	52.298***	0.0000
Ln(L)	227.23***	0.0000	86.527***	0.0000
Ln(REC)	109.27***	0.0000	76.958***	0.0000
Ln(NREC)	82.377***	0.0000	40.608***	0.0000

*** significantly different from zero at the 1% level, **, significantly different from zero at the 5% level, *, significantly different from zero at the 10 % level. This table provides the results of the cross-sectional dependence test of Pesaran (2004). Under the null hypothesis of cross-sectional independence, the statistic is distributed as a two-tailed standard normal.

Table A3. Panel unit root tests for developing and developed country samples

	Developing				Developed			
	Statistic	10%	5%	1%	Statistic	10%	5%	1%
				Level				
Ln(GDP)	-2.0506	-2.51	-2.56	-2.66	-2.0005	-2.58	-2.66	-2.81
Ln(K)	-2.4562	-2.51	-2.56	-2.66	-2.3072	-2.58	-2.66	-2.81
Ln(L)	-1.6443	-2.51	-2.56	-2.66	-1.8951	-2.58	-2.66	-2.81
Ln(REC)	-2.0603	-2.51	-2.56	-2.66	-2.1646	-2.58	-2.66	-2.81
Ln(NREC)	-2.0466	-2.51	-2.56	-2.66	-1.6007	-2.58	-2.66	-2.81
				First difference				
DLn(GDP)	-3.858***	-2.51	-2.57	-2.7	-2.863***	-2.58	-2.67	-2.83
DLn(K)	-2.535*	-2.51	-2.57	-2.7	-2.605*	-2.58	-2.67	-2.83
DLn(L)	-2.932***	-2.51	-2.57	-2.7	-4.14***	-2.58	-2.67	-2.83
DLn(REC)	-4.42***	-2.51	-2.57	-2.7	-4.517***	-2.58	-2.67	-2.83
DLn(NREC)	-2.647**	-2.51	-2.57	-2.7	-2.603*	-2.58	-2.67	-2.83

*** significantly different from zero at the 1% level, **, significantly different from zero at the 5% level, *, significantly different from zero at the 10 % level..This table provides the results of the CIPS test of Pesaran (2007). We include a constant and trend and two lags. 10%, 5%, 1% are the critical values at 10%, 5%, and 1% level.

Table A4. Panel cointegration tests for developing and developed country samples

	Statistics			
	G_τ	G_α	P_τ	P_α
Developing	-4.057	-0.528	-9.593***	-0.510
	(0.647)	(0.222)	(0.000)	(0.141)
Developed	-2.675**	-4.684	-7.471	-5.012
	(0.040)	(0.980)	(0.778)	(0.748)

*** significantly different from zero at the 1% level, **, significantly different from zero at the 5% level, *, significantly different from zero at the 10 % level. This table provides the results of the panel cointegration test of Westerlund (2007). The test regression are fitted with a constant and trend term. We use three lags and leads. The kernel bandwidth is the closest integer that equals to $4\left(\frac{T}{100}\right)^{\frac{2}{9}}$. The null hypothesis assumes that there is no co-integration. The numbers in parentheses are the bootstrap p-values, which are robust in the presence of the cross-sectional dependence.

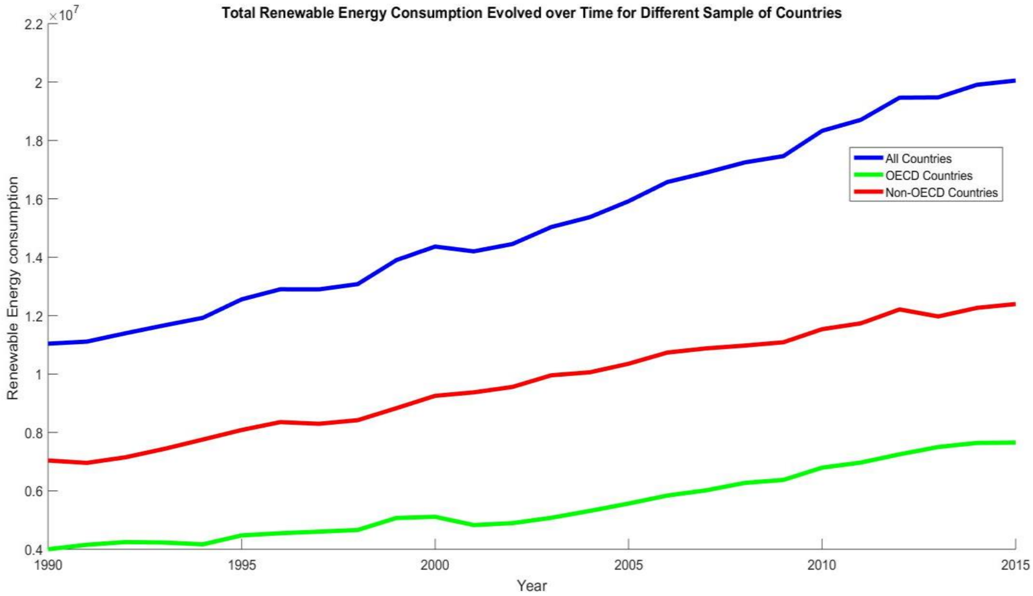

Fig. 1. Total renewable energy consumption evolution over time for a different sample of countries

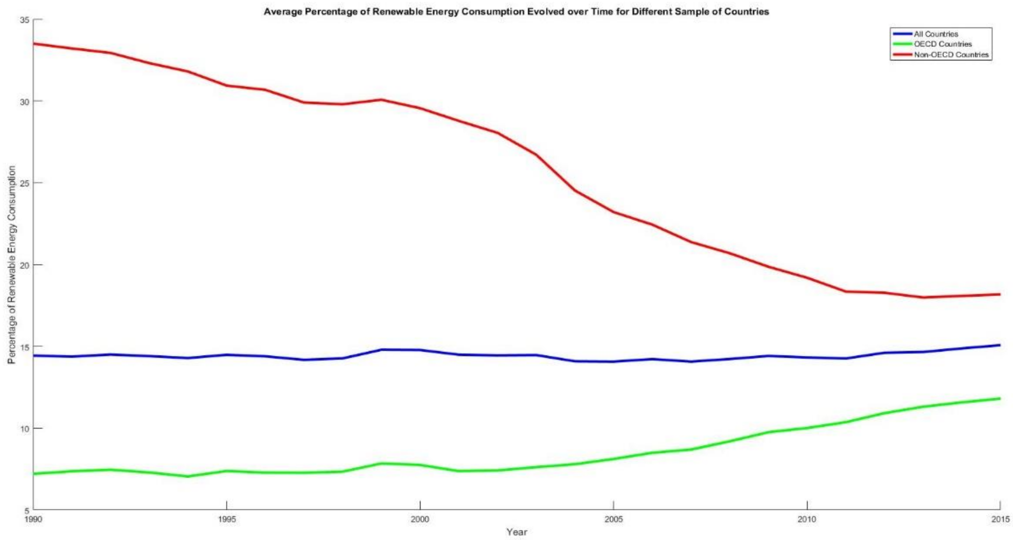

Fig. 2. Renewable energy consumption as a percentage of total energy consumption for a different sample of countries