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RESEARCH ARTICLE

# Environmental Kuznets curve hypothesis: asymmetry analysis and robust estimation under cross-section dependence

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**Abstract**

In this paper, we revisit the environmental Kuznets curve (EKC) hypothesis by using estimations that account for cross-sectional dependency (CSD) and asymmetry effect in 76 countries for the period 1971–2014. Our results lend moderate support to the EKC hypothesis. The country-specific results unfold that a total of 16 out of 76 countries support the EKC hypothesis using CCEMG estimator. Results from AMG reveal that the EKC hypothesis holds in 24 out of 76 countries. It is worth highlighting that 11 countries (Australia, China, Congo Dem. Rep., Costa Rica, Gabon, Hong Kong, India, Korea, Myanmar, Turkey, and Uruguay) exhibit an inverted U-shaped curve regardless of whether CCEMG or AMG is used. The asymmetry analysis using PMG is also able to support the EKC hypothesis. We conclude that the EKC hypothesis does not fit all countries. Policy implication and recommendation in designing appropriate energy and economic policies are provided.

**Keywords** EKC · Panel analysis · Cross-section dependence · Asymmetry · CCEMG · AMG · PMG

## Introduction

The concern on rising global temperature and extreme climate has been drawing attention from various parties especially in recent decades. These phenomena are often related to global warming. According to World Meteorological Organization (WMO 2019), the average global temperature is ranked fourth based on the record. In addition, the warming trend has continued in 2018 with 20 warmest years in the past 22 years. Other worrying signs include increase in the sea level, ocean heat and acidification, concentration of greenhouse gases (GHG) rise, and sea-ice and glacier melt (WMO 2019). The above phenomena are worrisome because it may lead to the submergence of coastal countries if the trend continues.

It has been identified that GHG are the main culprit causing the increase in global temperature and extreme climate. Among the GHG, carbon dioxide ($CO_2$) is the main pollutant that catalysts the warming of Earth's atmosphere. According to International Energy Agency (2017), increased CO2 emissions are mostly contributed by a rise in total energy consumption worldwide. As of 2017, more than 70% of the global energy demand was supplied by fossil fuels. This would lead to environmental degradation as a result of direct combustion of these fuels. In order to improve environmental quality, the reliance on non-renewable energy sources has to be reduced.

To curb the problem of global warming, Kyoto Protocol was adopted in 1997 to commit its members by setting international target of emissions reduction. However, the Protocol has failed to make a substantial impact on global $CO_2$ reduction. A recent landmark to combat climate change has been reached in the Paris Agreement on 12 December 2015. Its aim is to emphasize on necessary measures for sustainable low carbon economy in the future. However, the Agreement has suffered a setback as the United States (US), one of the largest emitters in the world, intended to withdraw from it in 2017. Despite these international efforts, global warming remains a serious issue. Thus, increased global actions are required to address the challenges of climate change.

Early research first attempted to study the linkage between $CO_2$ emissions and economic growth that is often expressed as the environmental Kuznets curve (EKC) hypothesis (e.g.

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Cialani 2007; Li et al. 2016; Narayan and Narayan 2010). This line of research sooner evolved and included additional variables into the analysis. Energy consumption was the most commonly added variable as it leads to higher $CO_2$ emissions (e.g. Apergis and Payne 2009; Saboori et al. 2014). Other than additional variables, panel data was used with the aim to increase the number of observation and provide robust evidence (e.g. Narayan and Narayan 2010; Apergis and Ozturk 2015; Baek 2015; Li et al. 2016). However, previous panel studies on the EKC did not consider potential existence of cross-section dependence (CSD) in the data. Ignoring CSD in the estimation especially for panel data would cause the loss of efficiency in the estimator and invalid test statistics. Besides, existing EKC studies that examine the asymmetry effect remain scarce. Therefore, the lack of robust evidence that supports the EKC hypothesis gives rise to the motivation of this study.

To fill the literature gap, we outline two objectives as follows: First, we examine the EKC hypothesis for 76 countries from 1971 to 2014, using recent panel data estimators that are robust under CSD. The two estimators are Common Correlated Effect Mean Group (CCEMG) and Augmented Mean Group (AMG). Other than its robustness, the CCEMG and the AMG are able to generate individual results for each of the countries which allow for comparison across countries. Second, we examine the asymmetry effect in the EKC framework using partial sum approach and Pooled Mean Group (PMG). This allows the EKC hypothesis to be tested in a different manner.

The rest of the paper is structured as follows. "Literature review" summarizes previous effort and contribution to the EKC hypothesis and framework, potential CSD problem in previous EKC studies, and the asymmetry effect in similar literature. "Data, model, and methodology" describes the data, theoretical model and framework, and the methodology used in this study. "Empirical results and explanation" reports the findings of this study. Finally, "Conclusion and policy recommendation" concludes this paper and discusses relevant policy suggestions.

## Literature review

Grossman and Krueger (1991) is the pioneering work that examines the linkage between emissions and income growth. Their results indicate that income growth initially leads to higher emissions and once the peak is reached, emissions would reduce. This phenomenon postulates an inverted U-shaped curve and coined as the EKC hypothesis. Since then, the EKC hypothesis is further supported by the other studies such as Apergis and Ozturk (2015), Jalil and Mahmud (2009), Li et al. (2016), Ng et al. (2019), Lau et al. (2019), and Sarkodie and Strezov (2019). Using Generalized Method of Moments (GMM), Apergis and Ozturk (2015) explore the relationship between $CO_2$ emissions and real GDP per capita in 14 Asian countries from 1990 to 2011. It is revealed from the study that inverted U-shaped EKC does exist in these countries. An earlier study by Jalil and Mahmud (2009) also supports the existence of an inverted U-shaped EKC. The study attempts to examine the long-run relationship between $CO_2$ emissions and economic growth in China for the period from 1975 to 2005.

In a more recent study, Li et al. (2016) investigate the impact of GDP growth on various pollutant emissions using Chinese provincial data from 1996 to 2012. The authors find the EKC hypothesis to be valid for three pollution indicators (i.e. waste solid emissions, water pollution, and $CO_2$ emissions) in China. Most recently, Ng et al. (2019) examine the effect of income growth on $CO_2$ emissions from 1990 to 2013 in OECD countries. An inverted U-shaped EKC is supported by the study. By using GMM and FMOLS estimators, Lau et al. (2019) study the relationship between economic growth, electricity production from nuclear source, and pollution in OECD countries. The results show that there is an inverted U-shaped linkage between economic growth and $CO_2$ emissions. Sarkodie and Strezov (2019) examine the impact of economic development, energy consumption, and FDI on $CO_2$ emissions using time series data ranging from 1982 to 2016. The study confirms the validity of EKC hypothesis in China and Indonesia.

The EKC hypothesis suggests that the growth at the initial stage of economic development increases the level of $CO_2$ emissions. However, when the economic growth reaches a certain stage, the level of $CO_2$ emissions would decrease. The reasons behind the stabilization point and the decrease in $CO_2$ emissions are the structural and technological changes that improve the environmental awareness and quality. Despite many studies lend support to the EKC hypothesis, Friedl and Getzner (2003), Shahbaz et al. (2019), and Zanin and Marra (2012) identify an N-shaped curve which violates the EKC hypothesis. Friedl and Getzner (2003) investigate the growth-pollution nexus in a small economy, i.e. Austria for the period between 1960 and 1999. The study finds a cubic relationship between economic growth and $CO_2$ emissions. Likewise, another study by Shahbaz et al. (2019) on Vietnam obtains a long-run N-shaped relationship between GDP and $CO_2$ emissions using a data set from 1974 to 2016. The result implies that Vietnam can experience a temporary decline in pollutant emissions when the economy grows to a certain level. As income reaches another turning point, $CO_2$ emissions will tend to increase again.

Using addictive mixed models, Zanin and Marra (2012) examine the EKC hypothesis in nine European countries. Similar to the finding of Friedl and Getzner (2003), the authors discover an N-shaped relationship between economic growth and $CO_2$ emissions in Austria. In addition, Bertinelli and Strobl (2005) and Rezek and Rogers (2008) have identified a linear increasing trend which is not consistent with the EKC hypothesis. Using a semi-parametric estimator, Bertinelli and Strobl (2005) conduct a study on a panel of countries. It is found that there is a linear increasing linkage between GDP and pollution. Similarly, Rezek and Rogers (2008) have proven a monotonically upward nexus between economic growth and $CO_2$ emissions in a group of industrialized nations. Other than that, studies such as Focacci (2003) and Liu et al. (2017) discover a monotonically downward curve and a U-shaped EKC, respectively. Based on a time span of 40 years, Focacci (2003) suggests a negative relationship between pollutant emissions and economic development for a panel of highly industrialized countries. A study by Liu et al. (2017) on ASEAN-4 for the period from 1970 to 2013 concludes that the inverted U-shaped EKC does not exist. Instead, a U-shaped correlation between economic growth and $CO_2$ emissions is found.

Recent works have been digging into multivariate framework which involves causality and cointegration. Using data from China for the period 1960–2007, Zhang and Cheng (2009) examine the causal relationship between energy consumption, GDP, and pollution. Two important causalities are found: one from economic growth to energy consumption and another from energy consumption to $CO_2$ emissions. In addition, it is discovered that both environmental degradation and energy consumption do not lead to economic growth. Turning to OECD countries, Saboori et al. (2014) attempt to investigate the bidirectional long-run linkage between transport energy usage, $CO_2$ emissions, and income growth for the period between 1960 and 2008. The Fully Modified Ordinary Least Square cointegration approach is used for the empirical analysis. The results indicate that a bidirectional relationship exists for (i) $CO_2$ emissions and GDP growth, (ii) transport energy usage and GDP growth, and (iii) transport energy usage and $CO_2$ emissions. Similarly, Bastola and Sapkota (2015) investigate the Granger causality between pollution, energy consumption, and economic growth in Nepal. It is discovered from the Granger causality test that a bidirectional causality is running from energy consumption to pollutant emissions. A unidirectional causality is also found running from GDP to both $CO_2$ emissions and energy consumption.

More recently, Wang et al. (2016) conduct a provincial analysis on the linkage between $CO_2$ emissions, GDP, and energy consumption in China for the period between 1995 and 2012. It is suggested that all the three variables are cointegrated in the long run. The findings of the study further reveal that a bidirectional relationship appears for energy consumption and pollution as well as for energy consumption and economic growth. Moreover, there is a unidirectional causality running from GDP to pollution. By using Autoregressive Distributed Lag (ARDL) bounds test approach, Alam et al. (2016) examine the energy consumption-pollution nexus in India, Indonesia, China, and Brazil for the period between 1970 and 2012. It is discovered that energy consumption and environmental degradation are positively related in all the four countries. In both short run and long run, there is an inverted U-shaped nexus between pollution and economic growth in Indonesia and Brazil. In China, however, the EKC hypothesis is found valid only in the long run. The EKC hypothesis is not supported in India.

A more recent study by Amri (2018) has also proven the direct linkage between energy consumption and pollution. Using ARDL method, the author has found a negative correlation between energy consumption and environmental quality in Tunisia. On top of that, the EKC hypothesis is rejected. Therefore, it is proposed that the policymakers should consider adopting more renewable energy sources in Tunisia. Other multivariate studies include Apergis and Payne (2009), Baek (2015), and Nasir and Rahmen (2011). Using a multivariate panel data framework, Apergis and Payne (2009) investigate the energy consumption-growth nexus on 11 Commonwealth countries from 1991 to 2005. The results show that a unidirectional causal relationship exists from energy consumption to GDP in the short run. In the long run, however, a bidirectional relationship is found between the two variables.

Baek (2015) examines the impact of nuclear energy, GDP, and energy consumption on $CO_2$ emissions using cointegration analysis for 12 countries. Nuclear energy is found beneficial to the environment. It is also proven from the results that EKC does not exist. Instead, there is a negative relationship between economic growth and $CO_2$ emissions. By using Johansen method of cointegration, Nasir and Rahmen (2011) study the linkage between economic growth, energy consumption, trade openness, and pollutant emissions in Pakistan from 1972 to 2008. The results indicate that EKC hypothesis is valid in the long run. In addition, there is a long-run positive relationship between energy consumption and $CO_2$ emissions. A unidirectional causal relationship is also found from growth to both energy consumption and $CO_2$ emissions.

Even though there is an abundant of past research on EKC, studies that address the issue of CSD are limited. Up to date, there are merely a handful of EKC studies which have taken CSD into account in the estimation process. Churchill et al. (2018) examine the EKC hypothesis for 20 OECD countries using data from 1870 to 2014. They find evidence supporting the EKC hypothesis for the panel while individual country results are mixed. In total, nine countries support the EKC hypothesis. Specifically, five out of the 20 countries exhibit an inverted U-shaped EKC. An N-shaped EKC is found in two countries. Interestingly, one of the 20 countries has shown an inverted N-shaped EKC. Destek and Sarkodie (2019) investigate the validity of EKC hypothesis for ecological footprint in 11 newly industrialized countries for the period 1977–

2013. By applying AMG estimator and heterogeneous panel causality test, their results have shown support of an inverted U-shaped EKC. The results of the causality test suggest that a bidirectional causal relationship exists between ecological footprint and economic growth.

Apergis (2016) attempts to validate the EKC hypothesis in 15 countries for the period 1960–2013 using Common Correlated Effects (CCE) estimation procedure. Results are shown for both panel and individual country analysis. For individual country analysis using quantile cointegration approach, it is discovered that the EKC hypothesis exists in 12 out of the 15 countries. As the relationship between GDP and pollution varies across countries, the author has raised the concerns on the suitability of using panel analysis in examining the validity of EKC. By utilizing two unbalanced panel data sets for the period between 1990 and 2014, and 2001 and 2014, Zhang et al. (2017) test the linkage between economic growth and water degradation discharge (i.e. chemical oxygen demand and ammonia nitrogen) in China. For estimation, the study utilizes panel unit root tests, cointegration test, and Granger causality test that account for CSD. The EKC hypothesis is confirmed for chemical oxygen demand and ammonia nitrogen in China. Besides, a long-run bidirectional causality is demonstrated between economic growth and water degradation discharge.

Though important, the testing of asymmetry properties remains scarce in the EKC/energy literature. Shahbaz et al. (2017) examine the relationship between energy consumption, financial development, capital, labour, and economic growth in India using a nonlinear and asymmetric analysis. The results of the study show that only negative shocks to energy consumption affect economic growth. Negative shocks to financial development are also discovered to impact economic growth. In contrary, capital stock leads to economic development symmetrically in India. A study by Farhani and Solarin (2017) investigates the effects of trade liberalization, financial development, FDI, economic growth, and capital formation on energy consumption in the US using quarterly time series data from 1973 to 2014. Using asymmetric causality test, it is revealed that economic growth, FDI, trade, and capital Granger cause energy consumption. The results also indicate that trade liberalization, FDI, and capital formation stimulate financial development. However, the asymmetry analysis is more common in the literature of other studies. For instance, Salisu and Isah (2017) examine whether the stock prices of oil trading (exporting and importing) countries react asymmetrically to the fluctuations in oil price. Similarly, the role of asymmetries in the relationship between oil price and general price level in selected oil trading countries has been examined by Salisu et al. (2017). In addition, an earlier study by Rafailidis and Katrakilidis (2014) also considers the asymmetric responses between stock prices and oil prices in the US.

Most recently, a study by Jin and Kim (2020) on the relationship between economic growth and carbon emissions has discovered that the EKC hypothesis is valid in merely five out of the 34 Annex I countries examined for the period between 1990 and 2016. Overall, the inverted U-shaped nexus between pollution and GDP is not found in the Annex I countries. The study has taken into account the issue of CSD by utilizing the CCEMG, AMG, and MG estimators. The findings of the study imply that Annex I countries have not done enough in mitigating climate change, though a handful of countries have some progress in the mitigation efforts. Different from Jin and Kim (2020), our study will take a step further by examining the existence of EKC hypothesis in a global context (a panel of 76 countries). Moreover, unlike Jin and Kim (2020) who employ only CCEMG, AMG, and MG estimators, our paper also looks into the asymmetry effects between economic growth and $CO_2$ emissions using partial sum approach and Pooled Mean Group (PMG). In other words, our main contribution to the literature is that we attempt to examine the validity of EKC hypothesis in a world panel by considering not only the issue of CSD but also the asymmetric effects in the framework of EKC.

## Data, model, and methodology

### Data and model specification

In line with our objectives, we form a balanced panel dataset consisting 76 countries for the period 1971–2014. The choice of country and sample period is based on data availability.[1] The data for all variables used are from the World Development Indicator (WDI), World Bank. A panel model stemming from the EKC hypothesis is shown as follows:

$$CO2_{i,t} = f\left(Y_{i,t}, Y^2{}_{i,t}, EC_{i,t}\right) \quad (1)$$

where $CO2$ represents $CO_2$ emissions measured in metric tons per capita, $Y$ and $Y^2$ represent GDP and GDP$^2$ measured in constant 2010 US$ per capita, $EC$ is energy consumption per capita measured in kg of oil equivalent. $i$ and $t$ represent time and cross-section dimension.

Model (1) is transformed into natural logarithm ($ln$) form for the sake of econometric interpretation:

$$lnCO2_{i,t} = \beta_0 + \beta_1 lnY_{i,t} + \beta_2 lnY^2{}_{i,t} + \beta_3 lnEC_{i,t} + \varepsilon_{i,t} \quad (2)$$

If the EKC hypothesis holds, the sign of $\beta_1$ is expected to be positive while the sign of $\beta_2$ is expected to be negative. As high energy consumption results in more $CO_2$ emissions, the sign of $\beta_3$ is expected to be positive.

[1] Given that the WDI does not provide data on $CO_2$ emissions beyond 2014, our data period ends in 2014.

## Testing for CSD

Testing for the existence of CSD is gaining popularity in recent panel studies. For panel data with large cross-section dimensions ($N$), the residuals are not exhibited to be cross-sectional independent due to world globalization. Failure in addressing the CSD problem in panel data would cause the loss of efficiency in the estimator and invalid test statistics.

To test for existence of CSD in our dataset, we utilize four different tests, namely Lagrange multiplier (LM) proposed by Breusch and Pagan (1980) LM test, Pesaran (2004) scaled LM and CD tests, and Baltagi et al. (2012) bias-corrected scaled LM. The early Breusch and Pagan (1980) LM test is unable to account for large cross section, N. Pesaran (2004) extends the LM test known as the scaled LM test to address this matter. However, the scaled LM test also has the limitation in correcting size distortion for small time dimension ($T$). To minimize the size distortion, Pesaran (2004) proposes another test statistic based on the mean of the pairwise correlation coefficients. The last test is the bias-corrected scaled LM test by Baltagi et al. (2012).

## Second-generation unit root test

After testing for potential CSD problem in the panel dataset, the cross-sectionally augmented IPS (CIPS) test by Pesaran (2007), which accounts for CSD, is used. This test is formulated from the results of the panel-member-specific ADF regressions, which includes cross-sectional averages of the dependent and independent variables in the model. Hence, the test is suitable for identifying the existence of unit roots in heterogeneous panels. The test statistic has a non-standard distribution with the null hypothesis of nonstationarity.

Specifically, the CIPS test uses the cross-section average to capture the common effect and construct the test statistics based on the $t$-ratio of the OLS estimate of $b_i\left(\widehat{b_i}\right)$ in the cross-sectional augmented Dickey Fuller (CADF) regression below:

$$Dy_{it} = \alpha_i + b_i y_{i,t-1} + c_i y_{t-1} + d_i Dy_t + \varepsilon_{it} \tag{3}$$

The CIPS test specification as follows:

$$CIPS(N,T) = t\text{–}bar = N^{-1} a_{i=1}^{N} t_i(N,T) \tag{4}$$

where $t_i(N, T)$ is the augmented Dickey Fuller statistic across the cross section for the $i$th cross-section unit set by the $t$-ratio of $b_i$ in Eq. (3).

## Second-generation cointegration test

Similar to the panel unit root tests, most of the previous EKC literature utilized the panel cointegration tests that did not account for CSD. Westerlund (2007) developed a test known as the second-generation panel cointegration test that is robust to CSD. The objective of the test is to examine the absence of cointegration by determining if error correction does exist among the individual panel members or among the whole panel.

Specifically, the test generates new sample using bootstrapping to construct two-group mean statistics and two-panel statistics. The test is based on the following equation:

$$Dy_{it} = c_i + \alpha_i\left(y_{i,t-1} - b_i x_{it-1}\right) + \alpha_{j=1}^{P_i} \alpha_{ij} Dy_{it-j} + \alpha_{j=0}^{P_i} g_{ij} Dx_{it-j} + \epsilon_{it} \tag{5}$$

where $\alpha_i$is the term of adjustment speed. The test examines the null hypothesis of no cointegration between the variables.

## CCEMG and AMG

To realize the first objective of our study, we adopt the CCEMG estimator introduced by Pesaran (2006) and the AMG estimator proposed by Bond and Eberhardt (2009) and Eberhardt and Teal (2011). Both estimators are robust to CSD as they consider the correlation across panel members. Other than CSD, the two estimators allow for heterogeneous slope coefficients, which provide individual country results.[2]

## Asymmetry analysis and PMG

The PMG estimator was proposed by Pesaran, Shin, and Smith (1999), which is more efficient due to the valid long-run restrictions. Another advantage of the PMG is that it is robust to the outliers and lag orders. Moreover, the PMG estimator requires long-run coefficients across cross sections to be similar. However, it allows for differences in the short-run coefficients, error variances, and the intercepts. In the meantime, the PMG is a consistent and an efficient long-run estimator. The order of integration for each variable is not important for the estimation of PMG with the condition that cointegration exists between variables (Pesaran and Shin 1998).

We adopt the PMG estimator in this study for two reasons. First, it is able test the EKC hypothesis in a different manner. Specifically, the squared term of Y as in Eq. 2 is omitted to avoid potential multicollinearity problem (Bento and Moutinho 2016).

[2] For detailed and technical explanation on the CCEMG and AMG, refer to Pesaran (2006), Bond and Eberhardt (2009), Eberhardt and Teal (2010), and Atasoy (2017).

**Table 1** Cross-sectional dependence and CIPS test

| Variable | CO2 | Y | EC |
|---|---|---|---|
| Panel A: CSD tests | | | |
| Breusch-Pagan (LM) | 41811*** | 73449*** | 50676*** |
| Pesaran Scaled LM | 516.05*** | 935.10*** | 633.48*** |
| Bias-corrected scaled LM | 515.17*** | 934.22*** | 632.59*** |
| Pesaran CD | 64.189*** | 192.67*** | 129.83*** |
| Panel B: second-generation unit root tests | | | |
| CIPS test (level) | − 2.021 | − 1.759 | − 1.807 |
| CIPS test (first difference) | − 5.688*** | − 4.425*** | − 5.595*** |

Critical values of the CIPS test (1%) are taken from Pesaran's (2007) Table 2b. ** and *** indicate significance at 5% and 1%, respectively

Though the squared term of Y is omitted, the EKC hypothesis could be examined through the long-run and short-run dynamics. The EKC hypothesis is said to be supported when the short-run dynamics of the Y exhibits a positive sign while the opposite holds in the long run (Ng et al. 2019). This enables the EKC hypothesis to be tested in a different manner and at the same time, reduces the bias due to potential multicollinearity problem (Bento and Moutinho 2016).

Second, the asymmetric impact as in our second objective could be examined by decomposing the two variables, namely economic growth and energy consumption into the followings:

$$Y\_POS_t = \sum_{j=1}^{t} \Delta Y_{i,j}^{+} = \sum_{j=1}^{t} \max\left(\Delta Y_{i,j}, 0\right) \quad (6)$$

$$Y\_NEG_t = \sum_{j=1}^{t} \Delta Y_{i,j}^{-} = \sum_{j=1}^{t} \min\left(\Delta Y_{i,j}, 0\right) \quad (7)$$

$$EC\_POS_t = \sum_{j=1}^{t} \Delta EC_{i,j}^{+} = \sum_{j=1}^{t} \max\left(\Delta EC_{i,j}, 0\right) \quad (8)$$

$$EC\_NEG_t = \sum_{j=1}^{t} \Delta EC_{i,j}^{-} = \sum_{j=1}^{t} \min\left(\Delta EC_{i,j}, 0\right) \quad (9)$$

where $POS_t$ and $NEG_t$ are the partial sums which capture the positive changes and negative changes respectively. Equation 2 is then transformed into the following asymmetry specification and estimated using PMG:

$$lnCO2_{i,t} = \beta_0 + \beta_1 lnY\_POS_{i,t} + \beta_2 lnY\_NEG_{i,t} + \beta_1 lnEC\_POS_{i,t} + \beta_3 lnEC\_NEG_{i,t} + \varepsilon_{i,t} \quad (10)$$

**Table 2** Westerlund panel cointegration test

| Statistic | Value | Z-value | p value | Robust p value |
|---|---|---|---|---|
| $G_t$ | − 2.069 | − 3.060 | 0.001 | 0.000 |
| $G_a$ | − 8.851 | − 1.452 | 0.073 | 0.000 |
| $P_t$ | − 19.263 | − 5.938 | 0.000 | 0.000 |
| $P_a$ | − 9.312 | − 6.961 | 0.000 | 0.000 |

## Empirical results and explanation

Table 1 tabulates the results of CSD and CIPS tests. The results reveal the existence of CSD in our panel data. It is shown by rejection of null hypothesis of cross-sectional independence for each variable. Thus, we proceed to the CIPS test by Pesaran (2007). The results shown in panel B Table 1 indicate that all variables become stationary after first order transformation. It is thus concluded that the variables are integrated at I(1).

Since our panel data suffer from CSD, the Westerlund (2007) panel cointegration test is preferred and used. From Table 2, the *p* values indicate the rejection of the null hypothesis of no cointegration between the variables. Hence, we can conclude that the variables are cointegrated in the long run.

Table 3 denotes the panel results from the CCEMG and AMG estimators. Accordingly, the results from AMG lend support to the EKC hypothesis while the results from CCEMG indicate the reverse. Y and Y squared from the AMG estimator

**Table 3** Results of CCEMG and AMG estimation

| Dependent: CO2 | CCEMG | AMG |
|---|---|---|
| Independent variable | Coefficient (test statistic) [*p* value] | Coefficient (test statistic) [*p* value] |
| Y | 2.491<br>(1.090)<br>[0.277] | 4.570**<br>(2.100)<br>[0.035] |
| Y2 | − 0.167<br>(− 1.140)<br>[0.253] | − 0.284**<br>(− 2.160)<br>[0.031] |
| EC | 1.004***<br>(10.570)<br>[0.000] | 0.852***<br>(10.18)<br>[0.000] |
| Constant | − 10.290<br>(− 0.750)<br>[0.451] | − 23.313**<br>(− 2.510)<br>[0.012] |
| Validity of EKC | No | Yes |

*,**, and *** indicate significance at 10%, 5%, and 1%, respectively

**Table 4** Results of PMG and asymmetric estimation

| Dependent: CO2 | PMG | Asymmetric |
|---|---|---|
| Independent variable | Coefficient (test statistic) [*p* value] | Coefficient (test statistic) [*p* value] |
| Panel A: long-run coefficient | | |
| Y | − 0.048*** (− 2.724) [0.007] | - |
| Y_POS | - | − 0.155*** (− 3.129) [0.002] |
| Y_NEG | - | 0.695*** (14.650) [0.000] |
| EC | 1.000*** (49.938) [0.000] | - |
| EC_POS | - | 1.393*** (20.139) [0.000] |
| EC_NEG | - | − 0.139* (− 1.871) [0.062] |
| Panel B: Short-run coefficient | | |
| ECT(-1) | − 0.206*** (− 7.507) [0.000] | − 0.117** (− 5.062) [0.000] |
| D(CO2(-1)) | - | − 0.153** (− 4.943) [0.000] |
| D(CO2(-2)) | - | − 0.124** (− 4.420) [0.000] |
| D(CO2(-3)) | - | 0.002 (0.105) [0.917] |
| D(CO2(-4)) | - | 0.019 (1.018) [0.309] |
| D(Y) | 0.249*** (3.857) [0.000] | - |
| D(Y(-1)) | 0.071 (1.030) [0.303] | - |
| D(Y(-2)) | 0.064 (0.848) [0.397] | - |
| D(Y(-3)) | 0.142* (1.864) [0.063] | - |
| D(Y_POS) | - | 0.203 (1.475) [0.141] |
| D(Y_POS(-1)) | - | 0.327** (2.435) [0.015] |
| D(Y_POS(-2)) | - | 0.175 (1.307) [0.192] |
| D(Y_NEG) | - | 0.261 (1.193) [0.233] |
| D(Y_NEG(-1)) | - | − 0.369 (− 1.470) [0.142] |
| D(Y_NEG(-2)) | - | 0.071 (0.283) [0.777] |
| D(EC) | 0.718*** (8.126) [0.000] | - |
| D(EC(-1)) | 0.071 (1.400) [0.162] | 4.570** (2.100) [0.035] |
| D(EC(-2)) | − 0.045*** (− 0.957) [0.339] | 4.570** (2.100) [0.035] |
| D(EC(-3)) | 0.017 (0.224) [0.823] | 4.570** (2.100) [0.035] |
| D(EC_POS) | - | 0.813*** (6.218) [0.000] |
| D(EC_POS(-1)) | - | 0.130 (0.979) [0.328] |
| D(EC_POS(-2)) | - | 0.012 (0.092) [0.927] |
| D(EC_NEG) | - | 1.040*** (4.128) [0.000] |
| D(EC_NEG(-1)) | - | 0.600** (2.477) [0.015] |
| D(EC_NEG(-2)) | - | 0.077 (0.458) [0.647] |
| Constant | − 1.201*** (− 7.771) [0.000] | − 0.092*** (− 2.985) [0.003] |

*,**, and *** indicate significance at 10%, 5%, and 1%, respectively

are significant and they are of correct sign as postulated in the EKC hypothesis. However, both estimators have consistent results for energy consumption. It plays a positive role in effecting $CO_2$ emissions as the direct combustion of fossil fuel contributes to higher $CO_2$ emissions. The coefficients from both estimators conclude that a 1% increase in energy consumption will lead to an increase in $CO_2$ emissions by 0.85–1%. This finding is also consistent with the studies of Alam et al. (2016) and Baek (2015).

**Table 5** Country-specific results of the CCEMG and AMG estimators

| Variable | Y | | $Y^2$ | | EC | | Validity of EKC | |
|---|---|---|---|---|---|---|---|---|
| Country | CCEMG | AMG | CCEMG | AMG | CCEMG | AMG | CCEMG | AMG |
| Algeria | 28.892 | 21.654* | − 1.816 | − 1.314* | − 0.151 | 0.378*** | No | Yes |
| | (1.580) | (1.670) | (− 1.550) | (− 1.660) | (− 0.480) | (2.800) | | |
| | [0.115] | [0.096] | [0.122] | [0.098] | [0.633] | [0.005] | | |
| Argentina | − 5.354 | − 11.569*** | 0.289 | 0.630*** | 1.747*** | 1.713*** | No | No |
| | (− 1.460) | (− 3.950) | (1.410) | (3.840) | (9.360) | (9.210) | | |
| | [0.143] | [− 0.000] | [0.157] | [0.000] | [0.000] | [0.000] | | |
| Australia | 13.606* | 19.741*** | − 0.613* | − 0.927*** | 1.130*** | 0.361 | Yes | Yes |
| | (1.920) | (3.630) | (− 1.810) | (− 3.770) | (6.160) | (1.380) | | |
| | [0.055] | [0.000] | [0.070] | [0.000] | [0.000] | [0.166] | | |
| Austria | 2.610 | − 6.456** | − 0.143 | 0.330** | 1.418*** | 1.046*** | No | No |
| | (0.390) | (− 2.160) | (− 0.430) | (2.140) | (8.590) | (5.320) | | |
| | [0.693] | [0.030] | [0.667] | [0.032] | [0.000] | [0.000] | | |
| Belgium | − 15.883 | − 6.603** | 0.779 | 0.329** | 1.041*** | 0.699*** | No | No |
| | (− 1.600) | (− 2.520) | (1.560) | (2.490) | (5.310) | (6.400) | | |
| | [0.110] | [0.012] | [0.119] | [0.013] | [0.000] | [0.000] | | |
| Benin | 0.166 | 0.709 | 0.165 | 0.168 | 1.614*** | 1.001** | No | No |
| | (0.000) | (0.001) | (0.040) | (0.070) | (3.350) | (2.520) | | |
| | [0.997] | [0.998] | [0.964] | [0.947] | [0.001] | [0.012] | | |
| Bolivia | − 36.351*** | 27.826*** | 2.585*** | − 1.822*** | 0.658*** | 0.143 | No | Yes |
| | (− 3.890) | (2.960) | (4.080) | (− 2.870) | (5.340) | (1.050) | | |
| | [0.000] | [0.003] | [0.000] | [0.004] | [0.000] | [0.293] | | |
| Brazil | 1.036 | 3.772 | − 0.069 | − 0.235 | 1.388*** | 1.632*** | No | No |
| | (0.240) | (1.170) | (− 0.270) | (− 1.240) | (3.970) | (4.770) | | |
| | [0.811] | [0.244] | [0.784] | [0.216] | [0.000] | [0.000] | | |
| Cameroon | − 28.476 | 19.431 | 2.010 | − 1.243 | 2.595 | 0.717 | No | No |
| | (− 0.800) | (0.570) | (0.810) | (− 0.530) | (1.230) | (0.670) | | |
| | [0.423] | [0.567] | [0.416] | [0.598] | [0.221] | [0.502] | | |
| Canada | − 9.141 | − 5.178** | 0.448 | 0.281** | 1.036*** | 0.306** | No | No |
| | (− 1.260) | (− 2.050) | (1.290) | (2.370) | (3.780 | (1.980) | | |
| | [0.207] | [0.041] | [0.197] | [0.018] | [0.000] | [0.048] | | |
| Chile | 1.597 | − 4.950*** | − 0.099 | 0.282*** | 1.419*** | 1.374*** | No | No |
| | (0.490) | (− 5.260) | (− 0.520) | (5.580) | (7.490) | (10.870) | | |
| | [0.625] | [0.000] | [0.602] | [0.000] | [0.000] | [0.000] | | |
| China | 1.195*** | 1.695*** | − 0.075*** | − 0.109*** | 1.344*** | 1.434*** | Yes | Yes |
| | (5.360) | (6.130) | (− 4.740) | (− 6.90) | (18.100) | (15.400) | | |
| | [0.000] | [0.000] | [0.000] | [0.000] | [0.000] | [0.000] | | |
| Colombia | 0.623 | 1.396 | 0.232 | − 0.033 | 0.368* | 0.913*** | No | No |
| | (0.120) | (0.490) | (0.080) | (− 0.200) | (1.670) | (5.450) | | |
| | [0.906] | [0.627] | [0.938] | [0.840] | [0.095] | [0.000] | | |
| Congo, Dem. Rep. | 17.700*** | 14.122*** | − 1.299*** | − 1.017*** | 0.575 | 0.755* | Yes | Yes |
| | (5.760) | (9.540) | (− 5.210) | (− 8.570) | (1.330) | (1.670) | | |
| | [0.000] | [0.000] | [0.000] | [0.000] | [0.183] | [0.095] | | |
| Congo, Rep. | 23.240 | 28.827 | − 1.344 | − 1.786 | 1.935*** | 0.841** | No | No |
| | (0.490) | (0.600) | (− 0.440) | (− 0.580) | (3.510) | (2.320) | | |
| | [0.624] | [0.551] | [0.660] | [0.565] | [0.000] | [0.020] | | |
| Costa Rica | 17.089** | 19.204*** | − 0.911** | − 1.070*** | 0.322* | 0.584*** | Yes | Yes |
| | (2.310) | (5.120) | (− 2.140) | (− 5.110) | (1.850) | (3.440) | | |
| | [0.021] | [0.000] | [0.033] | [0.000] | [0.064] | [0.001] | | |
| Cote d'Ivoire | 51.141*** | 49.024*** | − 3.407*** | − 3.225*** | 0.481 | 0.024 | No | Yes |
| | (3.590) | (4.020) | (− 3.570) | (− 3.940) | (1.160) | (0.100) | | |
| | [0.000] | [0.000] | [0.000] | [0.000] | [0.247] | [0.922] | | |
| Cuba | − 10.179** | − 8.677** | 0.639** | 0.542** | 0.325** | 0.754*** | No | No |
| | (− 2.480) | (− 2.180) | (2.550) | (2.280) | (1.990) | (4.410) | | |
| | [0.013] | [0.029] | [0.011] | [0.022] | [0.046] | [0.000] | | |
| Denmark | 0.919 | 19.116*** | − 0.002 | − 0.867*** | 1.356*** | 1.294*** | No | Yes |
| | (0.010) | (5.120) | (− 0.001) | (− 4.900) | (11.170) | (10.500) | | |
| | [0.994] | [0.000] | [0.997] | [0.000] | [0.000] | [0.000] | | |
| Dominican Republic | 6.454 | 4.067 | − 0.319 | − 0.291** | 0.227 | 1.052*** | No | No |
| | (1.560) | (1.470) | (− 1.250) | (− 1.810) | (0.950) | (5.940) | | |
| | [0.120] | [0.143] | [0.213] | [0.070] | [0.340] | [0.000] | | |

**Table 5** (continued)

| Variable | Y | | $Y^2$ | | EC | | Validity of EKC | |
|---|---|---|---|---|---|---|---|---|
| Country | CCEMG | AMG | CCEMG | AMG | CCEMG | AMG | CCEMG | AMG |
| Ecuador | 38.914** | 16.102 | − 2.398** | − 0.934 | 0.043 | 1.045*** | Yes | No |
| | (2.510) | (1.210) | (− 2.500) | (− 1.170) | (0.110) | (2.870) | | |
| | [0.012] | [0.226] | [0.012] | [0.242] | [0.913] | [0.004] | | |
| Egypt, Arab Rep. | 4.355* | − 0.387 | − 0.259 | 0.074 | 0.419*** | 0.463*** | No | No |
| | (1.850) | (− 0.290) | (− 1.580) | (0.770) | (2.600) | (3.240) | | |
| | [0.064] | [0.772] | [0.114] | [0.440] | [0.009] | [0.001] | | |
| El Salvador | 18.075 | 68.769*** | − 1.094 | − 4.322*** | − 0.104 | 0.066 | No | Yes |
| | (1.400) | (8.930) | (− 1.330) | (− 8.840) | (− 0.930) | (0.460 | | |
| | [0.162] | [0.000] | [0.184] | [0.000] | [0.351] | [0.646] | | |
| Finland | − 11.926** | − 10.570*** | 0.549** | 0.490*** | 2.154*** | 1.887*** | No | No |
| | (− 2.450) | (− 5.100) | (2.310) | (5.000) | (9.930) | (13.370) | | |
| | [0.014] | [0.000] | [0.021] | [0.000] | [0.000] | [0.000] | | |
| France | − 37.376** | − 24.178*** | 1.857** | 1.229*** | 1.396*** | − 0.304 | No | No |
| | (− 2.000) | (− 4.420) | (2.010) | (4.490) | (3.430) | (− 1.300) | | |
| | [0.045] | [0.000] | [0.045] | [0.000] | [0.001] | [0.193] | | |
| Gabon | 27.017*** | 39.688*** | − 1.403*** | − 2.072*** | 0.315*** | 0.311*** | Yes | Yes |
| | (3.680) | (6.580) | (− 3.600) | (− 6.440) | (2.770) | (5.190) | | |
| | [0.000] | [0.000] | [0.000] | [0.000] | [0.006] | [0.000] | | |
| Ghana | − 14.313** | − 1.967 | 1.037** | 0.177 | 0.432** | 0.147 | No | No |
| | (− 2.040) | (− 0.490) | (2.050) | (0.620) | (2.170) | (0.930) | | |
| | [0.042] | [0.622] | [0.040] | [0.537] | [0.030] | [0.352] | | |
| Greece | 0.191 | − 3.160 | − 0.010 | 0.140 | 1.240*** | 1.472*** | No | No |
| | (0.050) | (− 0.630) | (− 0.050) | (0.560) | (12.360) | (16.760) | | |
| | [0.962] | [0.531] | [0.962] | [0.574] | [0.000] | [0.000] | | |
| Guatemala | 12.456 | 66.845*** | − 0.718 | − 4.292*** | 0.710*** | 0.910*** | No | Yes |
| | (0.420) | (3.160) | (− 0.370) | (− 3.120) | (3.200) | (3.160) | | |
| | [0.674] | [0.002] | [0.708] | [0.002] | [0.001] | [0.002] | | |
| Honduras | 42.372** | 8.285 | − 2.864** | − 0.615 | 1.034*** | 1.849*** | Yes | No |
| | (2.450) | (0.370) | (− 2.440) | (− 0.410) | (3.800) | (3.630) | | |
| | [0.014] | [0.709] | [0.015] | [0.684] | [0.000] | [0.000] | | |
| Hong Kong SAR, China | 5.819*** | 4.489*** | − 0.293*** | − 0.218*** | 0.574*** | 0.518*** | Yes | Yes |
| | (3.960) | (3.190) | (− 3.950) | (− 2.810) | (6.070) | (4.830) | | |
| | [0.000] | [0.001] | [0.000] | [0.005] | [0.000] | [0.000] | | |
| Iceland | − 3.488 | 2.016 | 0.204 | − 0.066 | − 0.174 | − 0.453*** | No | No |
| | (− 0.520) | (0.740) | (0.630) | (− 0.480) | (− 1.290) | (− 4.700) | | |
| | [0.600] | [0.461] | [0.529] | [0.629] | [0.197] | [0.000] | | |
| India | 3.341*** | 3.700*** | − 0.276*** | − 0.310*** | 2.183*** | 2.345*** | Yes | Yes |
| | (4.230) | (4.670) | (− 4.630) | (− 5.530) | (12.790) | (10.620) | | |
| | [0.000] | [0.000] | [0.000] | [0.000] | [0.000] | [0.000] | | |
| Indonesia | − 1.652 | 3.164** | 0.122 | − 0.155 | 0.420 | 0.024 | No | No |
| | (− 0.510) | (2.280) | (0.580) | (− 1.620) | (0.950) | (0.100) | | |
| | [0.611] | [0.023] | [0.561] | [0.105] | [0.343] | [0.921] | | |
| Iran, Islamic Rep. | − 1.552 | − 2.218 | 0.126 | 0.167 | 0.021 | 0.024 | No | No |
| | (− 0.510) | (− 0.680) | (0.710) | (0.880) | (0.130) | (0.200) | | |
| | [0.611] | [0.497] | [0.478] | [0.377] | [0.894] | [0.838] | | |
| Iraq | − 2.718 | − 4.435 | 0.170 | 0.283 | 0.432*** | 0.211* | No | No |
| | (− 0.670) | (− 1.160) | (0.660) | (1.160) | (2.950) | (1.790) | | |
| | [0.504] | [0.245] | [0.512] | [0.244] | [0.003] | [0.073] | | |
| Ireland | − 1.347 | − 1.259 | 0.061 | 0.046 | 1.111*** | 1.415*** | No | No |
| | (− 1.160) | (− 1.050) | (1.110) | (0.860) | (13.360) | (11.680) | | |
| | [0.247] | [0.295] | [0.268] | [0.390] | [0.000] | [0.000] | | |
| Israel | − 6.537 | 21.432*** | 0.381 | − 1.028*** | 0.229** | 0.597*** | No | Yes |
| | (− 1.020) | (4.690) | (1.190) | (− 4.560) | (2.250) | (4.660) | | |
| | [0.309] | [0.000] | [0.235] | [0.000] | [0.024] | [0.000] | | |
| Italy | − 3.175 | − 9.246*** | 0.166 | 0.498*** | 1.266*** | 0.377*** | No | No |
| | (− 0.820) | (− 3.120) | (0.850) | (3.310) | (12.670) | (2.990) | | |
| | [0.415] | [0.002] | [0.394] | [0.001] | [0.000] | [0.003] | | |
| Jamaica | 22.808 | 26.446* | − 1.388 | − 1.612* | 1.122*** | 1.151*** | No | Yes |
| | (1.530) | (1.740) | (− 1.550) | (− 1.770) | (10.250) | (13.210) | | |
| | [0.127] | [0.082] | [0.120] | [0.076] | [0.000] | [0.000] | | |

**Table 5** (continued)

| Variable | Y | | $Y^2$ | | EC | | Validity of EKC | |
|---|---|---|---|---|---|---|---|---|
| Country | CCEMG | AMG | CCEMG | AMG | CCEMG | AMG | CCEMG | AMG |
| Japan | − 13.963*** | − 14.177*** | 0.686*** | 0.704*** | 0.616*** | 0.206** | No | No |
| | (− 4.380) | (− 6.370) | (4.420) | (6.340) | (3.150) | (2.500) | | |
| | [0.000] | [0.000] | [0.000] | [0.000] | [0.000] | [0.012] | | |
| Kenya | − 28.300 | − 39.236 | 2.101 | 2.884 | 0.877 | 1.422 | No | No |
| | (− 0.650) | (− 0.860) | (0.650) | (0.850) | (0.650) | (0.910) | | |
| | [0.518] | [0.392] | [0.517] | [0.397] | [0.518] | [0.362] | | |
| Korea, Rep. | 1.046*** | 2.151*** | − 0.051** | − 0.123*** | 0.784*** | 0.590*** | Yes | Yes |
| | (2.780) | (8.720) | (− 2.280) | (− 7.490) | (5.940) | (5.840) | | |
| | [0.005] | [0.000] | [0.023] | [0.000] | [0.000] | [0.000] | | |
| Luxembourg | − 0.917 | 5.900** | 0.053 | − 0.284*** | 1.264*** | 1.275*** | No | Yes |
| | (− 0.340) | (2.570) | (0.390) | (− 2.660) | (27.060) | (13.560) | | |
| | [0.732] | [0.010] | [0.693] | [0.008] | [0.000] | [0.000] | | |
| Malaysia | − 5.695*** | − 2.440* | 0.418*** | 0.200** | 0.245 | 0.659*** | No | No |
| | (− 2.970) | (− 1.730) | (3.770) | (2.380) | (1.380) | (3.120) | | |
| | [0.003] | [0.084] | [0.000] | [0.017] | [0.167] | [0.002] | | |
| Malta | − 0.125 | 0.884 | 0.009 | − 0.050 | 0.894*** | 0.975*** | No | No |
| | (− 0.110) | (0.950) | (0.140) | (− 0.910) | (15.800) | (27.350) | | |
| | [0.913] | [0.343] | [0.890] | [0.363] | [0.000] | [0.000] | | |
| Mexico | − 8.464 | − 27.017*** | 0.457 | 1.500*** | 1.390*** | 1.498*** | No | No |
| | (− 0.780) | (− 3.270) | (0.750) | (3.260) | (6.620) | (9.540) | | |
| | [0.437] | [0.001] | [0.451] | [0.001] | [0.000] | [0.000] | | |
| Morocco | − 1.182 | 3.649*** | 0.077 | − 0.229*** | 0.939*** | 0.648*** | No | Yes |
| | (− 0.610) | (3.420) | (0.610) | (− 3.430) | (4.640) | (4.710) | | |
| | [0.540] | [0.001] | [0.542] | [0.001] | [0.000] | [0.000] | | |
| Myanmar | 3.773*** | 3.913*** | − 0.264*** | − 0.284*** | 1.801*** | 1.795*** | Yes | Yes |
| | (3.580) | (4.230) | (− 2.980) | (− 3.930) | (4.170) | (4.420) | | |
| | [0.000] | [0.000] | [0.003] | [0.000] | [0.000] | [0.000] | | |
| Nepal | 3.372 | 3.735 | − 0.024 | − 0.180 | 2.758 | − 1.012 | No | No |
| | (0.160) | (0.290) | (− 0.010) | (− 0.170) | (1.500) | (− 0.530) | | |
| | [0.872] | [0.775] | [0.989] | [0.867] | [0.135] | [0.593] | | |
| Netherlands | − 5.847 | − 1.393 | 0.273 | 0.064 | 0.970*** | 0.837*** | No | No |
| | (− 0.900) | (− 0.600) | (0.880) | (0.590) | (8.170) | (8.070) | | |
| | [0.370] | [0.547] | [0.379] | [0.552] | [0.000] | [0.000] | | |
| Nicaragua | 0.362 | − 7.064 | 0.087 | 0.523 | − 0.675 | − 0.382 | No | No |
| | (0.070) | (− 1.230) | (0.250) | (1.330) | (− 1.460) | (− 0.680) | | |
| | [0944] | [0.217] | [0.806] | [0.183] | [0.146] | [0.497] | | |
| Nigeria | 43.122*** | 25.111 | − 2.950*** | − 1.649 | 5.114*** | 3.556*** | Yes | No |
| | (2.680) | (1.570) | (− 2.710) | (− 1.520) | (2.790) | (2.780) | | |
| | [0.007] | [0.118] | [0.007] | [0.127] | [0.002] | [0.005] | | |
| Norway | − 7.823 | 3.564 | 0.393 | − 0.206 | 1.473*** | 1.401*** | No | No |
| | (− 0.780) | (0.530) | (0.850) | (− 0.660) | (5.080) | (3.260) | | |
| | [0.437] | [0.599] | [0.397] | [0.511] | [0.000] | [0.001] | | |
| Oman | 41.205** | 23.658 | − 2.159** | − 1.282 | 0.421** | 0.077 | Yes | No |
| | (2.340) | (1.160) | (− 2.310) | (− 1.190) | (2.460) | (0.520) | | |
| | [0.019] | [0.246] | [0.021] | [0.235] | [0.014] | [0.602] | | |
| Pakistan | − 0.550 | 1.845 | 0.078 | − 0.048 | 1.272*** | 0.884*** | No | No |
| | (− 0.180) | (0.930) | (0.350) | (− 0.300) | (3.240) | (3.670) | | |
| | [0.855] | [0.352] | [0.724] | [0.760] | [0.001] | [0.000] | | |
| Panama | 6.562 | 5.698 | − 0.376 | − 0.315 | 0.902*** | 0.947*** | No | No |
| | (1.290) | (1.360) | (− 1.260) | (− 1.320) | (3.600) | (7.670) | | |
| | [0.196] | [0.173] | [0.208] | [0.186] | [0.000] | [0.000] | | |
| Paraguay | 0.705 | 5.970** | 0.049 | − 0.397** | 1.249*** | 1.532*** | No | Yes |
| | (0.200) | (2.540) | (− 0.210) | (− 2.550) | (4.850) | (9.120) | | |
| | [0.842] | [0.011] | [0.831] | [0.011] | [0.000] | [0.000] | | |
| Peru | − 2.246 | − 3.677 | 0.170 | 0.262 | 0.845*** | 0.469* | No | No |
| | (− 0.490) | (− 0.780) | (0.590) | (0.890) | (2.880) | (1.730) | | |
| | [0.625] | [0.433] | [0.553] | [0.372] | [0.004] | [0.083] | | |
| Philippines | − 22.860*** | − 10.870 | 1.620*** | 0.758 | 0.828*** | 1.232*** | No | No |
| | (− 3.820) | (− 1.210) | (3.990) | (1.260) | (3.620) | (3.760) | | |
| | [0.000] | [0.227] | [0.000] | [0.207] | [0.000] | [0.000] | | |

**Table 5** (continued)

| Variable | Y | | $Y^2$ | | EC | | Validity of EKC | |
|---|---|---|---|---|---|---|---|---|
| Country | CCEMG | AMG | CCEMG | AMG | CCEMG | AMG | CCEMG | AMG |
| Portugal | 9.932*** | 1.775 | −0.519*** | −0.089 | 1.255*** | 1.188*** | Yes | No |
| | (2.700) | (0.940) | (−2.640) | (−0.920) | (11.470) | (13.900) | | |
| | [0.007] | [0.347] | [0.008] | [0.357] | [0.000] | [0.000] | | |
| Saudi Arabia | −6.854 | −1.622 | 0.363 | 0.100 | 0.275** | 0.255*** | No | No |
| | (−0.870) | (−0.220) | (0.930) | (0.280) | (1.990) | (3.290) | | |
| | [0.384] | [0.823] | [0.354] | [0.780] | [0.046] | [0.001] | | |
| Senegal | 82.883 | 27.134 | −6.083 | −2.010 | −0.168 | 0.569 | No | No |
| | (1.240) | (0.340) | (−1.230) | (−0.340) | (−0.360) | (1.170) | | |
| | [0.217] | [0.736] | [0.217] | [0.734] | [0.718] | [0.243] | | |
| Singapore | 2.106 | 11.782*** | −0.088 | −0.632*** | 0.247 | 0.223 | No | Yes |
| | (0.430) | (3.430) | (−0.350) | (−3.090) | (0.710) | (1.000) | | |
| | [0.670] | [0.001] | [0.727] | [0.002] | [0.476] | [0.319] | | |
| South Africa | −1.165 | −8.600 | 0.062 | 0.487 | 1.245*** | 1.414*** | No | No |
| | (−0.100) | (−0.560) | (0.090) | (0.560) | (13.130) | (16.470) | | |
| | [0.922] | [0.572] | [0.927] | [0.575] | [0.000] | [0.000] | | |
| Spain | −21.261*** | −19.747*** | 1.045*** | 0.947*** | 1.783*** | 1.548*** | No | No |
| | (−6.220) | (−5.270) | (6.060) | (5.330) | (13.350) | (9.930) | | |
| | [0.000] | [0.000] | [0.000] | [0.000] | [0.000] | [0.000] | | |
| Sri Lanka | 3.230 | 2.172 | −0.163 | −0.109 | 2.052*** | 2.327*** | No | No |
| | (0.890) | (0.720) | (−0.710) | (−0.630) | (5.100) | (7.640) | | |
| | [0.374] | [0.474] | [0.478] | [0.529] | [0.000] | [0.000] | | |
| Sweden | −51.070*** | −54.929*** | 2.413*** | 2.593*** | 1.217*** | 1.076*** | No | No |
| | (−6.040) | (−8.280) | (5.990) | (8.410) | (6.440) | (5.950) | | |
| | [0.000] | [0.000] | [0.000] | [0.000] | [0.000] | [0.000] | | |
| Thailand | 0.949 | 3.998*** | −0.019 | −0.222*** | 0.479*** | 0.868*** | No | Yes |
| | (0.650) | (5.500) | (−0.200) | (−4.040) | (2.950) | (7.060) | | |
| | [0.518] | [0.000] | [0.843] | [0.000] | [0.003] | [0.000] | | |
| Togo | 5.019 | −6.349 | −0.409 | 0.575 | 2.018*** | 0.590 | No | No |
| | (0.170) | (−0.220) | (0.170) | (0.250) | (3.400) | (1.110) | | |
| | [0.865] | [0.827] | [0.862] | [0.804] | [0.001] | [0.269] | | |
| Trinidad and Tobago | −0.832 | −0.955 | 0.083 | 0.082 | 0.197 | 0.201 | No | No |
| | (−0.190) | (−0.210) | (0.340) | (0.340) | (0.920) | (0.960) | | |
| | [0.851] | [0.830] | [0.734] | [0.735] | [0.357] | [0.337] | | |
| Tunisia | 2.021 | 0.147 | −0.116 | −0.042 | 0.883*** | 1.575*** | No | No |
| | (0.820) | (0.050) | (−0.750) | (−0.240) | (3.820) | (5.090) | | |
| | [0.411] | [0.960] | [0.454] | [0.810] | [0.000] | [0.000] | | |
| Turkey | 2.923* | 7.378*** | −0.156* | −0.397*** | 1.082*** | 0.728*** | Yes | Yes |
| | (1.850) | (3.140) | (−1.840) | (−3.300) | (9.700) | (2.890) | | |
| | [0.064] | [0.002] | [0.066] | [0.001] | [0.000] | [0.004] | | |
| United Kingdom | −7.781* | 2.155 | 0.384* | −0.069 | 1.208*** | 0.203 | No | No |
| | (−1.760) | (0.990) | (1.760) | (−0.660) | (7.710) | (1.320) | | |
| | [0.078] | [0.325] | [0.079] | [0.509] | [0.000] | [0.186] | | |
| United States | −5.025** | −4.456*** | 0.245** | 0.256*** | 1.055*** | 0.217** | No | No |
| | (−2.450) | (−3.750) | (2.470) | (4.320) | (20.090) | (2.210) | | |
| | [0.014] | [0.000] | [0.013] | [0.000] | [0.000] | [0.027] | | |
| Uruguay | 19.816*** | 17.177*** | −1.135*** | −1.007*** | 1.846*** | 2.080*** | Yes | Yes |
| | (4..390) | (5.400) | (−4.560) | (−5.610) | (1.0950) | (14.000) | | |
| | [0.000] | [0.000] | [0.000] | [0.000] | [0.000] | [0.000] | | |

*,**, and *** indicate significance at 10%, 5%, and 1%, respectively

Although the results from CCEMG and AMG are inconsistent in supporting the EKC hypothesis, the results from the PMG are able to provide some insights to look at the EKC hypothesis from a different angle. First, the squared term of economic growth is excluded in the PMG estimation to avoid multicollinearity problem. Second, the EKC hypothesis is examined through the long-run and short-run coefficients of economic growth. From the results denoted in Table 4, the PMG estimation is in favour of the EKC hypothesis. This is shown by the significantly negative long-run coefficient of Y and opposite sign for its short-run coefficient, though not all short-run coefficients are significant. This indicates that short-run economic growth contributes to higher $CO_2$ emissions but the reverse holds in the long run. Overall, our findings support those by Apergis and Ozturk (2015) and Churchill et al. (2018).

To further enhance the analysis, we decompose economic growth and energy consumption into their positive and negative changes using partial sum approach to capture the asymmetry properties. To our best knowledge, the asymmetry approach is a relatively new attempt in this line of research. There are two notable findings from this asymmetry analysis. First, the EKC hypothesis is supported from a different perspective. This can be seen from the significance and sign of Y_POS and Y_NEG. When the growth is low, $CO_2$ emissions tend to increase. When there is a growth in the economy, $CO_2$ emissions fall. Second, reducing energy consumption helps in improving environmental degradation, particularly $CO_2$ emissions, as shown by the significance and sign of EC_POS and EC_NEG.

Table 5 provides country-specific results of the CCEMG and AMG estimators. A total of 16 out of 76 countries support the EKC hypothesis using CCEMG estimator while AMG indicates that 24 out of 76 countries are in favour of the EKC hypothesis. On top of this, it is worth to mention that 11 countries exhibit the inverted U-shaped curve regardless of whether CCEMG or AMG is used. The 11 countries are Australia, China, Congo, Costa Rica, Gabon, Hong Kong, India, Korea, Myanmar, Turkey, and Uruguay. For those countries with an inverted U-shaped EKC, it can be argued that much effort have been put in by the policy makers in ensuring high economic growth without retarding the environmental quality. Summarizing the findings, majority of the countries included in this study do not support the EKC hypothesis. The invalid EKC further indicates that these countries' commitment in environmental protection is still lacking. In other words, more emissions reduction initiatives are required to combat environmental degradation in these countries.

## Conclusion and policy recommendation

In this paper, we fill the literature gap by revisiting the EKC hypothesis using estimators that take CSD into account as limited studies have been focusing on the issue of CSD. Besides, we enhance our contribution by adding asymmetry analysis which is able to examine the EKC hypothesis in a different manner. Our findings lend moderate support to the EKC hypothesis. First, the panel results from the CCEMG and AMG are contradictory. The AMG estimator indicates the validity of the EKC hypothesis while CCEMG shows the opposite. The results from AMG are complemented by another estimator, namely PMG. Furthermore, the asymmetry analysis is able to support the EKC hypothesis. The country-specific results unfold that a total of 16 out of 76 countries support the EKC hypothesis using CCEMG estimator. Results from AMG indicate that EKC hypothesis is valid in 24 out of 76 countries. In addition, it is worth highlighting that 11 countries (Australia, China, Congo, Costa Rica, Gabon, Hong Kong, India, Korea, Myanmar, Turkey, and Uruguay) show an inverted U-shaped curve regardless of whether CCEMG or AMG is used.

Out of the 11 countries, Australia, Hong Kong, Korea, and Uruguay are classified as high-income countries. Therefore, it is possible that these countries have reached the turning point in the EKC hypothesis. This could be due the contribution and effect from a shift in paradigm and a change in the structure of the economy that lead to low carbon intensive industries, complemented with environmental awareness and regulation, technological advancement, and law and policy enforcement.

For developing countries that support the EKC hypothesis, the reason could be the recent trend and policy in developing alternative energy sources, such as renewable energy. China, for example, as one of the world's leading carbon emitters, recently emerges as a leading investor in renewable energy. As the largest hydroelectric power producer in the world, the country derived over 25% of its energy from hydroelectric power in 2015. Other renewable energy sources developed includes solar and wind power. In 2007, the country published its first National Action Plan on Climate Change which is the first in developing countries. Since then, the Chinese government continued with its effort by introducing the new National Plan on Climate Change 2014–2020 which outlines the achievement target of the country in terms of GHG emissions, climate change adaptability, and national emissions trading scheme. Despite these environmental plans, improvements in terms of legislation, adoption, and enforcement of policies are vital in all provinces and industries to sustain the declining trend in $CO_2$ emissions. Hence, future focus of the government should be on specific measures, enforcement of policies and regulations in accordance with its National Plan in combating climate change.

Similar to China, India has experienced a government-driven renewable energy generation paradigm. A significant move by the Indian government is the formation of the Ministry of New and Renewable Energy in 1992 which aims to develop and deploy new and renewable energy for supplementing the energy requirements of the country. This ministry successfully made significant impacts on the advancement of several renewable energies in India, such as solar, wind, and hydroelectric power. In line with the objective of the ministry, we recommend India to venture into other potential renewable energy sources such as geothermal. It is an energy that derived from the heat generated from the core of the earth. It has a significant potential for energy supply in the future since it is naturally replenished with unlimited supply, and hence with no risk of depleting.

In Turkey, the country still relies on coal as a primary energy source. The coal sector in Turkey is heavily subsidized to supply over one-third of the electricity in the country. Besides, the country has been facing deficit in its current account due to its large amount of import of oil and gas from Russia. As a result, the government has been putting in effort to reduce its reliance on fossil energy by including the environmental concern into its national plans. Specifically, concerns such as sustainable environment policies, strategies, and investment in renewable energy are outlined in its 10th Development Plan (2014–2018). To this end, we recommend Turkey to put in more efforts in promoting its renewable energy sector, for example hydroelectric, wind, and solar power to reduce the dependency of coal in electricity generation. Other countries that support the inverted U-shape curve in this study such as Costa Rica, Myanmar, Congo Dem. Rep., and Gabon also demonstrate significant development in renewable energy sources like hydroelectric, wind, and solar power.

Summarizing the above, the development of renewable energy sector could be an important factor in improving environmental degradation, particularly carbon emissions. Hence, the development of renewable energy sector should be given higher priority especially countries which do not support the EKC hypothesis. Besides, our findings also indicate that energy consumption derived from fossil fuel contributes to more $CO_2$ emissions. In this regard, policymakers should emphasize on reducing energy intensity and increasing energy efficiency. In other words, transformation towards green economy is the solution for reducing environmental degradation. In relation to this, we recommend that renewable energy such as wind and solar power to be one of the drivers for sustainable growth in the future, both in developed and developing countries.

As a conclusion, the findings from our study show that the EKC hypothesis does not fit all countries as only about a quarter of the countries investigated support the hypothesis. The robust results show that only four high-income countries support the EKC hypothesis. In addition, our results also indicate that some developing countries are in favour of the inverted U-shaped curve probably due to renewable energy development in these countries.

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