Energy Reports 6 (2020) 965–973

Contents lists available at ScienceDirect

Energy Reports

journal homepage: www.elsevier.com/locate/egyr

Research paper

Dynamic linkage between renewable and conventional energy use, environmental quality and economic growth: Evidence from Emerging Market and Developing Economies[☆]

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ARTICLE INFO

Article history:
Received 10 September 2019
Received in revised form 2 April 2020
Accepted 12 April 2020
Available online 21 April 2020

JEL classification:
C23
Q40
Q55
Q56

Keywords:
Economic growth
Renewable energy usage
Environmental quality
Conventional energy use
Sustainable development

ABSTRACT

The role of renewable and fossil fuel energy consumption on environmental sustainability remains inconclusive due to varied economic and technological structure. This study provides new insight by assessing the nexus between the utilization of two energy categories — renewable and conventional, environmental quality and economic growth embodying capital, trade openness and government expenditure. A panel data of 45 Emerging Market and Developing Economies (EMDEs) from 1990 to 2014 was employed in the study. We applied heterogeneous panel data approach and second-generational econometric techniques that permit cross-sectional dependence and slope heterogeneity. The evaluation of long-term effects conducted by AMG, along with CCEMG and MG estimators revealed that besides other factors such as government expenditure, capital, and trade openness, non-renewable and renewable energy utilization significantly contributes to the economic growth of the selected EMDEs. The study acknowledges the trade-off effect between environmental quality and economic growth. Using Dumitrescu and Hurlin test, we found strong evidence to support the feedback hypotheses among renewable energy, consumption of conventional fuels, economic growth and CO_2 emissions. From a policy perspective, the empirical findings recommend the implementation of effective policies that promote green power and economic structural adjustment in order to diminish the level of atmospheric CO_2 emissions.

1. Introduction

The world economy almost doubled from 37.224 trillion US$ (constant 2010 US$) in 1990 to 72.247 trillion US$ in 2014 (World Bank, 2018). This rapid growth necessitates the utilization of more energy and thus, hampers environmental sustainability (Sarkodie, 2018; Phong et al., 2018; Phong, 2019). The global energy consumption increased around 58.9% in the period 1990–2014 while the fossil fuel-based CO_2 emissions rose nearly 1.5 times in the period 1995–2014 (BP, 2018). According to the World Bank (2015) report, more than 60% of global CO_2 emissions resulted from primary energy consumption, which stimulated anthropogenic greenhouse gas emissions. The transition of energy consumption structure from nonrenewable energy (also referred to as "conventional energy", "conventional power" and "conventional fuels" in Srirangan et al. (2012) and Ellabban et al. (2014)) to clean and renewable energy is not only useful to reducing CO_2 emissions (Dong et al., 2017; Goh and Ang, 2018) but deemed a contributing factor that sustainably improves the economy (Bhattacharya et al., 2017). Toward sustainable development, insights into each type of power utilization-economic growth nexus are helpful for policy-makers and related parties to design and implement effective environmental and energy policies.

The aftermath of the linkage between power utilization and the growth of the US's economy explored by Kraft and Kraft (1978), some 41 years ago, has become topical, essential and most famous subject in the energy economics discipline. The subject is reigning over the past few decades partly because its findings remain inconclusive and controversial (Ozturk, 2010; Shahbaz et al., 2017, 2018; Bekun et al., 2019b). The reciprocal roles played by both energy consumption and economic growth are summarized by "feedback", "growth", "conservation", and

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[☆] This study has received funding from the European Union's Horizon 2020 research and innovation programme under Marie Skłodowska-Curie grant agreement No. 734712, University of Economics Ho Chi Minh City Vietnam & Ho Chi Minh City University of Law Vietnam for this research.

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https://doi.org/10.1016/j.egyr.2020.04.020

"neutrality" hypotheses (Ozturk, 2010; Kahia et al., 2017; Bekun et al., 2019b; Sarkodie et al., 2019a). The first hypothesis posits that the level of power consumed can affect the potential of growth in an economy and vice versa (Payne, 2010; Shahbaz et al., 2018; Zafar et al., 2019). Meanwhile, the second hypothesis relates to the energy-led growth assumption, which posits that the growth of an economy is induced by the upturn of power usage (Ozturk et al., 2010; Kumar et al., 2015; Mbarek et al., 2018). As opposed to the second hypothesis, the conservation type argues that higher income level boosts energy usage (Narayan et al., 2010; Rasoulinezhad and Saboori, 2018). Lastly, the neutrality hypothesis negates the impacts that the two aforementioned factors have on each other (Payne, 2009; Destek, 2016).

Most of the available literature examined aggregated energy consumption, however, recent studies examine disaggregate energy consumption — renewable and conventional and its impact on economic growth (Kahia et al., 2017; Bekun et al., 2019a; Zafar et al., 2019). For example, Kahia et al. (2017) disclosed that higher amount of renewable and conventional energy utilization was connected with the growth of GDP in 11 nations from 1980 to 2012 — which affirmed the feedback hypothesis. Bekun et al. (2019a) investigated the long-term interaction and causation among conventional and renewable forms of energy, CO_2 emissions and GDP growth by incorporating natural resources rent. In a balanced panel of 16 EU nations from 1996 to 2014, the study validated the feedback mechanism. Zafar et al. (2019) included trade openness, capital, and R&D expenditures to analyze the influence of conventional and renewable power usage in APEC's economy from 1990–2015. The findings supported the feedback hypothesis.

Some relevant variables have been embodied in the energy-growth literature such as energy consumption (Shahbaz, 2012; Kumar et al., 2014), conventional and renewable energy (Kahia et al., 2017; Akadiri et al., 2019; Zafar et al., 2019), CO_2 emissions (Bekun et al., 2019a; Gorus and Aydin, 2019; Ummalla and Samal, 2019), government expenditure (Khadan, 2016; Fang and Chen, 2017; Adebumiti and Masih, 2018; Matthew et al., 2019), trade (Shahbaz et al., 2013; Kumar et al., 2015; Amri, 2017) and capital, labor and other pertinent factors (Huang et al., 2008; Shahbaz et al., 2012; Omri, 2013). Recently, several papers have inspected the relationship between pollution, economic growth and the utilization of energy in single or cross-country (Asumadu-Sarkodie and Owusu, 2016a,b,c, 2017a,b; Bekun et al., 2019a,b; Sarkodie and Strezov, 2019b).

Consequently, in order to orient sustainable energy policies for sustainable development, this article empirically scrutinizes the relationship between the utilization of energy, the amount of CO_2 emitted and growth of Emerging Market and Developing Economies (EMDEs). Based on the extant literature, this study follows four main hypotheses:

(*i*) The utilization of renewable energy and conventional fuels, along with CO_2 emissions, can encourage GDP in the long run.
(*ii*) The causation between the utilization of renewables, conventional fuels, and economic growth is bidirectional, which confirms the feedback hypothesis.
(*iii*) The causation between renewable energy, fossil fuel energy consumption and CO_2 emissions is bidirectional.
(*iv*) There exists bidirectional causation in the emission of CO_2-economic growth relationship.

This study can provide important recommendations for policymakers in EMDEs which occupies approximately 70% of the world's output and consumption growth from 2000 to 2015 (Gruss et al., 2018) but faces energy security issues and low standards of environmental protection (Gruss et al., 2018; Slesman et al., 2019). Moreover, this study contributes to the available knowledge of energy and environmental economics. First, previous studies focused on the impact of energy consumption but omitted the structure of energy utilization (i.e. renewable and conventional energy). As a result, we incorporate the two forms of energy consumption in this study, which possibly provides essential information for effective energy policies contributing to the sustainable development goals. Second, we enlarge the production function by employing the structure of energy consumption, government expenditure, capital, and trade openness as regressors — thus, avoiding the omission of important variables and generating more robust results. This helps widen the current literature for EMDEs in a manner that is lacking in the existing literature. Third, contrary to the widely applied "*first-generational*" econometric approaches that cannot perform well in heterogeneous and cross-sectional dependence panel data setting, we employ "*second-generational*" econometric techniques that can capture cross-sectional dependence in the heterogeneous panel and guarantee a high level of robustness.

The remainder of the study is as follow: Section 2 specifies the empirical model; Section 3 demonstrates the estimated outcomes along with pertinent interpretations and Section 4 summarizes the empirical findings and provides policy recommendations for policy-makers.

2. Materials and methods

2.1. Data

The study utilized an annual panel data from 1990–2014 with 1125 observations across 45 selected Emerging Market and Developing Economies defined by Morgan Stanley Capital Income (Appendix A).

In this work, the variables GDP per capita (y), government expenditure (gc), trade openness (*to*) and capital (*k*) are measured in constant 2010 US$. Additionally, the units of conventional fuels usage (ce) and renewable energy consumption (*re*) are in millions of kWh. Data were collected from WDI (World Bank) and EIA (Energy Information Administration). Each variable was converted into "per capita" form and subsequently transformed into a natural logarithmic format. Detailed information concerning the variables is provided in Appendix B, the descriptive statistics are displayed in Appendix C, and the correlation matrix of the variables and multicollinearity tests are presented in Appendix D.

2.2. Model specification

The model is built on the Cobb–Douglas production framework extended by Shahbaz (2012), Shahbaz et al. (2013), and Kumar et al. (2014). The output per capita is defined as follows:

$$y_t = A_t k_t^{\alpha}, \alpha > 0 \tag{1}$$

The notations in (1) are explained as: y_t stands for GDP per capita while A denotes technology and k indicates capital stock per capita.

In the model, technology can vary over time and be endogenously determined by energy, government expenditures, and trade openness. Furthermore, Ang (2008), Omri (2013), Akadiri et al. (2019) and Emir and Bekun (2019) embodied CO_2 emissions to assess the influence of this variable on GDP growth. Hence:

$$y_t = \left(A_0 e^{gT} re_t^{\beta} ce_t^{\gamma} c_t^{\delta} gc_t^{\theta} to_t^{\varphi}\right) k_t^{\alpha} \tag{2}$$

where A_0 represents the initial stock of knowledge, *re* represents renewable power usage, *ce* stands for conventional fuels consumption, *c* indicates CO_2 emissions, *gc* means general government final consumption expenditure and *to* symbolizes trade openness, *T* is time.

Turning equation (2) into a linear form, we have:

$$\ln y_{it} = \pi_{it} + \alpha \ln k_{it} + \beta \ln re_{it} + \gamma \ln ce_{it} + \delta \ln c_{it} + \theta \ln gc_{it} + \varphi \ln to_{it} + \varepsilon_{it} \tag{3}$$

In Eq. (3), *i* denotes the *ith* country in the panel; *t* represents time; π symbolizes the constant; $\alpha, \beta, \gamma, \delta, \theta$ and φ respectively denote the elasticity coefficients of capital formation ($\ln k$), renewable energy utilization ($\ln re$), non-renewable energy usage ($\ln ce$), CO_2 emissions ($\ln c$), general government final consumption expenditure ($\ln gc$) and trade openness ($\ln to$); ε_{it} indicates the error term. As a data preprocessing technique, we divided the values of all variables by total population to transform them into per capita format.

2.3. Econometric methodology

Working with panel data requires careful inspection of the possible impacts of some "unobserved common processes" (or "factors") on the error term as well as the variables. This phenomenon is called cross-sectional dependence (CD). CD may arise from the shocks of unobserved common factors (strongly or weakly) affecting all panel units and spillovers across panel units (Chudik et al., 2011). With regards to computational methods, we employed second-generation econometric techniques to prevent biased and unreliable estimation when the panel is heterogeneous and suffers from cross-sectional dependence (Phillips and Sul, 2003; Pesaran, 2004; Breitung, 2005).

The estimation procedure consists of six steps. First, we conducted the cross-sectional dependence (CD) test (Pesaran, 2004). Second, we applied the slope homogeneity test provided by Pesaran and Yamagata (2008). Third, after cross-sectional dependence was detected, we implemented second-generation of panel unit root tests of Pesaran (2007) including CADF and CIPS. To inspect the long-term relationship between the variables, we utilized the second-generational cointegration test developed by Westerlund (2007). We applied the AMG estimator proposed by Eberhardt and Bond (2009) to evaluate the long-run output elasticities. The CCEMG (Pesaran, 2006) and MG estimators (Pesaran and Smith, 1995) were employed for robustness check. Finally, to analyze the dynamic linkages among the variables, we carried out Dumitrescu and Hurlin's tests (Dumitrescu and Hurlin, 2012).

2.3.1. Cross-sectional dependence test

Cross-sectional dependence (CD) is one of the most important issues to be investigated before analyzing panel data models because the choice of appropriate econometric techniques will depend on its occurrence. To examine CD in panel data, Breusch and Pagan (1980) suggested the LM test for the null hypothesis of no cross-sectional dependence in the panel data. However, the LM test may be unsuitable for panels with large cross-section units. To fix this drawback, Pesaran (2004) constructed the CD test based on the following statistic:

$$CD = \sqrt{\frac{2T}{N(N-1)}} \sum_{i=1}^{N-1} \sum_{j=i+1}^{N} \frac{(T-k)\widehat{\rho}_{ij}^{2} - E\left[(T-k)\widehat{\rho}_{ij}^{2}\right]}{var\left[(T-k)\widehat{\rho}_{ij}^{2}\right]} \tag{4}$$

where $\widehat{\rho}_{ij}$ is the correlation between each pair of the residuals extracted from OLS estimation.

Moreover, the CD test well suits panel with a small cross-sectional dimension and small time dimension as well as one with a large cross-sectional dimension and small time dimension.

2.3.2. Slope homogeneity test

To test for Slope homogeneity, Pesaran and Yamagata (2008) introduced the following statistic developed from Swamy (1970):

$$\tilde{S} = \sum_{i=1}^{N} \left(\hat{\beta}_i - \tilde{\beta}_{WFE}\right)' \frac{X_i' M_\tau X_i}{\tilde{\sigma}_i^2} \left(\hat{\beta}_i - \tilde{\beta}_{WFE}\right) \tag{5}$$

In Eq. (5), $\tilde{\beta}_{WFE}$ stands for the weighted fixed effect (WFE) pooled estimator of slope coefficients while $\hat{\beta}$ represents the pooled OLS regression coefficients for each unit. Besides, $\tilde{\sigma}_i^2$ denotes the estimate of σ_i^2, and M_τ indicates the identity matrix.

Moreover, the standardized dispersion statistic $\bar{\Delta}$ and the biased-adjusted dispersion $\bar{\Delta}_{adj}$ are specified as:

$$\bar{\Delta} = \sqrt{N}\left(\frac{N^{-1}\tilde{S} - k}{\sqrt{2k}}\right) \tag{6}$$

$$\bar{\Delta}_{adj} = \sqrt{N}\left(\frac{N^{-1}\tilde{S} - E\left(\bar{z}_{it}\right)}{\sqrt{var\left(\bar{z}_{it}\right)}}\right) \tag{7}$$

where $E\left(\bar{z}_{it}\right) = k$ and $var\left(\bar{z}_{it}\right) = \frac{2k(T-k-1)}{T+1}$.

2.3.3. Panel unit root test

There are two "generations" of panel unit root tests for checking the stationarity of the variables. The first-generation techniques assume that the units in the panel data are cross-sectionally uncorrelated while the second-generation permits cross-sectional dependence of panel units. Regarding the second-generation panel unit root tests, Pesaran (2007) developed the CADF and CIPS tests with the null hypothesis of non-stationarity. The CADF statistic is expressed in Eq. (8):

$$\Delta X_{i,t} = a_i + b_i X_{i,t-1} + c_i \bar{X}_{t-1} + d_i \Delta \bar{X}_{i,t} + \mu_{it} \tag{8}$$

where

$$\bar{X}_{t-1} = \frac{1}{N}\sum_{i=1}^{N} X_{i,t-1};\ \Delta\bar{X}_{i,t} = \frac{1}{N}\sum_{i=1}^{N} \Delta X_{i,t} \tag{9}$$

Also, Pesaran (2007) specified the CIPS statistic as:

$$CIPS(N,T) = \frac{1}{N}\sum_{i=1}^{N} t_i(N,T) \tag{10}$$

where $t_i(N, T)$ indicates the t statistic of b_i.

2.3.4. Panel cointegration test

Concerning panel cointegration tests, common first-generation techniques such as Pedroni (1999, 2004) and Kao (1999) assumed that panel units are independent. When CD exists in the panel, first-generation cointegration tests might be biased. Westerlund (2007) developed the panel cointegration test which is presented in the following error correction equation:

$$\Delta Y_{i,t} = \theta_i' d_t + \omega_i \left(Y_{i,t-1} - \beta_i' X_{i,t-1}\right) + \sum_{j=1}^{k} \varphi_{ij} \Delta Y_{i,t-j} + \sum_{j=0}^{k} \delta_{ij} \Delta X_{i,t-j} + \varepsilon_{i,t} \tag{11}$$

where ω_i is the coefficient of the error correction term for ith individual.

To inspect the null hypothesis (no cointegration among the variables), Westerlund (2007) proposed 2 group statistics including two-group mean statistics and two-panel statistics.

The G_τ and G_α statistics are used to check if cointegration occurs in at least one cross-sectional unit, and they are computed as:

$$G_\tau = \frac{1}{N}\sum_{i=1}^{N}\frac{\widehat{\omega}_i}{Se\left(\widehat{\omega}_i\right)} \tag{12}$$

$$G_\alpha = \frac{1}{N}\sum_{i=1}^{N}\frac{T\widehat{\omega}_i}{1-\sum_{j=1}^{k}\widehat{\omega}_{ij}} \tag{13}$$

The P_τ and P_α statistics are used for investigating whether cointegration exists in the entire panel, and their formulas are presented in Eqs. (14) and (15):

$$P_\tau = \frac{\widehat{\omega}}{Se\left(\widehat{\omega}\right)} \tag{14}$$

$$P_\alpha = T\widehat{\omega} \tag{15}$$

2.3.5. Heterogeneous parameter estimates

In the presence of CD, normal methods such as OLS and GLS provide biased estimation (Phillips and Sul, 2003), while fixed effects (FE) and random effects (RE) models generate inconsistent and unreliable results (Sarafidis and Robertson, 2009).

To ensure robustness in case CD is detected, Pesaran (2006) suggested the CCEMG estimator which combines the unobserved common effects with the cross-sectional averages of independent and dependent variables, described as:

$$Y_{it} = \alpha_i + \beta_i X_{it} + \delta_i \overline{Y}_{it} + \theta_i \overline{X}_{it} + \varphi_i f_t + \omega_{it} \tag{16}$$

In Eq. (16), f_t represents the unobserved common effects and φ_i is the heterogeneous factor loadings; X_{it} and Y_{it} are independent and dependent variables respectively; β_i denotes the slope of each unit; α_i indicates the heterogeneous fixed effects of each unit, and ω_{it} is the error term.

The MG estimator for CCEMG is obtained from averaging the slopes of each unit:

$$CCEMG = \frac{1}{N}\sum_{i=1}^{N}\widehat{\beta}_i \tag{17}$$

where $\widehat{\beta}_i$ is the cross-sectional (or individual) coefficient computed from Eq. (16) using OLS regression.

Another method allowing CD developed by Eberhardt and Bond (2009) is AMG estimator, which is deemed highly robust. The AMG estimator uses a 2-step calculation method. The first step is to add the time dummies alongside the unobserved common factor in the first-difference OLS equation expressed as:

$$\Delta Y_{it} = \alpha_i + \beta_i \Delta X_{it} + \varphi_i f_t + \sum_{t=1}^{T}\rho_t D_t + \varepsilon_{it} \tag{18}$$

where Δ denotes the difference operator, D and ρ are the time dummies and their coefficients respectively.

The second step entails the estimation of the slopes of each unit (i.e. β_i in Eq. (18)) and then averaging all the estimates. This is mathematically expressed as:

$$AMG = \frac{1}{N}\sum_{i=1}^{N}\tilde{\beta}_i \tag{19}$$

where $\tilde{\beta}_i$ are the estimates of β_i in Eq. (18).

Although both the CCEMG and AMG estimators are robust to CD and allow for heterogeneous slopes, AMG estimator is unbiased and efficient for various combinations of cross-section and time dimensions (Bond and Eberhardt, 2013).

2.3.6. Panel causality tests

Dumitrescu and Hurlin (2012) proposed the test for the homogeneous noncausality as null hypothesis (HO) against the heterogeneous noncausality hypothesis (HE) by modifying Granger (1969) noncausality test. The HE hypothesis permits X to Granger cause Y for some but not all units, which is illustrated as:

$$Y_{i,t} = \alpha_i + \sum_{k=1}^{K}\gamma_{ik}Y_{i,t-k} + \sum_{k=1}^{K}\beta_{ik}X_{i,t-k} + \varepsilon_{i,t} \tag{20}$$

where γ_{ik} and β_{ik} represent the coefficients of $Y_{i,t-k}$ and $X_{i,t-k}$ for unit i $(i = 1, 2, \ldots, N)$, respectively; $t = 1, 2, \ldots, T$ denotes time dimension. Coefficients are assumed to differ across units and constant over time. The lag K is assumed to be identical for all units.

The null hypothesis can be defined as:

$$H_0\colon \beta_{i1} = \cdots = \beta_{iK} = 0 \tag{21}$$

The alternative hypothesis can be written as:

$$H_1\colon \beta_{i1} = \cdots = \beta_{iK} = 0, \forall i = 1, \ldots, N_1 \tag{22}$$

$$\beta_{i1} \neq 0 \, or \ldots or \, \beta_{iK} \neq 0 \;\forall i = N_1 + 1, \ldots, N \tag{23}$$

where $0 \leq \frac{N_1}{N} \leq 1$.

Dumitrescu and Hurlin (2012) suggested to regress Eq. (20) for N units and conducting F-test for K linear hypotheses $\beta_{i1} = \cdots = \beta_{iK} = 0$, and then averaging the Wald statistics (W_i) for N units:

$$\overline{W} = \frac{1}{N}\sum_{i=1}^{N}W_i \tag{24}$$

where W_i denotes the unit Wald statistics in time T and $\overline{W}$ is the average of W_i.

If W_i are independently and identically distributed across units, the linear combination of $\overline{W}$ and K (i.e. $\overline{Z}$) as shown in Eq. (25) will have standard normal distribution:

$$\overline{Z} = \sqrt{\frac{N}{2K}}\left(\overline{W} - K\right) \rightarrow N\left(0, 1\right) \tag{25}$$

In addition, Dumitrescu and Hurlin (2012) indicated that the approximated standardized statistic $\tilde{Z}$, which is adjusted for fixed T dimension, also follows a standard normal distribution:

$$\tilde{Z} = \sqrt{\frac{N}{2K} \times \frac{(T-2K-5)}{(T-K-3)}} \times \left[\frac{(T-2K-3)}{(T-2K-1)}\overline{W} - K\right] \rightarrow N\left(0, 1\right) \tag{26}$$

3. Empirical results and discussion

To begin with, we explored cross-sectional dependence in our panel data because it affects the robustness of later estimation results in case second-generational econometric techniques are not utilized. In other words, in the occurrence of cross-sectional dependence, we apply second-generational econometric techniques for consistent long-run estimates.

One may use the Lagrange Multiplier (LM) test of Breusch and Pagan (1980) to investigate panel cross-sectional dependence. However, Pesaran (2004) argued that the LM test is not appropriate if the cross-sectional dimension is large. Accordingly, Pesaran (2004) proposed the CD test. In this study, we applied a CD test (Pesaran, 2004) to detect CD across countries. The results in Table 1 support evidence of panel cross-sectional dependence at 1% significance level $(p < 0.01)$.

Next, we utilized Pesaran and Yamagata (2008) test to examine the slope homogeneity phenomenon. Evidence from Table 2

Table 1
The result of the CD test.

Variable	Statistics	P-value	Corr	Abs (corr)
$\ln y$	114.130***	0.000	0.73	0.84
$\ln k$	75.954***	0.000	0.48	0.55
$\ln re$	68.545***	0.000	0.44	0.53
$\ln ce$	92.534***	0.000	0.59	0.62
$\ln c$	73.594***	0.000	0.47	0.56
$\ln gc$	68.229***	0.000	0.43	0.59
$\ln to$	96.916***	0.000	0.62	0.69

Notes: The symbol *** indicates that p-value is smaller than 0.01.

Table 2
Test for heterogeneous panel.

Variable	$\bar{\Delta}$ statistics	P-value	$\bar{\Delta}_{adj}$ statistics	P-value
$\ln y$	59.169***	0.000	129.61***	0.000
$\ln k$	114.814***	0.000	177.77***	0.000
$\ln re$	517.921***	0.000	627.90***	0.000
$\ln ce$	112.638***	0.000	150.56***	0.000
$\ln c$	248.632***	0.000	541.95***	0.000
$\ln gc$	160.444***	0.000	362.30***	0.000
$\ln to$	122.057***	0.000	177.34***	0.000

Note: The symbol *** indicates that *p-value* is smaller than 0.01.

Table 3
Results from stationary properties in the panel.

Variables	CADF		CIPS	
	Level	Δ	Level	Δ
$\ln y$	−1.917	-2.821***	−1.860	-3.742***
$\ln k$	−1.697	-3.458***	−1.694	-4.390***
$\ln re$	−1.579	-3.570***	−1.331	-4.121***
$\ln ce$	−1.755	-3.280***	−1.892	-4.778***
$\ln c$	−1.749	-3.301***	−1.788	-4.574***
$\ln gc$	−1.549	-2.991***	−1.419	-4.248***
$\ln to$	−1.870	-3.107***	−1.917	-4.415***

Notes: The symbol *** indicates that p-value is smaller than 0.01.

Table 4
Test for cointegration among the variables.

Stat.	Value	Z-value	Robust P-value
G_τ	-6.932***	−6.379	0.002
G_α	-12.561***	−4.899	0.000
P_τ	-18.927***	−2.121	0.001
P_α	-9.519***	−1.958	0.000

Notes: The symbol *** indicates that p-value $\leq$0.01.

reveals that the null hypothesis of slope homogeneity is rejected at 1% significant level — indicating the occurrence of slope heterogeneity is valid.

Proof of parameter heterogeneity and cross-sectional dependence imply that the application of traditional methods such as PP, IPS, and LLC are not appropriate in this study — due to challenges with cross-sectional dependence (Pesaran, 2007). Consequently, we used the novel panel unit root tests by Pesaran (2007) namely CADF and CIPS. In Table 3, it is observed that the null hypothesis of unit root cannot be rejected at level but rejected at first-differenced ($p - value < 0.01$), thus, the variables are integrated of order 1 — $I(1)$ variables only.

Because all of our variables are integrated of order 1, we proceeded to identify their long-run relationship. We ignored traditional cointegration tests because they fail to address parameter heterogeneity and cross-sectional dependence among cointegrating variables. Rather, we employed Westerlund cointegration test (Westerlund, 2007) which utilizes the error correction. Table 4 demonstrates that all the robust p-values are very small ($p - value < 0.01$), which provides proof of a long-run relationship among real GDP, conventional energy consumption, renewable power, government expenditure, trade openness, and capital formation.

Grounded by the empirical results in Table 4, the study proceeded to estimate the long-run parameters. As first-generational estimators are inconsistent and biased due to issues of heterogeneous parameters and cross-sectional dependence, we employed the AMG estimator (Eberhardt and Bond, 2009), that is efficient, unbiased and produces consistent estimates (Bond and Eberhardt, 2013). In addition, we included Pesaran and Smith (1995)'s MG estimator alongside the CCEMG technique of Pesaran (2006) for robustness check. Concerning the diagnostic test, the rejection of the null hypothesis is supported by the result of Pesaran CADF test with low p-values, and thus the residuals are stationary. Moreover, the AMG estimator has a better model fit when its root-mean-square error (RMSE) is lowest. The null hypothesis of CD-test (i.e. no cross-sectional dependence) is not rejected. Therefore, the residuals are cross-sectionally independent, which affirms the robustness and reliability of our method. Table 5 displays the outcomes of the long-run estimation results.

It is obvious in Table 5 that all the coefficients estimated by the AMG estimator are highly significant, and all the variables lnk, lnre, lnnre, lngc, and lnto positively affect GDP per capita. Specifically in the long-run, a 1% increase in capital formation per capita spurs GDP by 0.129%, which affirms the key role of capital as a contributing factor for EMDEs' growth. This finding is similar to the results of Apergis and Payne (2010) for 13 countries within Eurasia and Akadiri et al. (2019) for 28 European countries. Regarding the influence of a 1% increase in the usage of each energy category, renewable power stimulates GDP per capita by 0.057% while conventional fuels propel GDP per capita by 0.128%. In general, the energy sector is deemed as key to economic growth given the close linkage between GDP and the expansion of power usage (Owusu and Asumadu, 2016). Concerning CO_2, a 1% increase in CO_2 emissions contributes 0.038% to GDP growth, which is not dissimilar to the findings of Akadiri et al. (2019). The long-run estimation acknowledges our first research hypothesis, indicating that renewable energy, conventional power usage, and CO_2 emissions facilitate EMDEs' growth. Besides, GDP per capita increases by 0.081% under the impact of general government final consumption expenditure per capita. Moreover, when trade openness expands by 1%, EMDEs' economy appreciates by 0.048%.

The aforementioned long-run analysis implies that EMDEs' economic growth is subject to investment, power utilization, CO_2 emissions, international trade and the role of government in government expenditure. The robustness of the estimation is verified by MG and CCEMG techniques presented in Table 5 — where the coefficients are consistent and robust in terms of their signs and magnitudes.

Apart from the evaluation of the long-run coefficients by AMG, MG and CCEMG estimators, we further scrutinized the causation among the variables to provide complete information for policy recommendations. The first-generational panel Granger causality techniques assume that the data is homogeneous. However, as we already identified the problems preventing the use of first-generational methods, we tested the D-H Granger causality (Dumitrescu and Hurlin, 2012) to analyze the dynamic links of the variables (see Table 6).

From the results presented in Table 6, we observe a feedback mechanism for renewable energy utilization, conventional energy usage, GDP and CO_2 emissions. The relationship among them is described in Fig. 1 as follows:

The causation analysis confirms our second research hypothesis regarding the existence of feedback hypothesis in which conventional power use, GDP growth, CO_2 emissions, and renewable energy impact each other, consistent with Bekun et al.

Table 5
Long-run estimation.

Regressors	AMG estimator			MG estimator			CCEMG estimator		
	Coef.	t-stat.	*P*-value	Coef.	t-stat.	*P*-value	Coef.	t-stat.	*P*-value
$\ln k$	0.129***	8.75	0.000	0.126***	6.29	0.000	0.149***	9.41	0.000
$\ln re$	0.057***	3.11	0.002	0.059***	2.86	0.004	0.048***	2.84	0.004
$\ln ce$	0.128***	6.03	0.000	0.131***	6.11	0.000	0.139***	5.68	0.000
$\ln c$	0.038**	2.00	0.046	0.052**	2.10	0.036	0.048**	1.98	0.049
$\ln gc$	0.081***	4.96	0.000	0.089***	4.64	0.000	0.101***	5.17	0.000
$\ln to$	0.048**	2.16	0.030	0.049***	2.79	0.005	0.051**	2.06	0.039
CD-test	0.243		0.958	0.416		0.641	1.137		0.302
Diagnostic									
I(0)	[0.000]			[0.000]			[0.000]		
RMSE	0.0173			0.0207			0.0198		

Notes: The symbol *** indicates that p-value is smaller than 0.01. The notation ** means that p-value falls between 0.01 and 0.05. CD test is conducted on the regression residuals with the null hypothesis of no cross-sectional dependence. Coef. is coefficient; I (0) denotes p-values for of CADF test with the null hypothesis of non-stationarity; RMSE represents Root Mean Squared Error.

Table 6
Outcome of causation tests.

Variables	$\ln y$	$\ln k$	$\ln re$	$\ln ce$	$\ln c$	$\ln gc$	$\ln to$
$\ln y$	–	5.2819*** (16.5256)	2.5639*** (5.7715)	2.5597*** (5.7546)	2.0917*** (3.9031)	2.1939*** (4.3074)	3.4612*** (9.3217)
$\ln k$	3.9679*** (11.3267)	–	3.0968*** (7.8799)	2.6353** (6.0540)	2.6030*** (5.9261)	3.4411*** (9.2421)	3.5736*** (9.7664)
$\ln re$	3.3193*** (8.7603)	1.9242*** (3.2402)	–	2.8134*** (6.7586)	2.1480*** (4.1260)	2.4019*** (5.1306)	2.8712*** (6.9872)
$\ln ce$	3.0972*** (7.8817)	2.8460*** (6.8878)	1.7868*** (2.6966)	–	2.3548*** (4.9439)	2.0451*** (3.7188)	3.1148*** (7.9512)
$\ln c$	3.8874*** (11.0083)	3.0599*** (7.7340)	2.1021*** (3.9441)	2.7890*** (6.6619)	–	3.5725*** (9.7623)	3.0145*** (7.5542)
$\ln gc$	8.0007*** (27.2834)	5.1509*** (16.0076)	2.4849*** (5.4589)	4.4875*** (13.3824)	3.3235*** (8.7768)	–	4.3935*** (13.0108)
$\ln to$	2.8268*** (6.8118)	1.9761*** (3.4455)	2.1450*** (4.1141)	2.6831*** (6.2430)	2.4082*** (5.1553)	2.6351*** (2.6351)	–

Notes: The W-statistics marked with *** are significant at 1% level. *Z*-statistics are given in parentheses (.).

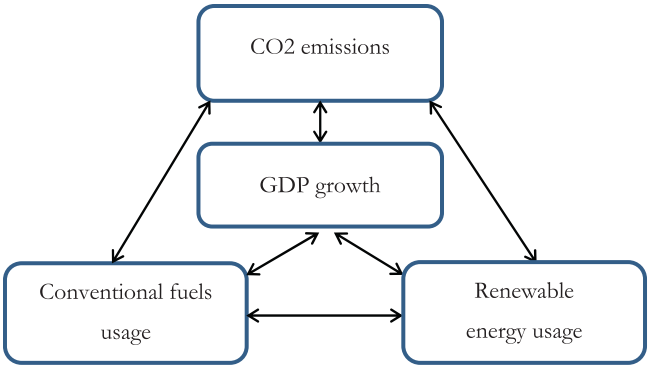

Fig. 1. The dynamic linkages between conventional power, renewable fuel, CO_2 and GDP. Note: The directions of arrows indicate the directions of causal effects.

(2019a). The consumption of renewable energy is advantageous in the following ways: possibly decreases the import of fossil fuels and thus avoiding the negative impacts of fuel price fluctuation and contributing to energy security as well as widening the flexibility of energy sources selection (Owusu and Asumadu, 2016).

Our third research hypothesis is also validated by the presence of two-way causal effects between renewable power usage and CO_2 emissions as well as the use of conventional fuels and CO_2 emissions. This agrees with the findings of Bekun et al. (2019a). The consumption of fossil fuel energy sources can considerably worsen environmental quality by boosting CO_2 emissions. Meaning that EMDEs can lower environmental pollution by raising the share of renewable power, especially green energy, in its total energy utilization.

Finally, our fourth research hypothesis is validated by the evidence of a feedback mechanism between CO_2 and GDP growth. This result is not different from Bekun et al. (2019a) and Samu et al. (2019), thus signifying that industrial activities foster the development of the economy while its structural dynamics rapidly stimulate the amount of CO_2 released to the environment. Accordingly, the transition from an energy-hungry economy emitting a huge amount of CO_2 to a decarbonized one is very necessary to limit climate change and its negative effects (Sarkodie and Strezov, 2019b). In order to achieve the objective to sustainably reduce emissions especially in the industry sector, effective environmental policies and clean energy consumption are crucial and need to be encouraged (Agnolucci and Theodoros, 2019).

Overall, EMDEs mostly consist of emerging economies with strong industrialization processes and fast economic growth. As a result, the majority of them substantially depend on energy, especially conventional sources like oil, coal and gas, to produce goods and services because of incomplete industrialization processes. Besides, their limited and obsolete technological capabilities pose challenges for efficient energy usage and environmental damage minimization.

4. Conclusion

This study investigated the influence of power utilization (renewable and conventional), together with CO_2 emissions, capital formation, trade openness, and government expenditure, on the economic growth of 45 EMDEs from 1990 to 2014. We employed second-generational econometric techniques that produce consistent estimates in heterogeneous panel data setting. After detecting all I(1) variables using CADF and CIPS unit root tests, we scrutinized the long-run relationship using Westerlund panel cointegration test. We assessed the long-run coefficients using the AMG estimator, along with robustness check with CCEMG and MG estimators. The long-run effect estimation shows that renewable and conventional energy usage, trade openness, capital formation, CO_2 emissions, and government expenditure significantly foster EMDEs' economic growth.

From the empirical findings generated by this work, we found that EMDEs rely on the increasing utilization of different energy sources for their economic activities. Meanwhile, the escalating fossil fuel-based CO_2 emissions lead to higher concerns of individuals, policy-makers and government agencies for the sustainable development objective of EMDEs. The dilemma of reducing the energy demand to promote environmental sustainability hampers economic growth. Thus, EMDEs should pursue sustainable development by facilitating the penetration of more cleaner and renewable energy technologies in the total energy mix while reducing the share of fossil fuels. Renewable energy exploitation offers EMDEs with double dividend: promoting economic growth and reducing CO_2 emissions. The incremental percentage of renewable energy sources can replace conventional ones and serve the increasing demand for energy. This can help EMDEs to focus on economic development without concerns about CO_2 emissions and the threats related to environmental damage. In addition, the penetration of renewables in the energy mix allows EMDEs to attain sustainable development objectives. In the efforts of EMDEs to gain high effectiveness in sustainable energy and environmental policies when environmental protection regulations remain relatively weak (see Gruss et al., 2018; Slesman et al., 2019), we recommend the facilitation of institutional quality across all EMDEs in order to attain the benefits of economic stability and environmental sustainability. Besides, from the research results, we witness that flexible fiscal policies to stabilize the macroeconomy combined with appropriate trade-led growth policies are important. Accordingly, EMDEs should ease capital for efficient resources allocation, foster foreign investment in the export sector and encourage investment in fostering green power and transforming technology, which contributes to green and sustainable development.

In this study, we focused on the CO_2 emission as representative for environmental damage. However, we propose an extension of the scope and topic by adding ecological footprint to account for the environmental-related dynamics. In addition, studies in the same topic can consider other control variables such as innovation, R&D, and other aspects of institutional quality or governance. Besides, more thorough research can be conducted for individual countries, which may be useful for policy-makers and other relevant parties in designing and implementing effective country-specific policies related to the energy – economic growth – environment linkage. Finally, regarding econometric techniques, different models have their own merits. To deal with heterogeneous panel with the presence of cross-sectional dependence and slope heterogeneity in our study, we utilized "second-generation" econometric techniques. Accordingly, to ensure the robustness of the model estimation, we employed novel approaches including the Augmented Mean Group (AMG), Mean Group (MG), and Common Correlated Effects Mean Group (CCEMG) estimators. Though the estimators estimated the common correlated effects but are limited in terms of dynamic common correlated effects and accounting for pooled coefficients. To overcome the limitations of the Granger causality test, we used the second-generation causality approach which allows heterogeneous panel data with cross-sectional dependence. Nonetheless, in future studies concerning this subject, different estimation techniques can be employed to compare and contrast the results.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

CRediT authorship contribution statement

Hoang Phong Le: Conceptualization, Data curation, Formal analysis, Funding acquisition, Methodology, Software, Validation, Visualization, Writing - review & editing. **Samuel Asumadu Sarkodie:** Funding acquisition, Writing - original draft, Writing - review & editing.

Acknowledgments

The authors owe extensive gratitude to the editor and the 5 anonymous reviewers for their constructive comments, which helped the author to improve the paper. Besides, the authors would like to thank Prof. Aaro Hazak, Assoc. Prof. Karin Jõeveer, Assoc. Prof. Viet Dung Tran, Ho Hoang Gia Bao and Tuan Phong Nguyen for their helpful support. However, the authors are solely responsible for any errors.

Appendix A. Supplementary data

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.egyr.2020.04.020.

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