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RESEARCH ARTICLE

Renewable energy, carbon emissions, and economic growth in 24 Asian countries: evidence from panel cointegration analysis

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Abstract This article aims to investigate the relationship among renewable energy consumption, carbon dioxide (CO_2) emissions, and GDP using panel data for 24 Asian countries between 1990 and 2012. Panel cross-sectional dependence tests and unit root test, which considers cross-sectional dependence across countries, are used to ensure that the empirical results are correct. Using the panel cointegration model, the vector error correction model, and the Granger causality test, this paper finds that a long-run equilibrium exists among renewable energy consumption, carbon emission, and GDP. CO_2 emissions have a positive effect on renewable energy consumption in the Philippines, Pakistan, China, Iraq, Yemen, and Saudi Arabia. A 1% increase in GDP will increase renewable energy by 0.64%. Renewable energy is significantly determined by GDP in India, Sri Lanka, the Philippines, Thailand, Turkey, Malaysia, Jordan, United Arab Emirates, Saudi Arabia, and Mongolia. A unidirectional causality runs from GDP to CO_2 emissions, and two bidirectional causal relationships were found between CO_2 emissions and renewable energy consumption and between renewable energy consumption and GDP. The findings can assist governments in curbing pollution from air pollutants, execute energy conservation policy, and reduce unnecessary wastage of energy.

Keywords Renewable energy consumption · CO_2 emissions · Panel cointegration · Granger causality test · Panel cross-sectional dependence

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Introduction

Many scholars have indicated that traditional fossil fuels led to economic growth; however, such fossil fuels released carbon dioxide (CO_2) into the environment, thereby causing global warming and climate change. Reducing the risk of climate change requires all countries to adopt urgent action. Various governments considered the increased concern over issues related to energy security and carbon reduction policy and decided to encourage renewable energy use (i.e., wind, solar, geothermal, hydro, biomass, wave, and tidal). The further exploration of renewable energy as an alternative to fossil fuels has been emphasized. Kaya (1990) decomposed energy-related CO_2 emissions into four factors: (1) population, (2) gross domestic product (GDP) per capita, (3) energy intensity, and (4) carbon intensity.[1] From the viewpoint of Kaya, identifying renewable energy supply plays an important role in lowering CO_2 emissions. When renewable energy supply sources are effective, energy intensity and carbon intensity will decrease. The International Energy Agency (IEA) forecasts that renewables will remain the fastest-growing source of electricity generation over the next 5 years, with their share growing to 28% in 2021 from 23% in 2015. The IEA also reported that annual renewable electricity capacity growth reached an all-time record at 153 GW in 2015. The use of renewable energy is viewed as a solution to maintain energy

[1] The Kaya identity is as follows: $CO_2 = Population \times \frac{GDP}{Population} \times \frac{GDP}{Population} \times \frac{GDP}{Population}$.

consumption and at the same time solve the problem of CO_2 emissions.

This study aims to analyze the effect of renewable energy on CO_2 emissions and GDP in 24 Asian countries. Unlike most of the previous studies in this issue, this article employs panel cointegration and panel vector error correction econometric models to investigate the relationship among renewable energy, CO_2 emissions, and GDP. The 24 Asian countries were selected for our analysis because of several reasons. First, the existing studies mainly focused on developed countries: Apergis and Payne (2010a) focused on OECD countries, Bilgili and Ozturk (2015) and Tugcu et al. (2012) studied G7 countries, and Acaravci and Ozturk (2010) and Menegaki (2011) investigated European countries. However, evidence and studies that involve emerging countries or regions are relatively rare. The development and investment in renewable energy for these emerging economies are growing rapidly. For instance, the annual report of the Renewable Energy Network (2010) indicated that renewable energy investment has increased tremendously in emerging economies in recent years, especially in Brazil, China, India, Indonesia, the Philippines, and Turkey, which are major renewable energy investor countries; five of these six countries are located in Asia. Second, a major criticism related to these studies is that the empirical results are inconsistent for existing papers. The inconsistent conclusions were due to heterogeneous countries, time intervals, and econometric method. To address such problems, we consider cross-sectional dependence and heterogeneous panel method for our sample to investigate the relationship among renewable energy consumption, CO_2 emissions, and GDP.

Empirical findings of the causality among renewable energy consumption, CO_2 emissions, and GDP have also remained mixed and unclear. For instance, Apergis and Payne (2014) found a bidirectional relationship among these three variables in seven Central American countries. Sebri and Ben-Salha (2014) reported that the causality runs from CO_2 emissions to renewable energy consumption; the results were opposite those of most studies. Sadorsky (2009) indicated an absence of causality among the variables in the short run. The empirical results vary with different regions and countries, as well as econometric tools. Thus, the linkage among renewable energy, CO_2 emissions, and GDP for 24 Asian countries is worth investigating. This paper employs the cross-sectional dependence test proposed by Pesaran (2004) to verify the individual dependence between countries. The use of a relatively new panel unit root test that considers the cross-sectional dependence proposed by Pesaran (2007) determines the order of integration of the three variables. Then, the panel cointegration model, common correlated effects mean group (CCEMG) estimator, and Dumitrescu and Hurlin (2012) causality test are applied to verify their long-run relationships and causalities. Findings indicate that the renewable energy consumption, CO_2 emissions, and GDP have a long-run equilibrium relationship. CO_2 emissions have a positive effect on renewable energy consumption in the Philippines, Pakistan, China, Iraq, Yemen, and Saudi Arabia. A 1% increase in GDP will increase renewable energy by 0.64%. Renewable energy is significantly determined by GDP in India, Sri Lanka, the Philippines, Thailand, Turkey, Malaysia, Jordan, United Arab Emirates, Saudi Arabia, and Mongolia. The directions of causality are reported as follows: A bidirectional causal relationship was found between CO_2 emissions and renewable energy consumption. This result is consistent with Salim and Rafiq (2012) and Apergis and Payne (2014). Moreover, there is a bidirectional causal relationship between renewable energy consumption and GDP in our sample, and the feedback hypothesis thus holds. This is consistent with Apergis and Payne (2011), Salim and Rafiq (2012), Apergis and Payne (2010b), Apergis and Payne (2011), and Koçak and Şarkgüneşi (2017). The findings may assist governments in curbing pollution from subsidy renewable energy during the expansion of GDP. The results also indicate that unidirectional causality runs from GDP to CO_2 emissions, implying that an increase in economic growth increases the consumption of energy and then leads to increased CO_2 emissions. The findings may assist governments in curbing pollution from air pollutants, executing energy conservation policies, and reducing unnecessary wastage of energy. An energy policy may follow these steps: maintain the energy demand and stimulate economic growth, replace traditional energy sources with renewable energy after economic growth, and eliminate energy wastage and energy-intensive production technologies.

The rest of this paper is organized as follows: Section 2 briefly reviews the empirical literature. Section 3 discusses the econometric model and data. Section 4 provides empirical findings. Section 5 presents conclusions and discusses policy suggestions.

Literature review

Background of renewable energy, CO_2 emissions, and growth

The energy consumption, CO_2 emissions, and economic growth nexus has been widely studied. However, research on the link among renewable energy, CO_2 emissions, and GDP is still in its infancy. According to Adewuyi and Awodumi (2017), the research linkage among renewable energy, CO_2 emissions, and GDP was more intense from 2009 to 2016, especially in 2014. We can classify the energy growth studies into two stages. The literature in the first stage attempted to identify and estimate the nexus between consumption of energy varieties (electricity, total energy, primary energy, and nuclear consumption) and economic growth.

Omri (2014) surveyed the connection between those issues. These studies significantly contribute to the literature in three points. First, the countries and regions involved in the literature are chosen purposely. The major countries and regions that were investigated were China and American (including Central, Latin, and South American), European, OECD, and developing countries. The different countries/regions have distinct results because of the different extents of economic development or structure. Despite the different results for various countries or regions, the empirical conclusions can be used to form various policies. Second, renewable energy is highly related to and introduced in the CO_2–growth nexus. The panel data econometric methods, including dynamic panel data method, vector error correction model (VECM)–Granger causality, VAR model, ARDL model, and Toda–Yamamoto causality tests, are widely used. The relationship between energy and growth can be tested more correctly by using panel methods under a minimum limit than by using traditional regression analysis. Ozturk (2010) surveyed the existing literature on the nexus. The literature attempted to introduce the renewable energy consumption into the energy–growth nexus. Renewable energy consumption, GDP, and CO_2 emissions are significant to sustainable development. The role of renewable energy consumption was examined in most previous studies. Four testable hypotheses to explain the direction of the relationship between energy consumption and economic growth can be verified.[2] The goal of carbon reduction can also be gauged by estimating the relationship between renewable consumption and CO_2 emissions. However, findings of the various studies on the link among energy consumption, economic growth, and CO_2 emissions are mixed and inconsistent across countries and regions.

The role of renewable energy consumption has been examined in many previous studies. Four testable hypotheses to explain the direction of the relationship between renewable energy and growth can be explored as follows: (1) growth hypothesis: There is a unidirectional causal relationship from renewable energy consumption to economic growth (e.g., Bhattacharya et al. 2016; Koçak and Şarkgüneşi 2017). In such a situation, decreases in energy consumption cause decreases in economic growth. It implies that economies are energy dependent and need to develop clean energy as well as promote energy efficiency. (2) Conservation hypothesis: There is a unidirectional causal relationship from economic growth to energy consumption. When this hypothesis holds, it implies that energy growth is a factor that supports (renewable) energy consumption (Sadorsky 2009). (3) Feedback hypothesis: There is a bidirectional causal relationship between energy consumption and growth. According to this hypothesis, renewable energy consumption and economic growth affect each other (Koçak and Şarkgüneşi 2017; Al-mulali et al. 2013; Apergis and Payne 2011, Apergis and Payne 2010c, 2010d, 2014; Salim and Rafiq 2012). (4) Neutrality hypothesis: There is no causal relationship between energy consumption and economic growth. In this case, saving energy does not have any effect on economic growth (Payne 2009; Menegaki 2011; Ocal and Aslan 2013; Yildirim et al. 2012). As shown, findings across various studies on the links between renewable energy consumption, economic growth, and CO_2 emissions are mixed and inconsistent across countries and regions.

[2] The four hypotheses in the literature are growth, conservation, feedback, and neutrality hypotheses.

Literature review on renewable energy–CO_2 emissions–growth nexus in different regions

Sadorsky (2009) stated that the demand for renewable energy consumption in emerging economies is low but rapidly growing and confirmed the close link between renewable energy consumption and income in emerging countries. The foregoing empirical results are different for distinct regions. We summarize this as follows: (1) for Central American countries: Apergis and Payne (2014) reported a bidirectional relationship among those variables for seven Central American countries. That is the feedback hypothesis holds. (2) For OECD countries: Apergis and Payne (2010a) found that the feedback hypothesis holds in 20 OECD countries. (3) For six Latin American countries: Apergis and Payne (2011) found that the feedback hypothesis holds in six Latin American countries. Bidirectional causality can be found between renewable energy consumption and economic growth. (4) For G7 countries: Sadorsky (2009) found that unidirectional causality runs from economic growth and CO_2 emissions to renewable energy consumption. Furthermore, short-run causality is neutral among the three variables. (5) For Asian countries: Apergis and Payne (2010b) found that the feedback hypothesis is supported for 13 Asian countries. There is bidirectional causality between renewable energy consumption and economic growth. (6) For sub-Saharan African countries: Menegaki and Tugcu (2016) used a sustainable income index instead of GDP per capita and analyzed the energy–growth relationship for specific countries or groups of countries. The results of Menegaki and Tugcu (2016) indicated that the feedback hypothesis holds when the sustainable income index is utilized in place of GDP. However, they also found that if GDP is used as the indicator of income, the neutrality hypothesis is supported. Evidence from individual countries can be summarized as follows. Koçak and Şarkgüneşi (2017) found that unidirectional causality runs from economic growth to renewable energy consumption for Greece, Bulgaria, Ukraine, and Russia; bidirectional causality between GDP and renewable energy consumption was revealed for Albania, Georgia, and Romania; and, finally, the neutrality hypothesis held for Turkey. Salim and Rafiq (2012) revealed that, in the long run, renewable energy consumption is significantly determined by income and CO_2 emissions in China, Brazil, India, and Indonesia. Bidirectional causality exists between income and renewable energy and between renewable energy and CO_2 emissions. Apergis and Payne (2010b) found that the feedback hypothesis holds in Eurasia. The literature in this domain is summarized in Table 1.

Econometric specification and data source

Econometric model

Renewable energy is an environmentally friendly energy source unlike fossil energy. In the extant literature, there are two approaches to model the relationships between renewable energy, CO_2 emissions, and economic growth, namely the production function approach and demand for energy approach. This study is an example of the latter, focusing on the demand for renewable energy as affected by income and CO_2 emissions (social concerns over global warming). This paper includes the pollutant emission (CO_2 emissions) to investigate the renewable energy consumption–economic activity (GDP) relationship. There is an impressive amount of literature on the relationship between energy consumption and economic growth, but few studies focus on the renewable energy–economic activity–CO_2 emission relationship. The existing studies such as Sadorsky (2009), Apergis and Payne (2010), Zhao and Luo (2017), and Salim and Rafiq (2012) suggest that GDP and pollutant emissions are important determinants in the long run. Salim and Rafiq (2012) include oil price as a variable in their model, but the elasticity of oil price is insignificant, whereas causal links between renewable energy and income and between renewable energy and pollutant emissions can be found. Based on the suggestions of previous literature, the *econometric model is shown as follows:*

$$\mathrm{RE}_{it} = \alpha_1 + \alpha_2 \mathrm{CO}_{2it} + \alpha_3 \mathrm{GDP}_{i,t} + v_{it} \quad (1)$$

where $i = 1, 2, \ldots, N$ and $t = 1, 2, \ldots, T$ denote the country and time period, respectively. RE_{it}, CO_{2it}, and GDP_{it} represent the nature logarithms of renewable energy consumption per capita, CO_2 emissions per capita, and GDP per capita, respectively. α_1 is the constant, and v_{it} is the random error term. The expected sign on CO_2 emissions per capita is positive because a higher level of CO_2 emissions should result in greater investment in RE_{it}. The expected sign on GDP is positive

Table 1 Summary of literature on renewable energy consumption, GDP, and CO_2 emissions

Author(s)	Country/region	Period	Conclusion
Al-mulali et al. (2013)	High, upper middle lower middle low-income countries	Different periods	Feedback hypothesis is supported by most countries; the neutrality hypothesis applies in some countries.
Bhattacharya et al. (2016)	38 Countries	1991–2012	RE→GDP, the neutrality hypothesis exists in the short run
Apergis and Payne (2011)	20 Countries in OECD	1985–2005	RE ↔ GDP (feedback hypothesis is supported)
Apergis and Payne (2010b)	13 Asian countries	1992–2007	RE ↔ GDP (feedback hypothesis is supported)
Apergis and Payne (2011)	6 Latin American countries	1980–2006	RE ↔ GDP (feedback hypothesis is supported)
Koçak and Şarkgüneşi (2017)	10 Countries in the Black Sea and Balkan countries	1990–2012	RE→GDP: Greece, Bulgaria, Russia, and Ukraine RE↔GDP: Albania, Georgia, Romania. Neutrality hypothesis: Turkey
Payne (2009)	USA	1949–2006	Neutrality hypothesis is supported
Menegaki (2011)	27 European countries	1997–2007	Neutrality between Y and RE
Menegaki and Tugcu (2016)	42 Sub-Saharan African (SSA) countries	1985–2013	Neutrality hypothesis is supported between GDP and energy consumption, and feedback hypothesis is supported between index of sustainable economic welfare growth (ISEW) and energy consumption.
Ocal and Aslan (2013)	Turkey	1990–2010	Neutrality between Y and RE
Apergis and Payne (2014)	7 Central American countries	1980–2005	RE ↔ CO_2; RE ↔ GDP (feedback hypothesis is supported)
Sadorsky (2009)	G7 countries	1980–2005	CO_2→RE; GDP→RE (conservation hypothesis is supported)
Salim and Rafiq (2012)	6 Major emerging countries	1998–2006	Short run: CO_2↔RE ; GDP↔RE Long run: GDP or CO_2→RE: Brazil, China, India, Indonesia; GDP→RE: Turkey and the Philippines
Yildirim et al. (2012)	USA	1949–2010	Neutrality between Y and RE

RE renewable energy, *GDP* GDP per capita, *CO_2* CO_2 emissions, → unidirectional causality, ↔ bidirectional causality because a higher income level leads to a higher renewable investment. This study applies a panel econometric model to analyze the link between renewable energy, CO_2 emissions, and GDP. A panel data technique combines cross sections and time series data, contains reasonable observations, and has some advantages to overcome the problems of a small sample size. The empirical procedure started with the specification of the long-term relationships between renewable energy and economic activity and then tested for the existence of cross-sectional dependence, *cointegration*, and *causality.* To test the long-run equilibrium between variables, the cointegration test proposed by Westlund (2006) is employed, and the CCEMG estimator is applied to estimate the panel cointegration vectors. The panel-based VECM approach is adopted to test the long-run and short-run causality among cointegrated variables.

Panel cross-sectional dependence tests

Recent econometric research concluded that panel data models are likely to exhibit substantial cross-sectional dependence in the errors, which may arise because of common shocks, spatial dependence, and unobserved components. Phillips and Sul (2003) show that if sufficient cross-sectional dependence exists in the data and dependence is ignored in the estimation, then the estimator will be biased and inconsistent, especially when time periods are rather small and cross-sectional units or series are large. Pesaran (2004) provided the following statistic based on the LM statistic proposed by Breusch and Pagan (1980):

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

where $\hat{\rho}_{ij}$ is the sample estimate of the pairwise correlation of the residuals and is defined as follows:

$$\hat{\rho}_{ij} = \hat{\rho}_{ji} = \frac{\sum_{t=1}^{T}\hat{u}_{it}\hat{u}_{jt}}{\left(\sum_{t=1}^{T}\hat{u}_{it}\right)^{\frac{1}{2}}\left(\sum_{t=1}^{T}\hat{u}_{jt}\right)^{\frac{1}{2}}} \tag{3}$$

The null hypothesis is no cross-sectional dependence (i.e., $H_0 : \rho_{ij} = \mathrm{cor}(u_{it}, u_{jt}) = 0$ for $i \neq 0$). Under the null hypothesis of no cross-sectional dependence, $\mathrm{CD} \rightarrow^{d} N(0, 1)$ for $N \rightarrow \infty$ and T is sufficiently large.

Panel cross-sectional dependence and unit root test

Before the panel cointegration analysis, we have to identify the variables for the presence of a unit root. Econometric literature suggests that the panel-based unit root test has higher power than unit root tests based on individual time series. We use the unit root test of Im et al. (2003) to infer the degree of integration and stationarity properties of each variable. However, conventional panel unit root tests such as Im et al. (2003) have received criticism (Pesaran 2007; O'Connell 1998) for assuming cross-sectional independence. Following the results of previous econometric studies, unobservable common factors, common macroeconomic shocks, and spatial effects could lead to cross-sectional dependence. For instance, global business cycle movements will affect all countries. Pesaran (2007) argue that ignoring the existence of cross-sectional dependence in panel unit root tests will lead to considerable size distortions and misleading conclusions. In this paper, we apply the panel unit root test proposed by Pesaran (2007) to deal with cross-sectional dependence and compare the results with those obtained with the conventional panel data unit root test such as those by Im et al. (2003). The cross-sectional augmented version of the IPS test proposed by Pesaran (2007) is formed below

$$\Delta y_{i,t} = \alpha_i + \rho_i y_{i,t} + \delta_i \overline{y}_{t-1} + \sum_{j=0}^{k}\delta_{ij}\Delta\overline{y}_{i,t-j} + \sum_{j=0}^{k}\varphi_{ij}\Delta y_{i,t-j} + \epsilon_{i,t} \tag{4}$$

where $i = 1, 2, \ldots, N$ represents the cross-sectional member, $t = 1, 2, \ldots T$ refers to the time period, $y \in \{RE_{it}, GDP_{it}, CO_{2it}\}$. $\overline{y}_{t-1} = \frac{1}{N}\sum_{i=1}^{N} y_{i,t-1}$ and $\Delta\overline{y}_t = \frac{1}{N}\sum_{i=1}^{N}\Delta y_{i,t}$. Pesaran (2007) proposed a cross-sectional augmented version of the IPS test as follows:

$$CIPS = \frac{1}{N}\sum_{i=1}^{N} CADF_i \tag{5}$$

where CADF_i is the cross-sectionally augmented Dickey–Fuller statistic for the ith cross-sectional unit given by the t ratio of ρ_i in Eq. (4).

Cointegration methodology

To investigate the long-run relationship among the series in this study, we apply a relatively new cointegration test proposed by Westerlund (2007). The advantage of this new cointegration test is that it is free from common factor restriction and handles the problems of cross-sectional dependence by bootstrapping the critical values of the test statistics. Westerlund (2007) designed four tests to test the cointegration between variables. To address the issues we aim to solve, the relation among renewable energy consumption ($\mathrm{RE}_{i,t}$), CO_2 emissions ($\mathrm{CO}_{2i,t}$), and economic growth ($\mathrm{GDP}_{i,t}$) is shown below

$$\mathrm{RE}_{i,t} = \mu_i + \alpha_{1i}\mathrm{CO}_{2i,t} + \alpha_{2i}\mathrm{GDP}_{i,t} + \varepsilon_{i,t} \tag{6}$$

On the basis of Eq. (3), the error correction model (ECM) can be presented as follows:

$$\Delta RE_{i,t} = \delta_i^{'} d_t + \alpha_i \left(RE_{i,t-1} - \beta_{1i} CO_{2i,t-1} - \beta_{2i} GDP_{i,t-1} \right) \quad (7)$$
$$+ \sum_{j=1}^{p_i} \varphi_{ij} \Delta RE_{i.t-j} + \sum_{j=1}^{p_i} \theta_{ij} \Delta CO_{2i.t-j}$$
$$+ \sum_{j=-q_i}^{p_i} \gamma_{ij} \Delta GDP_{i,t-j} + e_{i,t}$$

where $d_t = (1, t)^{'}$, the parameter α_i determines the speed at which the system returns to the equilibrium relation $RE_{i,t-1} - \beta_{1i}CO_{2i,t-1} - \beta_{2i}GDP_{i,t-1}$ after a sudden shock. If $\alpha_i < 0$, then error correction takes place, which implies that $RE_{i,t}$, $CO_{2i,t}$, and $GDP_{i,t}$ are cointegrated; if $\alpha_i = 0$, then no error correction takes place. We can depict the null hypothesis of no cointegration as $H_0 : \alpha_i = 0$ for all i. The alternative hypothesis depends on what is being assumed about the homogeneity of α_i. According to Westerlund (2006) and Persyn and Westerlund (2008), group mean tests, which do not require the α_i s to be equal, imply that H_0 is tested versus $H_1^g : \alpha_i < 0$ for at least one i. The group mean tests can be computed as follows:

$$D_\tau = \frac{1}{N} \sum_{i=1}^{N} \frac{\hat{\alpha_i}}{SE(\hat{\alpha}_i)} \quad (8)$$

$$D_\alpha = \frac{1}{N} \sum_{i=1}^{N} \frac{T\hat{\alpha_i}}{\hat{\alpha}_i^{*})} \quad (9)$$

The other pair of tests of Westerlund [22] and Persyn and Westerlund [35] is called panel tests. These tests assume that α_i is equal for all i and are designed to test H_0 versus $H_1^p : \alpha_i = \alpha < 0$ for all i. The panel statistics are as follows:

$$P_\tau = \frac{\hat{\alpha}}{SE(\hat{\alpha_i})} \quad (10)$$

$$P_\alpha = T\hat{\alpha} \quad (11)$$

The two tests are designed to examine the alternative hypothesis that the panel is cointegrated as a whole, while the other two tests examine the alternative that at least one unit is cointegrated.

Panel Granger causality tests

After examining the existence of cointegration, the direction of causality relationship between the variables needs to be determined. Therefore, we test the Granger causality among renewable energy consumption, CO_2 emissions, and economic growth.

In this paper, I apply the panel causality test introduced by Dumitrescu and Hurlin (2012). The panel data model is considered as follows:

$$y_{i,t} = \alpha_i + \sum_{k=0}^{K} \gamma_i^{(k)} y_{i,t-k} + \sum_{k=1}^{K} \beta_i^{(k)} x_{i,t-k} + \epsilon_{i,t}$$

where K denotes the lag length, x and y represent each variable under consideration variables observed for N individuals in T periods in our model, α_i are fixed individual effects, $\gamma_i^{(k)}$ denotes autoregressive parameters, and $\beta_i^{(k)}$ are regression coefficients varied across countries. The homogeneous non-causality hypothesis and its null are defined as

$$H_0 : \beta_i = 0, \forall i = 1, \ldots, N \, with \, \beta_i = \left(\beta_i^1, \beta_i^2 \ldots \beta_i^{(k)} \right) \; H_1 : \beta_i \neq 0, \forall i = 1, \ldots, N \; \beta_i = 0, \forall i = N_1 + 1, N_1 + 2 \ldots, N$$

Dumitrescu and Hurlin (2012) proposed the average statistic $W_{NT}^{HNC} = \frac{1}{N} \sum_{i=1}^{N} W_{i,t}$, $W_{i,t}$ is individual Wald statistical values for the each country. Under the null hypothesis of non-causality, each individual Wald statistic converges to a chi-squared distribution. The average statistic (W_{NT}^{HNC}) has an asymptotic distribution associated with the null hypothesis. The standardized test statistic Z_{NT}^{HNC} for $T, N \rightarrow \infty$ is as follows:

$$Z_{NT}^{HNC} = \sqrt{\frac{N}{2K}} \left(W_{NT}^{HNC} - K \right) \rightarrow N(0,1)$$

For fixed T samples, the standardized test statistic Z_{NT}^{HNC} is as follows:

$$Z_{NT}^{HNC} = \sqrt{\frac{N}{2K} \times \frac{T-2K-5}{T-K-3}} \times \left[\frac{T-2K-3}{T-2K-1} W_{NT}^{HNC} - K \right] \rightarrow N(0,1)$$

Data sources and description

This study uses annual time series data for 24 Asian countries, namely, Japan, Singapore, Bangladesh, South Korea, Lebanon, India, Sri Lanka, Israel, the Philippines, Vietnam, Nepal, Pakistan, China, Thailand, Indonesia, Turkey, Malaysia, Jordan, Iraq, Yemen, the United Arab Emirates, Saudi Arabia, Mongolia, and Hong Kong. Annual data for real GDP per capita, CO_2 emissions per capita, and renewable energy consumption per capita, except those for Hong Kong, were obtained from the World Development Indicators. Annual data for CO_2 emissions per capita in Hong Kong were obtained from the Environmental Protection Department in the Government of Hong Kong Special Administrative Region.[3] Output (GDP) is measured using GDP per capita (constant 2010 US$), while CO_2 emissions per capita (CO_2) is expressed in million tons

[3] The website is http://www.epd.gov.hk/epd/english/top.html

carbon dioxide equivalent ($MtCO_2e$). Renewable energy use (RE) is expressed in kilograms of oil equivalent per capita. The period studied is dependent on the availability of data; thus, the time period we use is 1990–2012. All variables are transformed using natural logarithms to reduce heteroscedasticity. All data used and analyzed are on a per capita basis herein. Natural logarithmic variables have mechanistic value in economics because they approximate elasticities or growth of the respective differenced variables. The descriptive statistics are reported in Table 2.

Empirical results

Results of cross-sectional dependence test

To test the hypothesis of cross-sectional dependence, we use Pesaran's (2004) CD test. As the result illustrated, the statistic of the CD test is 7.40, and the CD test strongly rejects the null hypothesis of no cross-sectional dependence. To avoid the possible pitfall of the CD test, we also compute the average absolute value of the off-diagonal elements of the cross-sectional correlation matrix of residuals. Here, the average absolute correlation is 0.47, which reaches a very high value. Thus, enough evidence suggests the presence of cross-sectional dependence for our sample of 24 Asian countries.

Results of panel unit roots

Given the existence of the cross-sectional correlation, the panel unit root tests proposed by Pesaran (2007) should be executed to verify the order of integration of the series, whereas the traditional IPS test viewed as the benchmark. According to results of Table 3, we confirm all variables are $I(1)$ through the IPS test for balanced 28 Asian countries. To consider the time series properties of cross-sectional dependence between those countries, we also explore the Pesaran (2006) panel unit root test with cross-sectional dependence to check for the order of integration of the series. No matter what unit root test is selected, renewable energy consumption, CO_2 emissions, and GDP are all $I(1)$.

Table 2 Descriptive statistics

Variables	Mean	Standard deviation	Minimum	Maximum
RE	4.75	1.31	0	7.08
CO_2	0.41	0.59	− 1.47	1.56
GDP	3.63	0.63	2.55	4.84

Table 3 Panel unit root test results

Variables	IPS test Statistic	CIPS test Statistic
RE_{it}	−0.57	−1.35
CO_{2it}	−1.44	−1.80
GDP_{it}	−0.09	−2.10
ΔRE_{it}	-4.19^{***}	-3.82^{***}
ΔCO_{2it}	-4.72^{***}	-4.50^{***}
ΔGDP_{it}	-4.01^{***}	-3.89^{***}

**Significant at 1% level

Results of panel cointegration tests

For all variables, both IPS and CIPS tests support non-stationarity at a 5% level of significance. Next, we examine whether renewable energy consumption, CO_2 emissions, and economic growth are cointegrated. This study applies a relatively new and robust cointegration test proposed by Westerlund (2007) to verify their long-run relationships. We execute cointegration tests with a constant and a trend. The lag terms were selected based on the minimum AIC. Table 4 presents the results of the four cointegration tests. We reject the null hypothesis of no cointegration at the 1% statistical significance. Thus, a strong link appears to exist among renewable energy consumption, CO_2 emissions, and economic growth.

Regarding the CCEMG results shown in Table 5, estimates of CO_2 emissions range from − 2.22 to 1.75. The panel CCEMG test results indicate that CO_2 emissions have a negative but insignificant effect on renewable energy consumption in our sample. For individual CCEMG estimates, results from 6 of the 24 economies suggest that CO_2 emissions have a positive and significant effect on renewable energy consumption; these six countries are the Philippines, Pakistan, China, Iraq, Yemen, and Saudi Arabia. For seven countries—Bangladesh, Lebanon, India, Sri Lanka, Vietnam, Indonesia, and Turkey—CO_2 emissions have a positive but insignificant effect on renewable energy consumption However, the results in some countries suggest that CO_2 emissions have a negative impact on renewable energy consumption, which implies that those countries do not endeavor to develop renewable energy strategies because the

Table 4 Panel cointegration test results

	Westerlund panel cointegration test	
	Statistic	p values
D_τ	-2.93^{***}	0.007
D_α	−5.11	0.000
P_τ	-87.13^{***}	0.000
P_α	-24.43^{***}	0.000

***Significant at 1% level

Table 5 CCEMG estimation results

Country	$lnCO_2$		lnGDP	
	Coefficient	*t* statistic	Coefficient	*t* statistic
Japan	−0.97*	−1.73	1.96	1.59
Singapore	−0.65***	−2.88	−0.39	−0.29
Bangladesh	0.05	0.50	0.16	1.07
South Korea	−2.22***	−2.68	−0.50	−0.49
Lebanon	0.21	0.71	0.63	1.45
India	0.00	0.05	0.33***	7.89
Sri Lanka	0.04	0.59	0.99***	3.14
Israel	−0.11	−0.31	−0.77	−0.77
Philippines	0.20*	1.81	0.70***	3.77
Vietnam	0.07	0.65	0.16	0.45
Nepal	−0.03	−0.52	0.37	0.57
Pakistan	0.29***	2.56	−0.13	−0.61
China	0.23***	4.88	0.04	0.31
Thailand	−1.20***	−7.04	1.50***	4.54
Indonesia	0.01	−0.04	−0.22***	−3.16
Turkey	0.03	0.07	0.94**	2.03
Malaysia	−0.25	−1.06	0.95*	1.82
Jordan	−1.62***	−5.50	1.06*	1.74
Iraq	1.75*	1.84	−0.21	−0.44
Yemen	0.20**	2.18	−0.73***	−4.11
United Arab Emirates	−1.02**	−0.94	5.63***	3.05
Saudi Arabia	0.90*	1.89	1.75*	1.71
Mongolia	−0.68***	−2.79	1.47*	1.92
Hong Kong	−0.13	−0.37	1.10	1.23

"***" and "**" are significant at 1 and 5% level., respectively. "***," "**," and "*" mean that the null hypotheses for the series are rejected at the 1, 5, and 10% level, respectively

Table 6 Panel causality test results

	W^{HNC}	Z_{NT}^{HNC}
CO_2→RE	4.99**	1.96**
RE→CO_2	5.18**	2.22**
GDP→RE	6.11***	3.48***
RE→GDP	5.66***	2.87***
GDP→CO_2	6.45**	3.93**
CO_2→GDP	4.39	1.15

"***," "**," and "*" mean that the null hypotheses for the series are rejected at the 1, 5, and 10% level, respectively

investment costs are too high, and the government does not encourage economies to adopt clean, renewable energy technologies.

As expected, the coefficient of GDP in most of the countries is positive, varying between 5.63 and − 0.77. The panel CCEMG estimate for GDP is 0.64 across the 24 countries, which means that a 1% increase in GDP in the 24 economies on average leads to a 0.64% increase in renewable energy consumption. To elaborate, the coefficient of GDP is positive and significant in 10 of 24 countries, namely, India, Sri Lanka, the Philippines, Thailand, Turkey, Malaysia, Jordan, United Arab Emirates, Saudi Arabia, and Mongolia. The coefficient of GDP is positive and insignificant in 7 of 24 countries, namely, Japan, Bangladesh, Lebanon, Vietnam, Nepal, China, and Hong Kong. The results in some countries suggest that GDP has a negative impact on renewable energy consumption, which implies that those countries rely on non-renewable energy, with a lower propensity to design and enact energy conservation policies or renewable energy policies.

Results of panel causality tests

The directions of causality are reported in Table 6. A bidirectional causal relationship was found between CO_2 emissions and renewable energy consumption. This result is consistent with Salim and Rafiq (2012) and Apergis and Payne (2014). Moreover, there is a bidirectional causal relationship between renewable energy consumption and GDP in our sample, and the feedback hypothesis thus holds. This is consistent with Apergis and Payne (2011), Salim and Rafiq (2012), Apergis and Payne (2010b), Apergis and Payne (2011), and Koçak and Şarkgüneşi (2017). The results in Table 2 also indicate that unidirectional causality runs from GDP to CO_2 emissions, implying that an increase in economic growth increases the consumption of energy and then leads to increased CO_2 emissions.

Conclusions

The Asian region is growing in importance in the world, and it should not be judged purely not only in terms of its rapid economic growth but also in terms of the spin-off of its economic benefits to the rest of the world. The environment and social consequences of its economic growth must be considered, including the sustainability of its growth. The various governments in the Asian region ask whether they should follow the Western pattern of economic development, which focuses on economic growth first and environment cleanup later. The rise in renewable investments in the Asian region (especially in India and China) and the fall in renewable generation costs show that the answer to this question is probably no. Policymakers should pursue an environmentally friendly development path and increase energy efficiency. This paper studies the relationship among renewable energy consumption, CO_2 emissions, and GDP in 24 Asian countries by applying panel cointegration method and ECMs from 1980 to 2012. The findings are as follows: The results from Pesaran's (2004) cross-sectional dependence test suggest the presence of cross-sectional dependence for our sample of 24 Asian countries. The CIPS test proposed by Pesaran (2007) considered the cross-sectional dependence and found that all variables are integrated by an order of one. Westerlund's (2007) cointegration tests indicate a long-run equilibrium relationship among renewable energy consumption, CO_2 emissions, and GDP. A 1% increase in GDP increases the renewable energy consumption by 0.66%. However, an increase in CO_2 emissions does not stimulate renewable energy growth. Renewable energy investment and installation rises with the increase in GDP. Asian countries need to promote economic growth and then seek alternative energy sources to reduce CO_2 emissions.

The findings from the CCEMG estimator for individual countries show that CO_2 emissions have a positive effect on renewable energy consumption in Bangladesh, India, Sri Lanka, the Philippines, Pakistan, China, Iraq, Yemen, and Saudi Arabia. These results can be a key solution in reducing pollution. Moreover, with respect to individual countries in terms of the link between renewable energy consumption and GDP, the estimates by the CCEMG estimator reveal that GDP has a positive effect on renewable energy consumption in India, Sri Lanka, the Philippines, Thailand, Turkey, Malaysia, Jordan, United Arab Emirates, Saudi Arabia, and Mongolia. These results indicate that income is an important factor that determines renewable energy use.

Finally, a bidirectional causal relationship was found between CO_2 emissions and renewable energy consumption. This result is consistent with Salim and Rafiq (2012) and Apergis and Payne (2014). Moreover, there is a bidirectional causal relationship between renewable energy consumption and GDP in our sample, and the feedback hypothesis thus holds. The results show that the increasing effect of GDP rises renewable energy consumption. The results also indicate that unidirectional causality runs from GDP to CO_2 emissions, implying that an increase in economic growth increases the consumption of energy and then leads to increased CO_2 emissions. The long-run causal relationship implies that renewable energy consumption, CO_2 emissions, and GDP comoved together. This nexus poses important challenges to the policymakers of the Asian countries that were studied. Policymakers need to be aware that energy policy in the short run needs to replace fossil energy sources with renewable energy sources and promote energy efficiency. However, those three variables are cointegrated, thereby implying that renewable energy, CO_2 emissions, and GDP are jointly determined and affected at the same time. The long-run result is similar to the findings of Apergis and Payne (2009), Ang (2008), and Pao and Tsai (2010). To maintain high growth rate and environment growth, Asian countries have to execute energy conservation policies, reduce unnecessary wastage of energy, and improve energy efficiency. A limitation of this research is the lack of detailed information garnered because of employing a restricted set of variables. This study only investigates the impact of GDP and carbon dioxide emissions on renewable energy demand. Future research could explore additional variables (such as government subsidies for renewable energy) to capture country level demand for renewable energy consumption and isolate national policy recommendations.

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