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RESEARCH ARTICLE

The role of renewable and non-renewable energy consumption in CO_2 emissions: a disaggregate analysis of Pakistan

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Abstract

The energy sector has become the largest contributor to greenhouse gas (GHG) emissions. Among these GHG emissions, most threatening is CO_2 emission which comes from the consumption of fossil fuels. This empirical work analyzes the roles of renewable energy consumption and non-renewable energy consumption in CO_2 emissions in Pakistan. The empirical evidence is based on an auto-regressive distributive lag (ARDL) model of data from 1970 to 2016. The disaggregate analysis reveals that renewable energy consumption has an insignificant impact on CO_2 emission in Pakistan and that, in the non-renewable energy model, natural gas and coal are the main contributors to the level of pollution in Pakistan. Economic growth positively contributes to CO_2 emission in the renewable energy model but not in the non-renewable energy model. Policies that emphasize the contribution of renewable energy to economic growth and that add more clean energy into the energy mix are suggested.

Keywords Renewable energy · Non-renewable energy · Economic growth · Disaggregate analysis · ARDL

Introduction

Energy sector is responsible for 75% of the global GHG emissions (International Energy Association 2015). Carbon dioxide (CO_2) emissions have increased over the years due to continuous rise in the global energy demand and have severe implications for the environment and a significant contributor to global climate change. In an effort to address the increasing concerns about climate change, the Conference of Parties (COP) of the United Nations Framework Convention for Climate Change (UNFCCC) agreed to limit the increase in the global temperature to 2 °C above pre-industrial levels by 2020 in 2015 (UNFCCC 2015). Since this target cannot be achieved until the pattern of energy consumption is changed, therefore, combating climate change with sustainable development has become an essential global agenda in planning for energy production and consumption. An economy may turn to a sustainable track if it uses a mixture of renewable and non-renewable energy resources (Dogan 2016). Therefore, policymakers must know the individual contributions of energy sources (renewable and non-renewable) on economic growth and CO_2 emissions.

Numerous studies concerned with energy consumption, economic growth, and environmental degradation such as Shahbaz et al. (2012); Alkhathlan and Javid (2015); and Ibrahiem (2015) concluded that high levels of energy consumption are central to economic growth while at the same time, they have a tendency to deteriorate the environment in developing and developed economies (Azad et al. 2015).

There has been a continuous increase in energy use for developing countries during recent years to achieve higher levels of living standards and economic development (Shahbaz et al. 2012). Attaining higher ladders of economic development at the cost of natural environment is never

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desirable. Therefore, examining the role of renewable and non-renewable energy consumption in CO_2 emissions has remained debatable in empirical literature due to differences in data sets, regions, and research methodologies employed (Mirza and Kanwal 2017). Our study attempts to find more evidence on causal relationships between renewable and non-renewable energy consumption, CO_2 emissions, and economic growth concurrently in a single study for the case of Pakistan.

Pakistan is an interesting case study for this empirical work as its share of energy-led emissions is increasing. As per the Global Climate Risk Index (2018), Pakistan has been one of the most affected countries due to climate during the last two decades. The impact of climate change compared to the country's diminutive per capita GHG emissions has been very high in Pakistan (Abas et al. 2017). Moreover, Pakistan has faced acute energy shortages from 2007 and onwards that have adversely affected its economic growth (Komal and Abbas 2015). To address these energy shortages, Pakistan has resorted primarily to non-renewable energy-producing sources, which are the main contributors to the country's CO_2 emissions[1] (Nasir and Ur Rehman 2011). During the last three years, Pakistan has initiated seven energy projects that are based on coal consumption and will further add to GHG emissions in the country. Although the country has set numerous goals and strategies to encourage consumption from renewable resources, the energy sector is ill-managed and the share of renewable energy consumption is very small. Despite the initiation of renewable energy policy in 2006 and the existence of huge potential[2] for renewable energy production, no time path is available to achieve sustainable energy development in Pakistan.

Therefore, having a large population and being one of the major contributors to GHG emissions among the developing countries, Pakistan is an ideal candidate for an exclusive study that examines the environmental and growth effects of any possible fuel substitutions in the coming years. In this paper, we attempt to carry out a disaggregated analysis to test for the existence of long-run and short-run relationship between individual energy consumption sources, CO_2 emissions, and economic growth. We also implement causality tests to study the direction of causality between these variables to suggest optimal policies. Analysis of renewable and non-renewable energy consumption by source at disaggregate levels facilitates the examination of the relationships among each source of energy consumption, economic growth, and CO_2 emissions. In addition, research at disaggregate level is essential for examining the barriers to replacing traditional energy resources with newer ones, along the lines of Greiner et al. (2018) who investigated whether natural gas consumption can mitigate CO_2 emissions produced from coal consumption.

Novelty of our study relative to the existing literature lies mainly in the difference in analytical perspective. Previous studies on Pakistan have investigated aggregate relationships among selected variables; however, this study examines the role of different renewable and non-renewable energy sources in CO_2 emissions. With disaggregated level analysis, we are able to compare the individual impact of renewable and non-renewable energy consumption on CO_2 emissions and economic growth. Our contribution also includes a comparative assessment of renewable and non-renewable consumption in a holistic manner to suggest a comprehensive policy framework towards CO_2 emission reduction. The analysis provides valuable information for policymakers to construct an optimal combination of renewable and non-renewable sources in order to meet the national demand.

The remainder of the paper is distributed as follows. The "Literature review" section reviews related work in the literature. The "Methodology and data" section describes the study's data collection and econometric approach. The results and discussion are presented in the "Empirical analysis and discussion of results" section, while the "Conclusion" section provides a conclusion.

Literature review

The relationships among renewable and non-renewable energy sources, economic growth, and CO_2 emissions have been investigated in many studies. Many have used *panel country data* to investigate these relationships. For example, Apergis and Payne (2011a) conducted a study of 80 countries and found bidirectional causality between renewable energy consumption and economic growth and between non-renewable energy consumption and economic growth. The same results were reported by Tugcu et al. (2012), who used the autoregressive distributive lag (ARDL) approach to assess the classical production function in the G-7 countries. Using fully modified ordinary least square (FMOLS), Sadorsky (2009) found a positive relationship between renewable energy consumption and real income per capita in 18 countries. By employing similar methods to a group of 69 countries, Ben Jebli and Ben Youssef (2015) validated the growth hypothesis for both renewable and non-renewable energy consumption. These results were later supported by Wesseh and Lin (2016a), who estimated a translog model for 34 African countries. Kahia et al. (2016) explored an energy-growth nexus for Middle East and North African (MENA) countries using data from 1980 to 2012. Applying a panel cointegration technique, they reported bidirectional causality between renewable and

[1] Eighty-six percent of Pakistan's energy requirements are met through consumption of non-renewable energy sources.

[2] Potential of 2,900,000 MW of solar, 2000 MW of small hydropower, 346,000 MW of wind, 3000 MW of biogas, and 1000 MW of waste-to-energy is available in Pakistan but the total renewable energy installed capacity is less than 1% of the existing potential (Wakeel et al. 2016).

non-renewable energy consumption, found significant but negative short-run coefficients, and specified substitutability of renewable and non-renewable energy resources. Similarly, Bhattacharya et al. (2016) applied a heterogeneous panel Granger causality test to multiple countries and found no causality between renewable energy consumption and GDP. Ito (2017) applied a GMM model to 42 developing countries and argued that renewable consumption reduces CO_2 emissions and has a positive influence on economic growth in the long run.

Other studies have used single-country data sets. For instance, Dogan (2016) investigated the case of Turkey by applying a vector error correction model (VECM) Granger causality test with a structural break and found bidirectional long-run and short-run causality between non-renewable energy consumption and GDP. They also reported one-way short-run causality from GDP towards renewable energy consumption, while in long run they found bidirectional causality. Using the Toda-Yamamoto causality method for Italy, Vaona (2012) supported the feedback hypothesis for non-renewable energy consumption and growth while neutrality hypothesis for the relationship between renewable energy consumption and economic growth. Apergis and Payne (2014) used the Toda-Yamamoto causality technique and found no relation among renewable, non-renewable energy consumption and economic growth in the USA. Table 6 shown in the Annexure lists the literature on renewable and non-renewable energy consumption, CO_2 emissions, and economic growth.

Some studies on Pakistan have assessed the role of renewable and non-renewable energy consumption on economic growth and CO_2 emissions by applying various econometric models. Studies on Pakistan's economy have focused only on aggregate analysis, while the relationships at the disaggregated level have not been explored for the case of Pakistan. For example, Mirza and Kanwal (2017) carried out an analysis on aggregate data of total energy consumption and found bidirectional long-run causalities between total energy consumption, economic growth, and CO_2 emissions. Danish et al. (2017) conducted an aggregate study on renewable and non-renewable energy consumption and observed bidirectional causality between renewable energy consumption and CO_2 emissions in Pakistan. Shahzad et al. (2017) used Granger causality to report that energy consumption is positively related to CO_2 emissions. Muhammad et al. (2014) examined the nexus between renewable and non-renewable energy consumption, real GDP, and CO_2 emissions for Pakistan by applying structural VAR technique. But they also used aggregate data for analysis. One common conclusion from the studies in this area is the support for renewable energy resources. Table 7 shown in the Annexure lists the literature on disaggregated studies that have been conducted in various countries. We cannot ignore the analysis at disaggregated levels because Pakistan's energy is a mixture of renewable and non-renewable energy resources. The current study addresses this research gap by considering each source of energy with its related CO_2 emissions and economic growth.

Methodology and data

Methodology

This study explores the relationships among renewable and non-renewable energy consumption, economic growth, and CO_2 emissions in Pakistan. The disaggregated analysis examines the corresponding effects of energy consumption on economic growth and CO_2 emissions. We use a standard linear-log function to test the per capita relationship between CO_2 emissions, renewable energy consumption, non-renewable energy consumption, and GDP. To discuss disaggregate contributions to CO_2 emissions, we employ the following linear-log model for analytical purposes:

$$CO_{2t} = \alpha_0 + \beta_1 \ln GDP_t + \beta_2 \ln Hydro_t + \beta_3 \ln Nuc_t + \beta_4 \ln Oil_t + \beta_5 \ln Coal_t + \beta_6 \ln Gas_t + \varepsilon_t \quad (1)$$

where CO_{2t} reflects carbon emissions, GDP denotes gross domestic products, Hydro reflects hydroelectricity, Nuc implies Nuclear energy, and ε_t is the disturbance term. In order to measure different contribution of renewable energy consumption and non-renewable energy consumption to CO_2 emissions, we have divided the above-mentioned model into two sub-models which can be described as below:

Model 1: renewable energy consumption, GDP, and CO_2 emissions

$$CO_{2t} = \alpha_0 + \beta_1 \ln GDP_t + \beta_2 \ln Hydro_t + \beta_3 \ln Nuc_t + \varepsilon_t \quad (2)$$

Model 2: non-renewable energy consumption, GDP, and CO_2 emissions

$$CO_{2t} = \alpha_0 + \beta_1 \ln GDP_t + \beta_2 \ln Oil_t + \beta_3 \ln Coal_t + +\beta_4 \ln Gas_t + \varepsilon_t \quad (3)$$

Model 1 shows the relationship between renewable energy consumption (hydroelectricity and nuclear energy), GDP, and CO_2 emissions while Model 2 shows non-renewable energy consumption (through oil, coal, and natural gas) GDP, and CO_2 emissions. For this study, we collected time series data from 1970 to 2016 from two major sources: World Development Indicators (WDI) (World Bank 2017) and BP Statistics (2017). The data for GDP per capita was obtained from WDI, while data on CO_2 emissions, oil, coal, natural gas, hydroelectricity, and nuclear consumption were collected from BP Statistics.

Estimation technique

This study applies the ARDL bound testing technique to capture the short-run and long-run dynamics at disaggregate levels. The ARDL methodology was introduced by Pesaran et al. (2001) to test for cointegration among variables. This methodology has several benefits and can be applied if variables are integrated at level I(0) or first difference I(1). It provides robust results regardless of sample size, adjusts the lags in the model, and delivers unbiased estimates with valid t-statistics of the long-run model (Harris and Sollis 2003). Moreover, with the help of a simple linear transformation, ARDL derives a dynamic unrestricted error correction model (UECM). The UECM joins long-run equilibrium with short-run dynamics while keeping long-run information intact. ARDL is a suitable model in the presence of endogeneity and serial correlation in time series data (Pesaran et al. 2001).

Based on the objective of this study, we employed ARDL twice for two different models, i.e., Model 1 for renewable energy consumption, GDP, and CO_2 emissions and Model 2 for non-renewable energy consumption, GDP, and CO_2 emissions. Both models are specified as follows:

ARDL Model 1: renewable energy consumption, GDP, and CO_2 emissions

$$\Delta \mathrm{CO2}t = c_0 + \sum_{i=1}^{p} \beta_1 \Delta \mathrm{CO}_{2,t-r} + \sum_{i=0}^{p} \beta_{2i} \Delta \mathrm{lnGDP}_{t-r} + \sum_{i=0}^{p} \beta_{3i} \Delta \mathrm{lnHydro}_{t-r} + \sum_{i=0}^{p} \beta_{4i} \Delta \mathrm{lnNuc}_{t-r} + \lambda_1 \mathrm{lnCO}_{2,t-1} + \lambda_2 \mathrm{lnGDP}_{t-1} + \lambda_3 \mathrm{lnHydro}_{t-1} + \lambda_4 \mathrm{lnNuc}_{t-1} + \varepsilon_t \quad (4)$$

where Δ is the first difference operator and p denotes the lag length. We derived two hypotheses from Eq. (4) for the long relationships. The first is null hypothesis of no cointegration (H_0:$\lambda_1 = \lambda_2 = \lambda_3 = \lambda_4 = 0$) which tested against the second one, i.e., the alternative hypothesis (H_1:$\lambda_1 \neq \lambda_2 \neq \lambda_3 \neq \lambda_4 \neq 0$).

ARDL Model 2: non-renewable energy consumption, GDP, and CO_2 emissions

$$\Delta \mathrm{CO2}t = c_0 + \sum_{i=1}^{q} \beta_1 \Delta \mathrm{CO}_{2,t-r} + \sum_{i=0}^{q} \beta_{2i} \Delta \mathrm{lnGDP}_{t-r} + \sum_{i=0}^{q} \beta_{3i} \Delta \mathrm{lnCoal}_{t-r} + \sum_{i=0}^{q} \beta_{4i} \Delta \mathrm{lnOil}_{t-r} + \sum_{i=0}^{q} \beta_{5i} \Delta \mathrm{lnGas}_{t-r} + \gamma_1 \mathrm{lnCO}_{2,t-1} + \gamma_2 \mathrm{lnGDP}_{t-1} + \gamma_3 \mathrm{lnCoal}_{t-1} + \gamma_4 \mathrm{lnOil}_{t-1} + \gamma_5 \mathrm{lnGas}_{t-1} + \varepsilon_t \quad (5)$$

where Δ is the first difference operator and q denotes the lag length. The null hypothesis of no cointegration is (H_0:$\gamma_1 = \gamma_2 = \gamma_3 = \gamma_4 = \gamma_5 = 0$) tested against the alternative hypothesis of cointegration (H_1:$\gamma_1 \neq \gamma_2 \neq \gamma_3 \neq \gamma_4 \neq \gamma_5 \neq 0$).

Empirical analysis and discussion of results

As a first step, we check the unit root in each series using the Augmented Dicky Fuller (ADF) and Phillips Pearson (PP) tests. Table 1 presents the results of the unit root tests, which reveal that the variables are stationary at I(1). As no variable is integrated at 2nd difference, we reject the null hypotheses of no stationary at I(1) for all of the series.

In order to check structural break in the data, we also employed Zivot and Andrews structural break unit root test. Table 2 reveals that structural breaks exist and all variables are integrated at first difference except Coal which is integrated at level. These breaks may occur due to changes in government and economic condition or due to the introduction of new regulations. For example, structure break of 2008 recalls the global financial crises when most of countries were affected economically. GDP rates in many countries declined in the comparison of CO_2 emissions. The problem of structural break can be overcome by adding additional variable or dummy variable from the period of structural change in dependence variable. We have also considered dummy variable to improve the long-run stability of the results. All the unit root tests allowed us to use ARDL technique as all variables are integrated at I(0) and I(I).

After checking the unit root, we move to ARDL bound testing to test for cointegration among variables. Table 3 depicts the results of bound testing for Model 1 and Model 2. The results show a long-run relationship among all of the selected variables. The calculated F-statistics are greater than the appropriate critical values of upper-bound. Hence, the null hypothesis of no cointegration is rejected. Diagnostic tests for serial correlation (the Breusch-Godfrey test) and heteroscedasticity (the Arch Test) support the conclusion that the error term is white noise. The Ramsey RESET test also indicates that the model is well-specified.

We also used the Johansen Cointegration technique to check the robustness of our findings. This technique provides

Table 1 Result of ADF and PP unit root tests

Variables	Augmented Dicky Fuller test		Phillips Pearson test		Order of integration
	Level	1st difference	Level	1st difference	
lnOil	0.0286 [0.9563]	− 4.3610 [0.0011]*	− 0.1709 [0.9348]	− 4.2210 [0.0017]*	I(1)
lnCoal	0.0733 [0.9602]	− 5.5932 [0.0000]*	− 0.2239 [0.9278]	− 5.5579 [0.0000]*	I(1)
lnGas	− 1.3753 [0.5859]	− 4.9823 [0.0002]*	− 1.2353 [0.6512]	− 4.9503 [0.0002]*	I(1)
lnHydro	− 2.8231 [0.0629]	− 7.6508 [0.0000]*	− 3.9423 [0.0037]	− 7.6410 [0.0000]*	I(1)
lnNUC	− 3.2865 [0.0213]	− 6.7367 [0.0000]*	− 3.8804 [0.0044]	− 6.7457 [0.0000]*	I(1)
lnCO_2	− 0.1249 [0.9402]	− 4.0507 [0.0028]*	0.3056 [0.9762]	− 3.8844 [0.0044]*	I(1)
lnGDP	− 0.1138 [0.9416]	− 5.3621 [0.0001]*	− 0.1911 [0.9322]	− 5.3232 [0.0001]*	I(1)

*Level of rejection at 1%

two types of values: trace statistics and maximum eigenvalue statistics. Table 8, presented in the Annexure, indicates that there is at least one cointegration relationship present between renewable and non-renewable energy consumption, economic growth, and CO_2 emissions.

After confirmation of cointegration through the ARDL technique, we check for the long-run and short-run dynamics of Model 1 and Model 2. Results are shown in Table 4 for both models.

In Model 1, the coefficient of GDP is positive and significant ($\beta = 1.665411$), which means that economic growth accelerates the CO_2 emissions in the long-run path when energy is consumed from renewable resources. This result is similar to those of Danish et al. (2017) and Mirza and Kanwal (2017) for Pakistan and Zoundi (2017) for 25 African countries. This relationship indicates that an increase in economic growth enhances the demand for energy and so indirectly adds to CO_2 emissions (Shahbaz et al. 2012). The results reflect the increasing population, urbanization, and industrialization in Pakistan, where energy demand is increasing in parallel. Energy use in Pakistan is based primarily on a combination of fossil fuels, so the share of renewable resources is minor. Therefore, energy consumption increases the GDP parallel to an increase in CO_2 emissions, as in the case of Algeria that Bélaïd and Youssef (2017) discussed. Some authors have found that renewable energy consumption causes a decline in CO_2 emissions when GDP increases, as Dogan and Ozturk (2017) found for the USA. However, this finding does not hold for Pakistan because of the seismic differences between the two economies. Shahzad et al. (2017) argued that Pakistan is operating below the threshold level of economic activities, so until it achieves the threshold level, CO_2 emissions are likely to rise in Pakistan. If energy consumption is below the threshold level, then the technology effect remains meager and the effects of scale and composition dominate. In the short run, there is a negative—albeit insignificant—relationship between GDP and CO_2 emissions. The relationship between GDP and CO_2 emissions has been studied many times for different data sets. Many authors (for example, Danish et al. 2017; Sinha and Shahbaz 2018) formulated their studies using the hypothesis of environmental Kuznets curve (EKC). The EKC hypothesis suggests that there might be an inverted U-shape or a U-type nexus between environmental quality and GDP per capita which implies that in the early stages of economic development, economic growth will sooner or later undo the environmental impact. Thus, we can say that a positive or negative relationship between GDP and CO_2 emissions is not obvious.

Our results show a positive but insignificant relationship between hydroelectricity use and CO_2 emissions. A 1% change in the use of hydroelectricity leads to a unit change in CO_2 emissions of only 0.11. Nuclear consumption and CO_2 emissions also have a positive but insignificant relationship, as a 1% change in nuclear consumption brings a unit change of 0.013 in CO_2 emissions. In the short run, then, hydroelectricity and

Table 2 Results of Zivot and Andrews structural break unit root tests

Variables	ZA test at level		ZA test at difference		Order of integration
	t-statistic	Break year	t-statistic	Break year	
lnOil	− 4.363256	2002	− 5.540532	1996	I(1)
lnCoal	− 4.197039	1990	− 3.877045	2009	I(0)
lnGas	− 4.662264	2003	− 5.399134	2006	I(1)
lnHydro	− 4.179896	1988	− 8.978337	2002	1(1)
lnNuclear	− 3.403430	2001	− 9.183302	2000	I(1)
lnCO_2	− 4.429400	2009	− 5.553552	2008	I(1)
lnGDP	− 3.806194	1980	− 5.959578	1993	I(1)

Table 3 Bound testing cointegration results

Estimated model	Bound testing approach			Diagnostic tests					
	F-statistics	Lag selection	Decision	LM-test		χ^2 Arch		χ^2 Ramsey	
Model 1: renewable energy consumption, GDP, and CO_2 emission									
lnCO_2/(lnGDP, lnHyd, lnNuc)	2.4126	(2, 0, 2, 0)	Yes	0.3087	0.7363	2.0384	0.1248	0.0395	0.8435
lnGDP/(lnCO_2, lnHyd, lnNuc)	5.7136	(1, 1, 0, 4)	Yes	1.7579	0.1892	1.9751	0.1093	2.3985	0.1075
lnHyd/(lnCO_2, lnGDP, lnNC)	5.0039	(2, 1, 0, 1)	Yes	0.4918	0.6157	1.7342	0.1950	4.0476	0.0518
lnNuc/(lnCO_2, lnGDP, lnHyd)	120.7811	(4, 0, 0, 3)	Yes	2.0344	0.1167	0.0583	0.8103	2.3422	0.0793
Model 2: non-renewable energy consumption, GDP, and CO_2 emission									
lnCO_2/(lnGDP, lnOil, lnCoal, lnGas)	6.2090	(5, 5, 5, 4 5)	Yes	1.1931	0.2961	0.0017	0.9672	2.0527	0.1704
lnGDP/(lnCO_2, lnOil, lnCoal, lnGas)	6.5013	(5, 0, 2, 3, 4)	Yes	0.3687	0.5499	0.1494	0.7012	1.1535	0.2944
lnOil/(lnCO_2, lnGDP, lnCoal, lnGas)	5.1410	(5, 5, 5, 5, 4)	Yes	2.8576	0.1167	0.0062	0.9375	2.4063	0.0331
lnCoal/(lnCO_2, lnGDP, lnOil, lnGas)	6.9187	(4, 5, 5, 4, 5)	Yes	3.1399	0.1103	0.3415	0.5623	1.1953	0.2941
lnGas/(lnCO_2, lnGDP, lnOil, lnCoal)	6.8695	(4, 2, 5, 1, 1)	Yes	0.0007	0.978	0.1557	0.6953	4.8884	0.0175
Pesaran et al. (2001)	1% significance level		5% significance level		10% significance level				
	Lower bound	Upper bound	Lower bound	Upper bound	Lower bound	Upper bound			
Critical values	4.29	5.61	3.23	4.35	2.72	3.77			

nuclear energy have positive but insignificant relationships with CO_2 emissions.

In the nexus among non-renewable energy consumption, GDP, and emissions (Model 2) is a negative but insignificant long-run relationship between GDP and CO_2 emissions such that GDP is negatively related to CO_2 emissions. However, such is not always the case; for example, Martínez-Zarzoso and Bengochea-Morancho (2004) stated that CO_2 emissions' declining as a result of increased income sustains to a certain level, after which CO_2 emissions increase with additional increases in income. This finding is an indication for Pakistan's economy that, as income rises, at some point will come an increase in CO_2 emissions such that this relationship becomes positive. The mediator in this relationship is non-renewable energy consumption. The use of fossil fuels increases the CO_2 emissions in Pakistan, which reduces the economy's energy efficiency and deteriorates the environment (Muhammad et al. 2014; Danish et al. 2018). Moreover, excessive CO_2 emissions result in the long run in economic benefits' being outweighed by the economic cost associated with the use of non-renewable resources (Apergis et al. 2010). Pakistan must pursue smart policies on the use of fossil fuels to prevent GDP's decreasing as a result of inefficient and excessive use of non-renewable energy resources (Soytas et al. 2007).

In the long run, coal consumption bears a positive and statistically significant relationship with CO_2 emissions. Our

Table 4 Long-run and short-run dynamics

Variable	Long-run estimates				Variable	Short-run estimates			
	Coefficient	Std. error	t-statistic	Prob.		Coefficient	Std. error	t-statistic	Prob.
Model 1: renewable energy sources									
lnGDP	1.6654	0.6208	2.6824	0.0105	D(lnGDP)	− 0.0804	0.1337	− 0.6015	0.5508
lnHydro	0.1072	0.2882	0.3719	0.7118	D(lnHydro)	0.0346	0.0582	0.5948	0.5552
lnNuc	0.0132	0.0173	0.7680	0.4469	D(lnNuc)	0.0022	0.0033	0.6550	0.5161
C	− 4.8644	0.4519	− 10.7642	0	CointEq (− 1)	− 0.1512	0.0720	− 2.0994	0.0420
Model 2: non-renewable energy sources									
lnGDP	− 0.9399	0.6906	− 1.3608	0.1812	D(lnGDP)	− 0.2430	0.2879	− 0.8442	0.4036
lnCoal	0.3304	0.1206	2.7391	0.0092	D(lnCoal)	0.2177	0.0438	4.9678	0.0000
lnGas	0.5325	0.1336	3.9840	0.0003	D(lnGas)	0.2906	0.0759	3.8295	0.0004
lnOil	0.2059	0.1336	1.5410	0.1312	D(lnOil)	0.3372	0.0844	3.9923	0.0003
C	− 3.9410	0.2834	− 13.9033	0.0000	CointEq (− 1)	− 0.0748	0.0652	− 1.1477	0.2579
Diagnostic test									
R^2	0.9943	0.9926							
Adjusted R^2	0.9936	0.9918							
F-statistics	1400.972	1377.436							
Prob. F-statistics	0.0000	0.0000							
Durbin-Watson stat	1.2889	1.0446							
χ^2 Arch	0.2786 [0.6003]	0.238[0.6281]							
χ^2 LM	1.6584 [0.1316]	1.255[0.2957]							
χ^2 RESET	9.1764 [0.0043]	0.093[0.7618]							

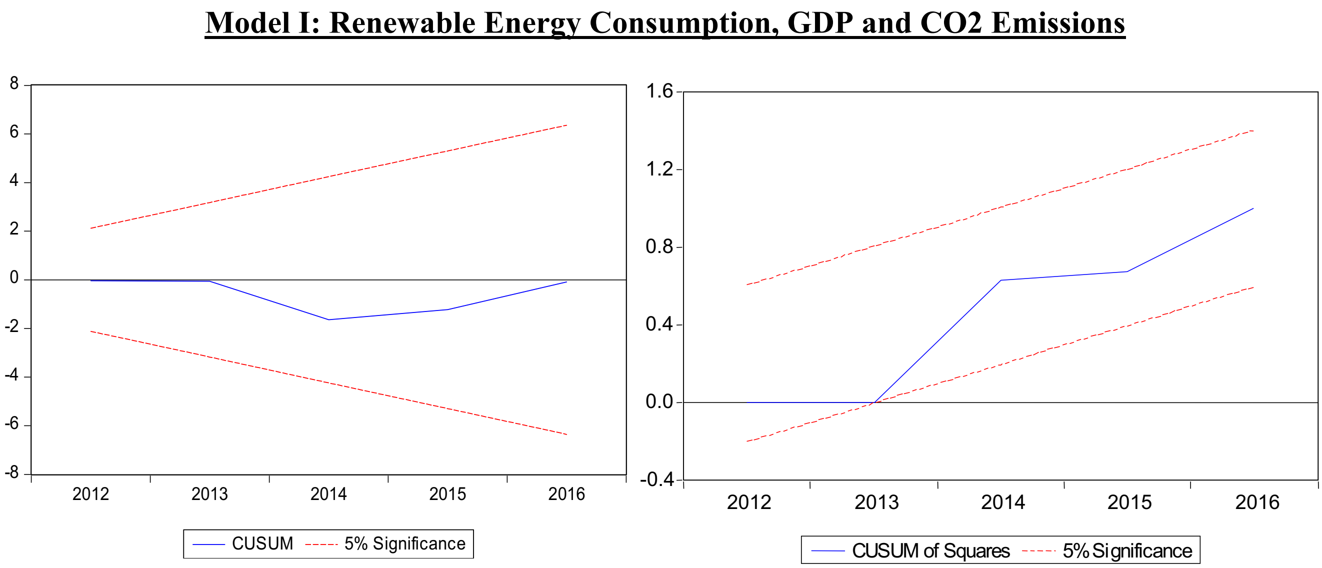

Fig. 1 CUSUM and CUSUM of squares plots of recursive residuals for Model 1

results match Shahbaz et al.'s (2015) results for China, Ahmad et al.'s (2016) results for India, and Mohiuddin et al.'s (2016) results for Pakistan that coal consumption can increase economic development, but its environmental cost is high. Chandran Govindaraju and Tang (2013) also examined a disaggregate link between coal consumption and CO_2 for India and China and found a strong long-run influence of coal consumption on growth and CO_2 emissions for China. China's policy of reducing coal consumption could cut CO_2 emissions but at the cost of economic growth, as is the case for Pakistan. Although coal consumption increases CO_2 emissions, technology can reduce its environmental effects. Policymakers must plan to decrease the share of coal consumption in Pakistan's overall energy mix.

In the long run, natural gas consumption has a positive relationship with CO_2 emissions. Natural gas has the largest share of Pakistan's total energy mix. Alkhathlan and Javid (2015) concluded that natural gas in Saudi Arabia is friendlier to the environment than other energy sources are, but in Pakistan, natural gas is the least environmentally friendly source of energy, so Alkhathlan and Javid's (2015) results contrast ours. The reason for difference may be the difference in economies and the level of reliance on natural gas for energy. This outcome is consistent with Shahzad et al.'s (2017) findings for Pakistan. Where there is heavy dependence on natural gas in the overall energy mix, the sustainability of native sources becomes questionable. Per the estimates of the Planning Commission of Pakistan (2017), at the current speed of consumption, the country's native natural gas resources will be depleted within seventeen years. Therefore, Pakistan must shift its consumption from natural gas to coal or, preferably, more renewable energy sources.

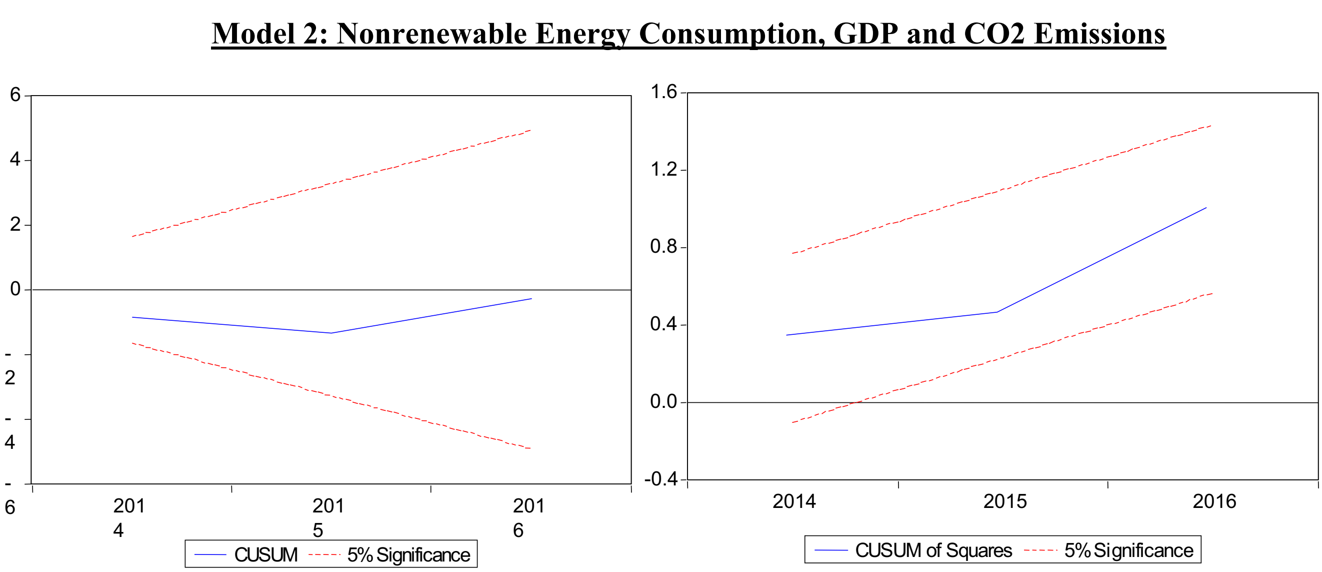

Fig. 2 CUSUM and CUSUM of squares plots of recursive residuals for Model 2

Oil, as the second-largest source of energy consumption in Pakistan, also contributes to the country's CO_2 emissions, although the positive relationship between oil and CO_2 in the country is insignificant. Dependence on oil in Pakistan has increased because of a severe energy crises and a reduction in natural gas resources but besides oil supply, risk has also increased (Mohsin et al. 2018). Exploration of sustainable ways to produce energy in Pakistan is vital. In the short run, as Model 2 indicates, GDP is negatively associated with CO_2 emissions, while all non-renewable energy sources have positive and significant relationships with CO_2 emissions. Therefore, per capita CO_2 emissions are largely affected by the non-renewable energy consumption. This result makes sense since Pakistan's primary sources of energy are mainly non-renewable (natural gas, oil, and coal).

We also performed diagnostic tests to examine the models' stability. Table 4 shows that, on disaggregate levels, there is no serial correlation, heteroscedasticity, or model misspecification. The cumulative sum (CUSUM) and CUSUM of squared recursive residual (CUSUMSQ) plots are executed to ratify that long-run and short-run links are stable. The results are shown in Figs. 1 and 2 for renewable and non-renewable energy sources, respectively.

Model I: renewable energy consumption, GDP, and CO_2 emissions

Model 2: non-renewable energy consumption, GDP, and CO_2 emissions

The CUSUM and CUSUMQ values fall between the upper and lower critical bounds at the 5% levels, indicating the stability and reliability of long-run and short-run dynamics.

Cointegration results indicate the presence of long-run relationships among the variables. We apply the VECM to find the direction of causal relationships. Toda and Philips (1993) indicated that if a long-term relationship exists, then an error correction model can be applied to determine the direction of causality. An error correction model also allows us to differentiate between long-term and short-term Granger causality. VECM Granger causality is determined by using the Wald statistic for all independent variables to determine the difference and lag difference coefficients. Table 5 depicts the causality results for Models 1 and 2, along with the growth and CO_2 emissions.

Short-run causality is determined based on the F-statistic calculated through the Wald test, while long-run causality is calculated with the help of the error correction term (ECT). An ECT_{t-1} that is statistically significant and that has a negative sign is sign of long-run causality (Danish et al. 2018). The econometric equations for Models 1 and 2 are as follows:

$$\text{Model 1}: \begin{bmatrix} \Delta LCO_{2it} \\ \Delta LGDP_{it} \\ \Delta LHyd_{it} \\ \Delta LNuc_{it} \end{bmatrix} = \begin{bmatrix} \delta_1 \\ \delta_2 \\ \delta_3 \\ \delta_4 \end{bmatrix} + \sum_{p-1}^{q} \begin{bmatrix} \theta_{11p} & \theta_{12p} & \theta_{13p} & \theta_{14p} \\ \theta_{21p} & \theta_{22p} & \theta_{23p} & \theta_{24p} \\ \theta_{31p} & \theta_{32p} & \theta_{33p} & \theta_{34p} \\ \theta_{41p} & \theta_{42p} & \theta_{43p} & \theta_{44p} \end{bmatrix} \times \begin{bmatrix} \Delta LCO_{2it-1} \\ \Delta LGDP_{it-1} \\ \Delta LHyd_{it-1} \\ \Delta LNuc_{it-1} \end{bmatrix} + \begin{bmatrix} \alpha_1 \\ \alpha_2 \\ \alpha_3 \\ \alpha_4 \end{bmatrix} ECT_{it-1} + \begin{bmatrix} \mu_{1it} \\ \mu_{2it} \\ \mu_{3it} \\ \mu_{4it} \end{bmatrix}$$

$$\text{Model 2}: \begin{bmatrix} \Delta LCO_{2it} \\ \Delta LGDP_{it} \\ \Delta LCoal_{it} \\ \Delta LOil_{it} \\ \Delta LGas_{it} \end{bmatrix} = \begin{bmatrix} \delta_1 \\ \delta_2 \\ \delta_3 \\ \delta_4 \\ \delta_5 \end{bmatrix} + \sum_{p-1}^{q} \begin{bmatrix} \theta_{11p} & \theta_{12p} & \theta_{13p} & \theta_{14p} & \theta_{15p} \\ \theta_{21p} & \theta_{22p} & \theta_{23p} & \theta_{24p} & \theta_{25p} \\ \theta_{31p} & \theta_{32p} & \theta_{33p} & \theta_{34p} & \theta_{35p} \\ \theta_{41p} & \theta_{42p} & \theta_{43p} & \theta_{44p} & \theta_{45p} \\ \theta_{51p} & \theta_{52p} & \theta_{53p} & \theta_{54p} & \theta_{55p} \end{bmatrix} \times \begin{bmatrix} \Delta LCO_{2it-1} \\ \Delta LGDP_{it-1} \\ \Delta LCoal_{it-1} \\ \Delta LOil_{it-1} \\ \Delta LGas_{it-1} \end{bmatrix} + \begin{bmatrix} \alpha_1 \\ \alpha_2 \\ \alpha_3 \\ \alpha_4 \\ \alpha_5 \end{bmatrix} ECT_{it-1} + \begin{bmatrix} \mu_{1it} \\ \mu_{2it} \\ \mu_{3it} \\ \mu_{4it} \\ \mu_{5it} \end{bmatrix}$$

The results ratify the presence of long-run causality among hydroelectricity, nuclear, GDP, and CO_2 emissions. ECT_{t-1} is significant in the long run for CO_2 emissions, hydroelectricity, and nuclear. Bidirectional causality is present between, nuclear and CO_2 emissions, which suggests that any change in hydroelectricity or nuclear will cause a change in CO_2 emissions and vice versa. Moreover, we observe unidirectional causality from GDP to hydroelectricity, GDP to nuclear, and GDP to CO_2 emissions. However, the short-run results of Model 1 reveal that causality runs in one direction, from GDP to CO_2 emissions, from CO_2 emissions to nuclear, from GDP to nuclear, and from hydroelectricity to nuclear. In the short run, there is no causality between hydroelectricity and CO_2 emissions, between hydroelectricity and GDP, or between hydroelectricity and nuclear. Numerous studies, such as Al-Mulali et al. (2015), Apergis and Payne (2014), Farhani and Shahbaz (2014), Ohler and Fetters (2014), and Yuan et al. (2008), have also confirmed the relationships among renewable energy consumption, economic growth, and CO_2 emissions. Short-run values are shown in the chi-square coefficient and p values, while long-run values are shown through t-statistics and p values.

For Model 2, the long-run results reveal a bidirectional relationship between GDP and coal and between GDP and oil. This result is consistent with Zhang and Yang (2013) and Lim et al. (2014), who examined the disaggregated nexus of energy-emissions growth for China and the Philippines, respectively. There is evidence that CO_2 Granger-causes GDP, as Lim et al. (2014) found that growth can continue without increasing CO_2 emissions. A unidirectional causality

Table 5 Results of VECM Granger causality

Variables	ΔLCO_2	ΔLY	$\Delta LHydro$	$\Delta lnUC$	ECT_{t-1}	
$lnCO_2$	–	4.2144 (0.0401)**	0.1434 (0.7049)	0.0021 (0.9629)	− 0.1615 [0.0570]*	
lnGDP	0.6354 (0.4254)	–	0.7288 (0.3933)	0.2664 (0.6057)	− 0.1227 [0.1509]	
lnHydro	0.3706 (0.5427)	0.0293 (0.8639)	–	1.6489 (0.1991)	− 0.4093 [0.0003]***	
lnN	4.9259 (0.0265)**	3.6658 (0.0555)**	3.6852 (0.0549)*	–	− 0.3158 [0.0122]**	
Variables	ΔLCO_2	ΔLY	$\Delta LCoal$	ΔOil	ΔGas	ECT_{t-1}
$lnCO_2$	–	1.4870 (0.2227)	0.0166 (0.8973)	2.0073 (0.1565)	2.1059 (0.1467)	− 0.0447 [0.5005]
LGDP	7.6829 (0.0056)***	–	1.6150 (0.2038)	7.7220 (0.0055)***	0.9384 (0.3327)	− 0.4031 [0.0021]***
lnCoal	6.1199 (.0134)*	0.0397 (0.8420)	–	0.2289 (0.6323)	7.0110(0.0081)*	− 0.2984 [0.0049]***
lnOil	5.11E-06(0.9982)	1.7714(0.1832)	0.7374(0.3905)	–	0.9206 (0.3373)	− 0.1825 [0.0020]***
lnGas	0.0926 (0.7608)	0.2370 (0.6263)	0.8058 Q(0.3693)	0.9622 (0.3266)	–	0.0065 [0.0638]

*, **, and *** refer to level of significance at 1%, 5%, and 10% respectively

runs from CO_2 to coal, so growing CO_2 emissions per capital increase coal consumption. Neutral causality is observed between oil and CO_2 emissions, between natural gas and CO_2 emissions, between natural gas and GDP, and between natural gas and oil. We endorse the policy of Shahbaz and Lean (2012) that government can protect its GDP rate if it explores alternate energy sources to cater the energy needs of Pakistan. In the short run, CO_2 emissions and oil Granger-cause GDP. CO_2 and natural gas consumption Granger-cause coal consumption in the short run.

Conclusion

This study examines the roles of renewable and non-renewable energy consumption in economic growth and CO_2 emissions at disaggregate levels for Pakistan. The study confirms that energy consumption is central to a country's economic development, but some energy resources are harmful to the environment. For Pakistan, our results indicate that consumption of renewable energy (hydroelectricity and nuclear) produces less CO_2 emissions than non-renewable energy consumption (oil, coal, and natural gas) does. At the disaggregated level, natural gas consumption is a major source of energy production and the main driver of CO_2 emissions, followed by oil and coal consumption.

Pakistan's economy is growing fast, but its growth depends heavily on energy consumption. Increased amounts of energy are needed to cater to the increasing demand from the production, household, and transport sectors, but more energy consumption will add more CO_2 emissions to the air if Pakistan's existing energy mix remains as it is. To achieve the desired growth rate without harming the environmental quality, policymakers should analyze the country's energy mix at disaggregated levels. A polluted environment not only has a negative effect on human health but also deteriorates water quality and agricultural production. Pakistan's government can limit CO_2 emissions by shifting from natural gas energy to other alternatives to lower the environmental burden. As Solarin et al. (2018) suggested, the government should encourage hydropower activities and more projects should be started to expand the hydropower production. Our results show that consumption of natural gas generates more CO_2 pollution than the other energy resources in the country's energy mix. Even so, natural gas reserves are inadequate, whereas coal reserves are ample, so coal is expected to remain the primary source of energy in Pakistan in the future.

The results of this study provide valuable information for policymakers to construct an optimal combination of renewable and non-renewable sources in order to meet the national demand. We put forward a policy such as there is need to plan a strategic mix of all available energy resources in Pakistan to meet the growing economy's energy demands while also reducing CO_2 emissions. The government should also encourage the industrial infrastructure to use high-level technologies for energy conversion. For example, natural gas-to-liquid technologies and coal-bed methane techniques are useful in converting energy to increase efficiency. Similarly, the government should construct more hydroelectricity plants, as hydroelectricity is more environmentally friendly and economical than coal-fired electricity or natural gas.

Moreover, Pakistan's government should use awareness campaigns to encourage and motivate consumers and producers to use energy-efficient technologies to improve the environmental quality. Nuclear power and hydroelectricity are the best alternatives to fossil fuels for helping economic development and reducing CO_2 emissions. Therefore, there is a strong need to increase investment in renewable energy sources like solar power, hydroelectricity, wind, and biofuels to stimulate sustainable development in Pakistan.

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Annexure

Table 6

Authors	Country(s) and period	Variables	Estimation technique	Main findings
Apergis and Payne (2011a)	USA 1949–2006	NRE, RE, Labor, Capital, and GDP	Toda-Yamamoto causality test	No causality found between RE and GDP or NRE and GDP.
Apergis and Payne (2011b)	16 evolving countries. 1990–2007	RE, NRE, EL, GDP, Capital, and Labor	Panel co-integration; Error Correction Model	RE↔GDP in the long run; NRE↔GDP in both the long and short run; GDP Granger-cause RE in the short run.
Vaona (2012)	Italy 1961–2000	GDP, RE, NRE	Toda Yamamoto causality test and Box & Jenkins.	Bidirectioal causality between RE and GDP and between NRE and GDP.
Apergis and Payne (2012)	80 countries 1990–2007	RE, NRE, Capital, Labor, and GDP	VECM Granger causality	Bidirectioal causality between RE and GDP and between NRE and GDP.
Tugcu et al. (2012)	G-7 countries 1980–2009	RE, NRE,GDP, labor, Capital, Human Capital, and PA	ARDL technique	For all countries, RE↔GDP and NRE↔GDP. No causality found between RE and GDP for France, Italy, Canada, and the United States, and no causality reported between NRE and GDP for other countries.
Pao and Tsai (2010)	Brazil 1980–2010	RE, NRE, Capital, Labor, and GDP	VECM Granger causality.	Bidirectioal causality between RE and GDP; GDP Granger causes NRE.
Salim et al. (2014)	OECD countries 1980–2011	RE, NRE, GDP, Labor, Capital	VECM Granger causality.	Bidirectioal causality between RE and GDP and between NRE and GDP.
Shafiei and Salim (2014)	OECD countries 1980–2011	RE, NRE, CO_2, GDP, IND, POP, SER, URB, and PDN	ECM and Granger causality.	NRE↔CO_2; CO^2→RE
Farhani and Shahbaz (2014)	10 MENA countries. 1980–2009	CO_2, GDP and GDP^2 , REL, NREL.	FMOLS and DOLS.	In the long-run, REL↔CO_2 and non-REL↔CO_2. In the short-run, REL→CO_2 and NREL→CO_2.
Ben Jebli and Ben Youssef (2015)	69 countries 1980–2010	RE, NRE, Capital, Labor, Imports, Exports,and GDP.	OLS, FMOLS and DMOLS.	RE→GDP; NRE→GDP.
Bhattacharya et al. (2016)	38 countries 1991–2012	RE, NRE, Labor, Capital, and GDP	Panel Heterogeneous Granger causality	No cuasality found between RE and GDP; unidirectional causality reported from NRE→GDP.
Wesseh and Lin (2016a)	34 African countries 1980–2011	RE, NRE, Labor, Capital, and GDP	TransLn.	RE and NRE Granger-cause GDP.
Wesseh and Lin (2016b)	ECOWAS countries 1980–2011	RE, NRE, Labor, Capital, and GDP	TransLn.	RE and NRE Granger- cause GDP.
Muhammad et al. (2014)	Pakistan 1991–2012	RE, NRE, GDP, CO_2	Structure VAR	RE, NRE, and CO_2 Granger-cause GDP.
Long et al. (2015)	China 1952–2012	RE, NRE, GDP, CO_2	Static and dynamic regression; Granger causality	Bidirectional causality found betweeen GDP and CO_2, between GDP and Natural gas, and between GDP and Energy Consumption.
Ito (2017)	42 developed countries 2002–2011	RE, NRE, GDP, CO_2	GMM and PMG	RE decreases CO_2. RE has a positive influence on growth. NRE has a negative influence on growth. RE and NRE are substitutes.

Table 7 Literature on disaggregated renewable and non-renewable energy consumption, economic growth, and CO_2 emissions

Author & Year	Country(s) & scope	Variables	Estimation methods	Main findings
Ohler and Fetters (2014)	20 OECD economies 1990–2008	Biomass Consumption, Hydro, Waste, RE, Solar, Capital, Labor, And GDP	VECM Granger causality	All renewable sources Granger-cause the GDP.
Yuan et al. (2008)	China 1963–2005	Oil, Coal, Capital, EM, Electricity, and GDP.	VECM Granger causality.	Oil and GDP Granger-cause each other, while GDP has causal effect on CO_2 Emissions.
Ziramba (2009)	South Africa 1980–2005	Coal, Electricity, Oil, Labor, Capital, and GDP	Toda-Yamamoto; Granger-causality.	Oil and GDP Granger-cause each other; there is a neutral relationship between Coal and GDP.
Lotfalipour et al. (2010)	Iran 1967–2007	Fossil fuels, Oil, Natural Gas, GDP, and CO_2.	Toda-Yamamoto; Granger causality.	Oil and Natural Gas consumption Granger-cause CO_2, while neutrality is found between Fossil Fuel and CO_2.
Marvão Pereira and Marvão Pereira (2010)	Portugal 1977–2003	GDP, EM, Investment, Coal, Natural Gas, Oil, Bio Electricity, and Energy Consumption	VAR	Oil and Natural Gas Granger-cause both CO_2 and GDP. There is bidirectional causality between Coal and CO_2 and between GDP and Coal.
Lean and Smyth (2010)	Malaysia 1980–2011	Capital, Labor, Energy Sources	ARDL technique	GDP Granger causes Oil, Natural Gas, Coal, and Diesel.
Zhang and Yang (2013)	China 1978–2009	GDP, Capital, Labor, Coal, Natural Gas, Oil, and Energy Consumption	Toda-Yamamoto; Granger causality	Bidirectional causality reported between Oil and GDP, Oil and GDP, and Coal and GDP.
Akhmat and Zaman (2013)	South Asia 1975–2010	GDP, Natural Gas, Coal, Oil, Nuclear, and Electricity	Bootstrap panel causality test	Bidirectional causalities reported between Oil and GDP for the Maldives, Bhutan, Nepal, and Sri Lanka. Unidirectional causality from GDP→Natural Gas for Nepal, Pakistan, and Sri Lanka.
Alkhathlan and Javid (2013)	Saudi Arabia 1980–2011	Energy Consumption, Natural Gas, Oil, CO_2, Electricity, and GDP	VECM Granger causality	Oil Granger-causes CO_2; bidirectional causality between Natural Gas & GDP, Oil & GDP, and also Natural Gas and CO_2.
Saboori and Sulaiman (2013)	Malaysia1 1980–2009	Oil, CO_2 Natural Gas, CO_2, and GDP	VECM Granger causality.	Bidirectional causality between CO_2 and oil; Oil and GDP. One-way causality from Coal to GDP and coal to CO_2.
Lach (2015)	Poland 2000–2009	Oil, Natural Gas, EM, and GDP	Toda–Yamamoto Test; VECM causality	In the short-run, Oil→GDP, Natural Gas→GDP. In the long run, GDP Granger causes Oil and Natural Gas.
Bildirici and Bakirtas (2016)	BRICTS countries. 1980–2011	GDP, Natural Gas, Coal, and Oil.	VECM Granger	Bidirectional long-run causality Oil↔GDP in all countries and Natural Gas↔GDP in Brazil and Turkey. In the short-run, Natural Gas↔GDP in Brazil, Russia, and Turkey; GDP→Natural Gas and GDP→Oil in Russia; Oil→GDP in India, Brazil, and Turkey; and Coal↔GDP in China and India.
Ahmad et al. (2016)	India 1971–2014	Energy Consumption, Oil, Natural Gas, Electricity	ARDL; VECM Granger causality	Bidirectional causality EC↔CO_2 emissions, EC↔growth, and CO_2↔GDP.

Table 8 Johansen cointegration test results

Model 1: Renewable Energy Consumption					
Hypothesized No. of CE(s)	Trace statistic	Prob.**	Trace statistic	Prob. **	Co-integration
None *	54.80309	0.0097	30.40525	0.0211	
At most 1	24.39784	0.1841	16.99120	0.1724	
At most 2	7.406634	0.5308	7.358617	0.4476	
At most 3	0.048017	0.8265	0.048017	0.8265	
Model 2: Non-Renewable Energy Consumption					
Hypothesized No. of CE(s)	Max-Eigenstatistic	Prob. **	Max-Eigen statistic	Prob. **	Co-integration
None *	89.04835	0.0007	42.19533	0.0041	Yes
At most 1	46.85302	0.0619	23.17822	0.1660	No
At most 2	23.67480	0.2145	12.96980	0.4550	No
At most 3	10.70500	0.2303	7.567486	0.4244	No
At most 4	3.137517	0.0765	3.137517	0.0765	No

The trace test and the maximum eigen statistic reveal one cointegrating equation at the 5% significance level

* refers to rejection of the hypothesis at the 5% significance level

** p-values from MacKinnon-Haug-Michelis (1999)

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