



Asymmetric causality among renewable energy consumption, CO₂ emissions, and economic growth in KSA: evidence from a non-linear ARDL model

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Abstract

This study applies asymmetric causality to renewable energy (REC), carbon dioxide emissions (CE), and real GDP using non-linear broadcasting between these variables through the non-linear autoregressive distributed lag model (NARDL) to examine the short- and long-run asymmetries in the inconsistency of greenhouse gas emissions among the variables and to unpack the asymmetric causality of selective variables through positive and negative shocks for time series data from the Kingdom of Saudi Arabia between 1990 and 2014. The bounds cointegration test shows the existence of long-term dealings among all considered variables in the presence of asymmetry. The non-linear asymmetric causality test shows that negative shocks in carbon dioxide emissions had only positive impacts on real GDP in the long-term but are unobservable in the short-term. Additionally, the short- and the long-term incidences of positive shocks on real GDP are not similar to the negative shock to REC, implying the existence of asymmetric impacts on REC in both short- and long-term forms. Finally, the asymmetric causal relationship from carbon dioxide emissions to REC is neutral in the long-term. Both positive and negative shocks to REC consistently had an adverse effect on CE in the long-term. The presence of asymmetry between economic growth, CE, and REC could be of major substantial for more helpful policymakers and the action plan of sustainable development goals (SDGs) in Saudi Arabia.

Keywords Real GDP · Carbon dioxide emissions · Renewable energy · Asymmetry

JEL classification C33. O57. Q20. Q30

Introduction

According to the 21st Conference on Climate Change (COP 21) in Paris in 2015, the green energy initiatives of developed and developing countries aim to maximize the energy

production capacity of 300 GW by the year 2030 while addressing serious problems related to the mitigation of traditional power and reducing the emissions of carbon dioxide (IEA 2015). Furthermore, the Kingdom of Saudi Arabia (KSA) aims to maximize renewable energy sources in their total energy budget through the National Renewable Energy Program (NREP) by 9.5 GW by 2023 (Ministry of Energy, Industry and Mineral Resources, 2017) based on forecasting for 2030, and this aim will gradually create a new renewable industry that will lead to minimizing CO₂ emissions and global warming.

The objective of Vision 2030 is to increase renewable energy production by at least 9.5 GW over the same period (by 2030). Renewable energy could account for an important part of the electricity generation sector by 2030 through reducing carbon dioxide emissions and minimizing the cost of electricity production. Furthermore, in the last two decades, the consumption of renewable energy in the total energy is increased and becomes clearly observed (Sinha and Shahbaz 2018).

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Economic growth is accelerating throughout the world, but many countries suffer from a lack of energy capacity, notably in electricity production. Renewable energy consumption must be augmented by at least twofold by 2030 to accompany development and meet the demand for electricity. To do so, renewable energy consumption is becoming the most economical option in an increasing number of situations. Furthermore, renewable technologies are available and reliable at increasingly competitive prices in developed and developing countries. It is now up to the nations of the world to create conditions conducive to speed up the improvement of renewable energy to pave the way for unimpeded sustainable development.

Saudi Arabia's National Voluntary Review was sustained by the United Nations Sustainable Development Goals in 2018. Goal 7 of the SDGs assures access to sustainable and modern energy for all and increases significantly the part of worldwide renewable energy by 2030. Saudi Arabia which delivered a National Action Plan for the achievement of the 2030 vision for sustainable development identified 17 Goals by 2030 (United Nations 2018).

The aim SDGs in Saudi Arabia attempts to ensure universal access to green energy utilities. In addition, SDGs has become the strategy of 2030 vision in the Kingdom of Saudi Arabia, and one of the most substantial confrontations, furthermore, SDGs have an anxious purpose related to increasing energy access and improving climate change planning. Sustainable development needs green energy consumption in the Kingdom of Saudi Arabia. The renewable energy use used to enable social and economic development and the increase of carbon dioxide emissions led them. In addition, the Kingdom of Saudi Arabia might still able to reach universal energy access by 2030. Furthermore, the presence of long-term asymmetries between economic growth, and renewable energy in the first step, and renewable energy and carbon dioxide emissions in the second step could be of major substantial for more helpful policymaking and the action plan of SDGs in Saudi Arabia economy.

The lag from fossil fuels to green energy such as renewable energy consumption is becoming more and more urgently. This action project is one of the large efforts in the development of the institutional framework in compliance with the target for sustainable development goals in KSA. It is anticipated that renewable energy development will help to reach the targets which have been set under this vision plan with their great potential.

The causal nexus between GDP and energy use (renewable energy consumption), such that economic growth and CO₂ emissions, has been a matter of diverse research in the past two decades. A various investigation has examined the relationship between renewable energy, carbon dioxide emissions, and real GDP, in linear regressions, but few studies have been devoted to the asymmetric relationship between chosen

variables. Thus, this study tested the asymmetric causality relationship between REC, real GDP, and carbon dioxide emissions in the KSA. We use the non-linear autoregressive distributed lag model (NARDL) to discuss the short- and long-term asymmetries in the instability of carbon dioxide emissions between the selected variables and demonstrate the trend of causality between them through the negative and positive shocks of explicative variables. The rest of the document is organized as follows: the methodology and the data used are presented in the “Data and methodology” section, the “Empirical results” section presents the empirical analysis, and the “Conclusions” section concludes this paper.

Literature review

An important literature review has been attempted to ascertain the dynamic relationship between renewable energy consumption, carbon dioxide emissions, and real GDP, but the literature that highlights this linkage between economic growth and energy consumption is a synthesis of the environmental Kuznets curve (EKC) developed by Kuznets (1955). For the last quarter of a century, Grossman and Krueger (1991) have been investigating the EKC assumption, which indicates that ECK is the most popular approach among researchers to show the linkage between pollution and global emissions. Indeed, EKC shows the disciplines working on global climate change and the convergence between pollution and concentration, Stern (2017). Owing to the Granger causality direction hypothesis (growth, feedback, conservation, and neutrality) between energy consumption, economic growth, and carbon dioxide, our literature review is organized into the following three categories.

First, the causality linkage between economic growth and energy consumption was explained by Ozturk (2010) and Payne (2010); in addition, the confirmed growth hypothesis between energy consumption and economic growth has been inspected by Apergis and Payne (2009a) in six Central American countries spanning the period from 1980 to 2004. The long-term relationship illustrated by the bounds test cointegration confirmed a positive and statistically substantial relationship between real GDP and energy consumption, but the growth hypothesis between these two variables is confirmed by the Granger causality test in both short- and long-term relationships. Furthermore, the growth hypothesis between real GDP and energy consumption has been used in a study by Narayan and Smyth (2008) in a panel of G7 countries. These findings shown by the Granger causality test demonstrate that energy use causes positive economic growth in the long-term, and an increase of 1% in energy consumption increases economic growth by 0.12–0.39%. The growth and the conservation hypothesis between both variables are confirmed by Apergis and Tang (2013) in differentiated

economies among 85 countries. The empirical results proved that both developed and developing economies led the growth hypothesis, but the conservation hypothesis is more appropriate for low-income countries in the Granger causality tests. Additionally, the growth and conservation hypothesis between energy use and revenue are assumed in energy economics. The two-way relationship between both variables was discovered in Argentina, but energy conservation has arisen in Turkey, France, Germany, and Japan, according to Soytaş and Sari (2003). Moreover, in sub-Saharan Africa, the improvement and conservation hypothesis appeared: the Granger causality dealings among energy consumption and income are bi-directional for Gambia, Ghana, and Senegal, and the Granger causality running from real GDP to energy use is unidirectional in Sudan and Zimbabwe; however, the causality link is unobservable in Nigeria, Kenya, and Togo, Akinlo (2008). Additionally, the growth and feedback hypothesis among per capita energy use and GDP are confirmed for Tunisia from 1971 to 2004, as seen by Belloumi (2009). The empirical estimation by an error correction model (ECM) implied a bi-directional long-run relationship between these two variables and unidirectional short-run causality running from energy use to real GDP. Another study by Apergis and Payne (2009b) considered the growth and feedback hypothesis between energy use and real GDP in the Commonwealth countries from 1991–2005. The empirical findings by an error correction term (ECT) reveal bi-directional causality linkages among non-renewable energy, economic growth, and unidirectional short-run causality running from non-renewable energy to real domestic product.

Furthermore, a feedback hypothesis between these two variables (growth and energy consumption) is examined by Fuinhas and Marques (2012) in the southern European Union for the period from 1965 to 2009. The empirical result by an ARDL boundary testing approach suggests a bi-directional causal link among both variables in pairs for long- and short-run causality. Likewise, the response hypothesis is confirmed between energy consumption and real GDP in 21 African districts spanning the period from 1970–2006, according to Eggoh et al. (2011). The empirical estimation by a panel cointegration approach shows an expansion or reduction in energy consumption, restoring or reducing the real GDP in the selected countries. Kaplan et al. (2011) inspected the nexus relationship between power and real GDP in Turkey during the period from 1971–2006. The empirical parts of both models produced by an ECM stipulate that the assumption of feedback is confirmed between both variables. Likewise, the feedback assumption between non-renewable energy and real GDP is apparent in a study by Belke et al. (2011) in 25 OECD regions during the period from 1981 to 2007. The panel cointegration technique shows bi-directional linkages between energy use and GDP. Additionally, Apergis and Payne (2010a) examined the linkage between non-

renewable energy and real GDP. This study used a panel cointegration method involving the fully modified ordinary least squares (FMOLS) estimation in nine South American countries during the period 1980–2005. The results from the Granger causality test showed a bi-directional long-run association among both these variables, which confirmed the feedback hypothesis. A neutrality hypothesis between energy consumption and income has been confirmed by the research of Soytaş et al. (2007) in the USA. The long-term Granger causality dealings between income and energy consumption are unobservable.

The dynamic links among renewable energy and GDP investigation comprise the second section of this literature review. The growth hypothesis between renewable energy and income is confirmed by Chien and Hu (2007) in 45 OECD and non-OECD districts from 2001–2002. The data envelopment analysis (DEA) model shows that an augmentation in renewable energy increases real GDP. Apergis and Payne (2010b) also inspected the linkages among renewable energy and gross domestic product in 20 OECD countries through the period from 1985 to 2005. The panel cointegration technique reveals a positive and statistically significant long-term relationship among renewable energy and real income; in addition, the Granger causality tests indicate bi-directional causality linkages running from renewable energy to real income in both the short- and long-term. Fang (2011) considered the long-run relationship among renewable energy and economic welfare in China spanning the period between 1978 and 2008. The empirical results of multivariate OLS regression showed that growth in renewable energy restored economic growth. Furthermore, Tiwari (2011) found the dynamic relationship between renewable energy and gross domestic product through a structural VAR approach. The generalized variance decomposition analysis reveals that a positive shock on the renewable energy transformed real GDP. In addition, the feedback hypothesis between renewable and GDP is confirmed by Apergis and Payne (2010c) in 13 countries of Eurasia from 1992 to 2007. The panel cointegration technique reveals a long-term relationship between both variables and bi-directional causal links in both the short and the long-term. In addition, the conservation hypothesis between renewable energy consumption and real income is detected in emerging economies, according to Sadorsky (2009). The empirical findings reveal a 1% expansion in real income expanded renewable energy consumption by 3.5% in the long-term, but the neutrality hypothesis between both variables is confirmed in European countries by Menegaki (2011) from 1997–2007. The empirical findings showed that Granger causality tests are unobservable between renewable energy and gross domestic product.

Third, the nexus linkages among renewable energy, CO₂ emissions, and gross domestic product studies comprise the final section of the literature review. Apergis et al. (2010)

tested the causal dynamic links among carbon dioxide emissions, renewable energy, and economic growth in 19 emerging and developing economies spanning the period from 1984 to 2007. The empirical evaluation by an ECM showed a long-term substantial relationship between carbon dioxide emissions and renewable energy, although renewable energy does not appear to decrease emissions in the short-run. Bento and Moutinho (2016) showed the existence of a causal linkage between CO₂ emissions, renewable electricity production, and real GDP in Italy over the period from 1960–2011. The panel cointegration technique using an ARDL approach indicates a negative relationship between per capita renewable electricity production on carbon dioxide in both short and long-term relationships. In addition, the Granger causality test shows unidirectional linkages running from the output to renewable electricity in the long-term. Irandoust (2016) investigated where the relationships between renewable energy and carbon dioxide emissions in Nordic countries exist. The obtained results by a vector autoregressive model indicate that the direction of causality from renewable energy consumption to carbon emissions in Denmark and Finland is unidirectional but is bi-directional in Sweden and Norway, and the direction of causality of renewable energy to real GDP is unobservable across the whole panel.

Jebli and Belloumi (2017) examined the causal relationship between carbon emissions, GDP growth, and combustible renewable energy in Tunisia from 1980–2011. The empirical evaluation of an ARDL approach shows a unidirectional causal link generated from real GDP and renewable energy to carbon emissions. Jebli and Youssef (2015) examined the causal links among renewable energy and wasteful consumption, real GDP, and carbon emissions for five North African regions from 1971 to 2008. The long-term estimation by a panel of cointegration techniques indicates a positive incidence of carbon emissions and renewable energy consumption to real GDP. Furthermore, the Error Correction Term (ECT) shows the existence of both short and long-term causality issued from combustible renewable, waste consumption, and carbon dioxide to economic growth. Likewise, Dogan and Seker (2016) described the findings of the environmental Kuznets curve (EKC) in the European Union from 1980–2012. The Dumitrescu-Hurlin heterogeneous causality approach indicates that the causal link among renewable energy and carbon dioxide emissions is bi-directional, and the causality running from real GDP to carbon dioxide emissions is unidirectional. Furthermore, Attiaoui et al. (2017) examined the relationships between renewable energy, CO₂ emissions, and real GDP in Africa over the period from 1990 to 2011. The empirical estimation by a PMG approach shows that the causality running from renewable energy to GDP is unidirectional if we test individual variables and bi-directionality between renewable energy, carbon dioxide, and real GDP when testing variable pairs. When analyzing developing

economies, Paramati et al. (2017) attempted to test the significance of renewable energy for the economic output spanning the period from 1990 to 2012. The heterogeneous non-causality test shows that the relationship between both variables is affirmative and negatively strained carbon dioxide emissions. Sinha et al. (2018) tested the causal links between carbon dioxide emissions, economic growth, and renewable energy in the next eleven countries over the period 1990–2016. The Geweke causality test confirms that the policy framework can be elected by enhancing causality test results.

Concerning the linkage between, carbon dioxide emissions, economic growth, and renewable energy, the nexus relationship between variables have exposed different results in the presence of asymmetries, positive and negative changes of the illustrative variables in both short and long-term are observed (Katrakilidis and Trachanas 2012). Shahbaz et al. (2015) examined the relationship between renewable energy and economic growth by the ARDL model in Pakistan over the period 1972–2011. The results of the Granger causality test show an evidence conflict in the policy implications. Rafindadi (2016) tested the causal links between economic growth, energy consumption, financial development, trade openness, and carbon dioxide emissions during the period 1971–2011. The ARDL bounds testing approach by the Granger causality test shows that financial development ameliorates energy use and increases carbon dioxide emissions. Furthermore, in the case of Nigeria, the divergence in policy implications has appeared. Likewise, Ibrahim (2016) examined the causal relationship between carbon dioxide emissions, economic growth, energy consumption, trade openness, and population density in Egypt over the period 1980–2010. The researcher denotes that the existence of divergence in policymaking can be observed. The presence of asymmetry between economic growth, carbon dioxide emissions, and renewable energy could be of major substantial for more helpful policymakers and the action plan of SDGs in Saudi Arabia economy. Furthermore, in order to propose to appear policy implications for the SDGs in Saudi Arabia about renewable energy, the asymmetric causal effects, by the non-linear Autoregressive Distributed Lag model (NARDL) between the selected variables, must be robust by the non-parametric causality tests.

Data and methodology

Data

This document examines the asymmetric causality among renewable energy, real GDP, and carbon dioxide emissions in the Kingdom of Saudi Arabia from 1990 to 2014 that encloses real GDP per capita calculated in constant 2005 dollars, carbon dioxide emissions (CE) quantified in metric tons per

Table 1 Descriptive statistics of variables

	CE	GDP	REC
Mean	2.728914	10.53272	0.013004
Median	2.799110	10.43821	0.009118
Maximum	2.971914	10.87097	0.037985
Minimum	2.346163	10.21981	0.006009
Std. Dev.	0.184460	0.184410	0.009632
Skewness	-0.697243	0.437939	1.655551
Kurtosis	2.375587	1.957819	4.301875
Jarque-Bera	2.431755	1.930526	13.18570
Probability	0.296450	0.380883	0.001370
Sum	68.22285	263.3181	0.325104
Sum Sq. Dev.	0.816614	0.816166	0.002227
Observations	25	25	25

capita, renewable energy (REC) measured by renewable fuels, and waste % of total energy established in thousands of metric tons. All variables are selected from the database of the World Bank (2017). Logarithmic processing has been applied from the per capita GDP and the greenhouse gas emissions, but

renewable energy consumption is measured in proportion. Table 1 reveals the minimum and the maximum values of the real GDP, REC, and carbon dioxide emissions, as well as the mean and number of observations for these selected variables. The highest value of carbon dioxide emissions in the KSA is 2.97, the real GDP is 10.87, and REC is 0.037, but the lowest values in these three variables are 2.34, 10.21, and 0.006, respectively.

To represent the asymmetrical relationship between REC, CE, and real GDP, positive and negative components are represented by the cumulative function of positive and negative shocks of these three variables, as reported in Hatemi-J (2012). The time plot of REC, carbon dioxide emissions, and real GDP along with the cumulative function of the positive and negative components of these three variables are represented in the Fig 1.

Methodology

The goal of this research is to investigate the asymmetric causal links among REC, CE, and real GDP in the KSA by applying the non-linear autoregressive distributed lag model

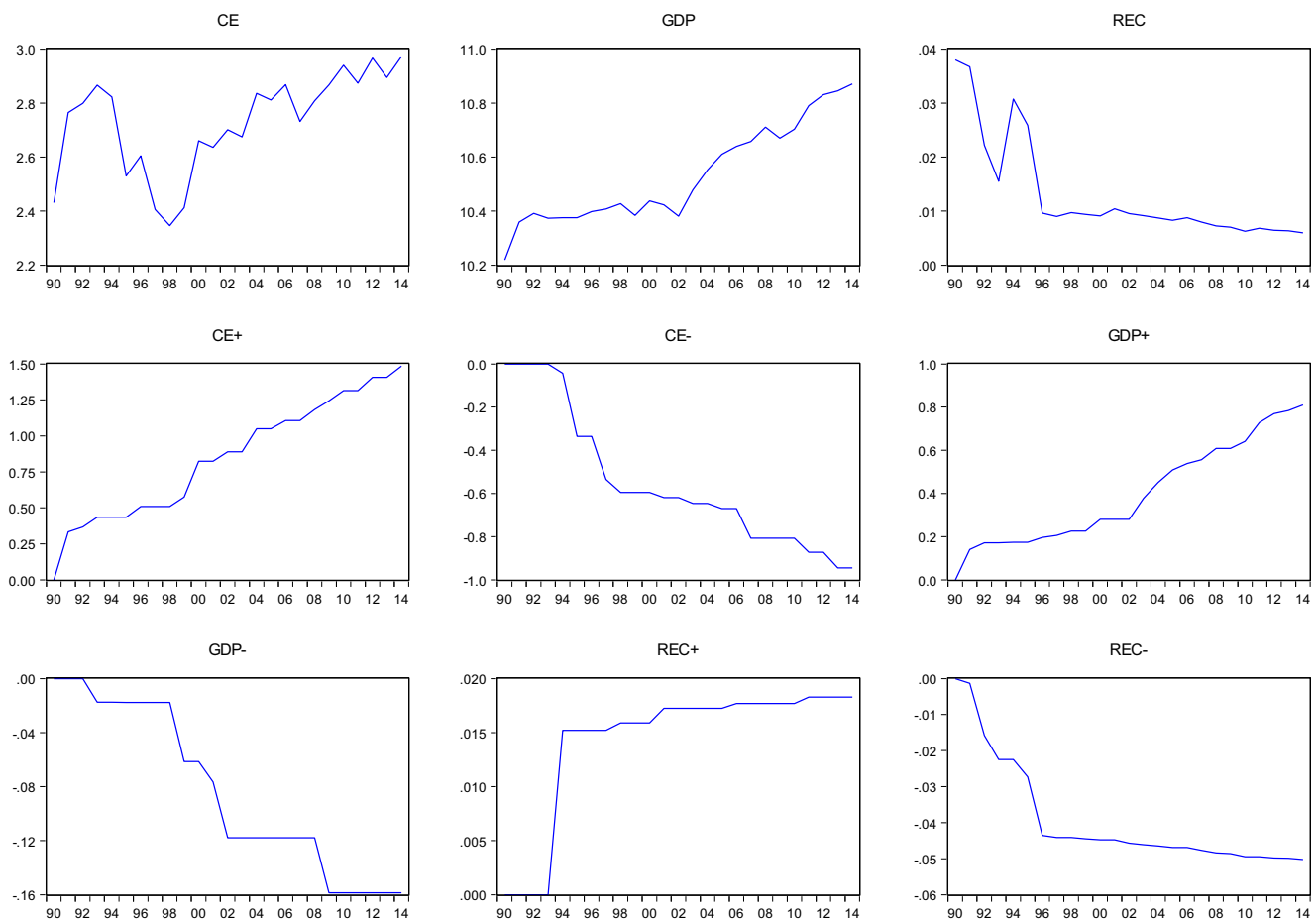


Fig. 1 Plot of CO₂ emissions, real GDP, and REC as well as their partial sum of positive and negative changes. Notes: The positive of partial sum of all variables are represented by the positive sign (+), and the negative of partial sum of all variables are represented by the negative sign (-)

Table 2 Unit root tests without the structural break: series at level

	Intercept	Trend	Intercept	Trend	Intercept	Trend
	CE		CE ⁺		CE ⁻	
Fisher-ADF	-1.9939 (0.2873)	-2.3113 (0.4125)	-1.5690 (0.4824)	-1.6266 (0.4541)	-1.2834 (0.6200)	-3.2080 (0.1097)
Fisher-PP	-2.1811 (0.2176)	-2.5519 (0.3029)	-2.9123 (0.1805)	-4.8408 (0.0038)	-1.2997 (0.6125)	-1.6194 (0.7546)
	REC		REC ⁺		REC ⁻	
Fisher-ADF	-2.0076 (0.2815)	-3.0249 (0.1463)	-2.3469 (0.1665)	-2.0118 (0.5658)	-3.7594 (0.0095)	-3.9136 (0.0282)
Fisher-PP	-2.947 (0.0547)	-3.0249 (0.1463)	-2.3713 (0.1598)	-2.0118 (0.5658)	-2.3197 (0.4085)	-4.9168 (0.0032)
	GDP		GDP ⁺		GDP ⁻	
Fisher-ADF	-0.3797 (0.8978)	-1.7919 (0.6768)	-0.1959 (0.9266)	-1.6155 (0.7562)	-0.7205 (0.8231)	-2.1666 (0.4854)
Fisher-PP	-0.3667 (0.9001)	-1.7919 (0.6768)	-0.2357 (0.9210)	-1.6155 (0.7562)	-0.6828 (0.8329)	-2.1666 (0.4854)

This table indicates the statistics of the time series unit root tests without a structural break. The values in parentheses are the corresponding *p* values

(NARDL) developed by Shin et al. (2014) and to identify asymmetry between all variables by considering the changes in dependent and explicative variables. The long-run asymmetry cointegration between variables Z_t and W_t requires that two variables have a unit root test and are integrated into order one $I(1)$. The long asymmetric cointegration between both variables denotes the subsequent assimilation in Eq. (1).

$$w_t = \beta^+ z^+_t + \beta^- z^-_t + \varepsilon_t \tag{1}$$

where z^+ and z^- are the effects of positive and negative changes in selected variables, respectively.

The cumulative function of positive and negative changes in real GDP, renewable energy consumption (REC), and carbon dioxide emissions (CE) are respectively structured as follows:

$$GDP^+ = \sum_{j=1}^t \Delta GDP^+_j = \sum_{j=1}^t \max(\Delta GDP_j, 0); GDP^- = \sum_{j=1}^t \Delta GDP^-_j = \sum_{j=1}^t \min(\Delta GDP_j, 0) \tag{2}$$

$$REC^+ = \sum_{j=1}^t \Delta REC^+_j = \sum_{j=1}^t \max(\Delta REC_j, 0); REC^- = \sum_{j=1}^t \Delta REC^-_j = \sum_{j=1}^t \min(\Delta REC_j, 0) \tag{3}$$

$$CE^+ = \sum_{j=1}^t \Delta CE^+_j = \sum_{j=1}^t \max(\Delta CE_j, 0); CE^- = \sum_{j=1}^t \Delta CE^-_j = \sum_{j=1}^t \min(\Delta CE_j, 0) \tag{4}$$

To discuss the asymmetrical short- and long-run dynamic cointegration among REC, real GDP, and carbon dioxide emissions, we introduce the positive and negative changes for the considered variables in the linear ARDL model developed by Pesaran et al. (2001). The NARDL of Shin et al. (2014) is presented as follows by the subsequent formulation:

$$\Delta GDP_t = \rho GDP_{t-1} + \Phi^+_1 REC^+ + \Phi^-_1 REC^- + \Phi^+_2 CE^+ + \Phi^-_2 CE^- + \sum_{i=1}^{p-1} \rho_i GDP_{t-i} + \sum_{i=0}^q \gamma^+_1 \Delta REC^+_{t-i} + \sum_{i=0}^q \gamma^-_1 \Delta REC^-_{t-i} + \sum_{i=0}^q \gamma^+_2 \Delta CE^+_{t-i} + \sum_{i=0}^q \gamma^-_2 \Delta CE^-_{t-i} + u_t \tag{5}$$

$$\Delta CE_t = \rho CE_{t-1} + \Phi^+_1 REC^+ + \Phi^-_1 REC^- + \Phi^+_2 GDP^+ + \Phi^-_2 GDP^- + \sum_{i=1}^{p-1} \rho_i CE_{t-i} + \sum_{i=0}^q \pi^+_1 \Delta REC^+_{t-i} + \sum_{i=0}^q \pi^-_1 \Delta REC^-_{t-i} + \sum_{i=0}^q \pi^+_2 \Delta GDP^+_{t-i} + \sum_{i=0}^q \pi^-_2 \Delta GDP^-_{t-i} + v_t \tag{6}$$

Table 3 Unit root tests without structural break: series in the first difference

	Intercept	Trend	Intercept	Trend	Intercept	Trend
	Δ (CE)		Δ (CE ⁺)		Δ (CE ⁻)	
Fisher-ADF	-5.9209 (0.0001)	-5.7977 (0.0005)	-7.9450 (0.0000)	-9.7139 (0.0000)	-2.6380 (0.0000)	-5.1352 (0.0004)
Fisher-PP	-5.9584 (0.0001)	-5.8811 (0.0004)	-7.5519 (0.0000)	-9.1692 (0.0000)	-2.9132 (0.0000)	-5.2809 (0.0016)
	Δ (REC)		Δ (REC ⁺)		Δ (REC ⁻)	
Fisher-ADF	-4.6722 (0.0012)	-4.9089 (0.0035)	-4.8964 (0.0007)	-5.2558 (0.0017)	-3.6288 (0.0132)	-4.8802 (0.0037)
Fisher-PP	-4.6722 (0.0012)	-4.9089 (0.0035)	-4.8964 (0.0007)	-5.2558 (0.0017)	-4.1451 (0.0039)	-4.8752 (0.0038)
	Δ (GDP)		Δ (GDP ⁺)		Δ (GDP ⁻)	
Fisher-ADF	-5.2729 (0.0003)	-5.4332 (0.0001)	-5.1427 (0.0004)	-5.4112 (0.0012)	-5.0567 (0.0005)	-4.9554 (0.0032)
Fisher-PP	-5.3539 (0.0003)	-7.3654 (0.0000)	-5.0774 (0.0005)	-5.9347 (0.0004)	-5.0602 (0.0005)	-4.9716 (0.0031)

This table indicates the statistics of the time series unit root tests without a structural break. The values in parentheses are the corresponding *p* values

Table 4 Bounds cointegration test

Dependent variable	F-Statistic	Prob.	Result
Carbon dioxide	7.325	0.0011***	Cointegration
Real GDP	8.664	0.006***	Cointegration
Renewable energy	6.623	0.016**	Cointegration

*** and ** denote significance at 1% and 5% levels, respectively

$$\begin{aligned} \Delta REC_t = & \rho REC_{t-1} + \Phi_1^+ GDP^+ + \Phi_1^- GDP^- + \Phi_2^+ CE^+ \\ & + \Phi_2^- CE^- + \sum_{i=1}^{p-1} \rho_i REC_{t-i} \\ & + \sum_{i=0}^q \delta_{1i}^+ \Delta REC_{t-i}^+ + \sum_{i=0}^q \delta_{1i}^- \Delta REC_{t-i}^- \\ & + \sum_{i=0}^q \delta_{2i}^+ \Delta CE_{t-i}^+ + \sum_{i=0}^q \delta_{2i}^- \Delta CE_{t-i}^- + \varepsilon_t \end{aligned} \quad (7)$$

where $t = 1990, 0.2014; j = 1, \dots, q-1; \beta^+ = \Phi_1^+ / \rho; \beta^- = \Phi_1^- / \rho; \Delta$ is the first operator. The exhibitors (+) and (-) in three models (5, 6, and 7) show the positive and negative changes for variables. P and Q clarify the lag orders for both dependent and explicative variables, respectively. The lag selection is fixed by the Akaike information criterion (AIC).

In the dynamic non-linear models (5, 6, and 7), the asymmetric long-run cointegration is tested by the equality of the coefficient of positive and negative constraint in the individual variables $\Phi_1^+ = \Phi_1^-$ by using the Wald test.

The long-term coefficient of the positive and negative changes in variables is identified by $\beta^+ = -\Phi_1^+ / \rho$ and $\beta^- = -\Phi_1^- / \rho$. The long-run asymmetry in the three models (positive and negative changes) is tested by $H_0: \rho = \Phi_1^+ = \Phi_1^- = \Phi_2^+ = \Phi_2^- = 0$ against the alternative hypothesis $H_1: \rho \neq \Phi_1^+ \neq \Phi_1^- \neq \Phi_2^+ \neq \Phi_2^- \neq 0$ Pesaran et al. (2001). Furthermore, the positive long-run asymmetry is tested by $H_0: \rho = \Phi_1^+ = \Phi_2^+ = 0$ against the alternative hypothesis $H_1: \rho \neq \Phi_1^+ \neq \Phi_2^+ \neq 0$. In addition, the negative long-run asymmetry is tested by $H_0: \rho = \Phi_1^- = \Phi_2^- = 0$ against the alternative hypothesis $H_1: \rho \neq \Phi_1^- \neq \Phi_2^- \neq 0$.

Table 5 NARDL estimation result (CO₂ is the dependent variable)

Variable	Coefficient	t-Statistic	Prob.
CE(-1)	-0.452434*	-1.882496	0.0892
GDP ⁺	-0.518377	-1.317743	0.2170
GDP ⁻	-2.967601	-1.676756	0.1245
REC ⁺	-114.9655**	-2.427255	0.0356
REC ⁻	-66.03927**	-2.247411	0.0484
Δ (CE(-1))	-0.069033	-0.261509	0.7990
Δ (REC ⁺)	107.0305**	2.252216	0.0480
Δ (REC ⁺ (-1))	59.34774	1.614479	0.1375
Δ (REC ⁻)	-11.71267	-1.327242	0.2139
Δ ((REC ⁻ (-1))	11.52069	1.726242	0.1150
Δ (GDP ⁺)	0.297270	0.269176	0.7933
Δ (GDP ⁺ (-1))	1.155533	1.388856	0.1950
Δ (GDP ⁻)	2.122418	0.729839	0.4822

Δ is the first difference operator, and (+, -) represents the positive and negative changes of the cumulative function

** and * denote significance levels of 5 and 10%, respectively

The short-run asymmetry in the instability of CO₂ emissions compared to both other variables in both positive and negative reactions is tested by $H_0: \pi_{1i}^+ = \pi_{1i}^- = \pi_{2i}^+ = \pi_{2i}^- = 0$ against the alternative hypothesis $H_1: \pi_{1i}^+ \neq \pi_{1i}^- \neq \pi_{2i}^+ \neq \pi_{2i}^- \neq 0$. However, the short-run asymmetry in the instability of CO₂ emissions with REC is tested by $H_0: \pi_{1i}^+ = \pi_{1i}^- = 0$ against the alternative hypothesis $H_1: \pi_{1i}^+ \neq \pi_{1i}^- \neq 0$ and, with real GDP, is tested by $H_0: \pi_{2i}^+ = \pi_{2i}^- = 0$ against the alternative hypothesis $H_1: \pi_{2i}^+ \neq \pi_{2i}^- \neq 0$ in carbon dioxide models. The tests for asymmetric causality for models 5 and 7 are applied in the same sense.

Unit root tests

In this research, we use both the Augmented Dickey-Fuller (Fisher-ADF) and Phillips and Perron (1988) (Fisher-PP) tests without the structural break to test the tendency of a unit root test over a time series. In addition, if the integration instructions of the selected variables are identified, the appropriate model is selected. The null hypothesis of the stationarity in both tests is the existence of the unit root under the alternative hypothesis.

By testing the stationarity of all selected variables (REC, GDP, CO₂, REC+, REC-, GDP+, GDP-, CE+, and CE-) with individual intercepts or along the individual intercepts and trends, the null hypothesis is confirmed at this level and in the first difference. Therefore, we can conclude that the instruction of integration of all selected variables is one $I(1)$, so the NARDL approach is suitable (Tables 2 and 3).

Empirical results

Cointegration test

In accordance with the result of the unit root test without the structural break and breakpoint ADF unit root test, we can use the bounds cointegration test without structural breaks between the models to demonstrate the long-run association between real GDP, carbon dioxide emissions, and renewable energy in the KSA. According to the table reported by Narayan (2005), the two crucial values are 2.734 and 3.920 at the 5% level and are 3.657 and 5.256 at the 1% level. The results of Table 4 confirmed the long-term association between the selected variables for all models because all the

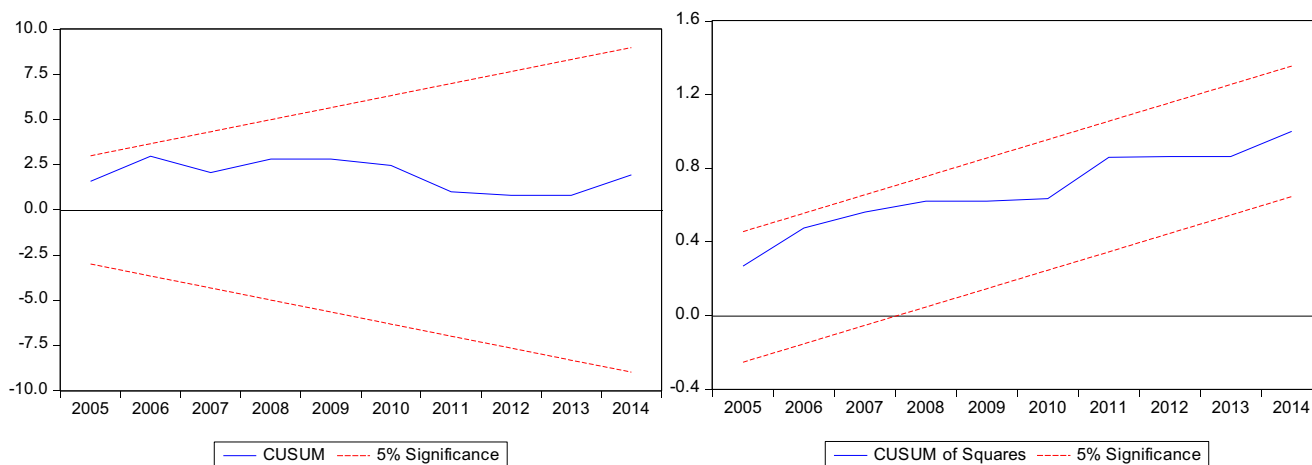


Fig. 2 CUSUM and CUSUMQ from the carbon dioxide model

F-statistics are heavily high at 1% at the level. We can thus infer that structural breaks can ameliorate the findings and confirm the long-run association between all variables for all models.

NARDL estimation result (CE is dependent variables)

As indicated in Table 5, when carbon dioxide emissions are dependent variables, only the cumulative function of positive changes has a positive impact on CE in the short-run, but in the long-run, it is apparent that the positive and negative shocks in the partial sum of renewable energy consumption reduce the emissions of carbon dioxide. However, this result

implies that the long-run impact of the positive shock on carbon dioxide emissions is not similar to the negative shock, which suggests the existence of asymmetric impacts in the long-term. Furthermore, the accumulated sum of recursive residuals (CUSUM) and the accumulated sum of squares of recursive residuals (CUSUMSQ) are stable for the carbon dioxide model. While the shape lies between the critical bounds, substantial and stable relationships are proposed between these variables (Fig. 2).

NARDL estimation result (real GDP is the dependent variable)

As mentioned in Table 6, when real GDP is the dependent variable, the positive fluctuation in the cumulative function of carbon dioxide emissions increases real GDP by 0.51% for a 1% change, but the negative change in the partial sum of CE increases the real GDP by 1.17% for a 1% fluctuation. However, this result implies that the long-term impact of the positive change on carbon dioxide emissions is not similar at the negative shock, suggesting asymmetric impacts in the long-term. In the short-run coefficients, that positive change in carbon dioxide emissions assigned real GDP more similarly than the negative shock, so we can conclude that both short-run coefficients imply asymmetric impacts on carbon dioxide in the short-term. In addition, the CUSUM and CUSUMSQ are stable for the real GDP model (Fig. 3).

NARDL estimation result (REC is dependent variable)

As mentioned in Table 7, when renewable energy consumption is the dependent variable, in the long-term, the positive shock in the cumulative function of carbon dioxide emissions increases REC by 0.095% for a 1% change, but the negative change in the partial function of CE increases REC by 0.047% for a 1% change. In the short-term, the positive changes in the cumulative function of carbon dioxide emissions and the

Table 6 NARDL estimation result (real GDP is dependent variable)

Variable	Coefficient	t-Statistic	Prob.
GDP(- 1)	- 0.006117	- 0.113780	0.9131
CE ⁺	0.514715***	3.812282	0.0088
CE ⁻	1.177159**	2.946054	0.0257
REC ⁺	- 5.363947	- 0.160924	0.8774
REC ⁻	- 11.12009	- 0.414903	0.6926
Δ (GDP(- 1))	- 0.463916*	- 1.999364	0.0925
Δ (GDP(- 2))	- 0.458597*	- 2.064370	0.0845
Δ (CE ⁺)	- 0.124597	- 0.665528	0.5305
Δ (CE ⁺ (- 1))	- 0.058249	- 0.319364	0.7603
Δ (CE ⁺ (- 2))	- 0.318705*	- 1.921392	0.1031
Δ (CE ⁻)	- 0.840334**	- 2.426669	0.0514
Δ (CE ⁻ (- 1))	- 0.649042**	- 2.504147	0.0463
Δ (REC ⁺)	- 16.18866	- 0.529748	0.6153
Δ (REC ⁺ (- 1))	- 9.702948	- 0.385136	0.7134
Δ (REC ⁻)	20.38846**	2.781148	0.0319
Δ (REC ⁻ (- 1))	6.650313	1.418325	0.2059

Δ is the first difference operator, and (+, -) represents the positive and negative changes of the cumulative function

** and * denote significance levels 5 and 10%, respectively

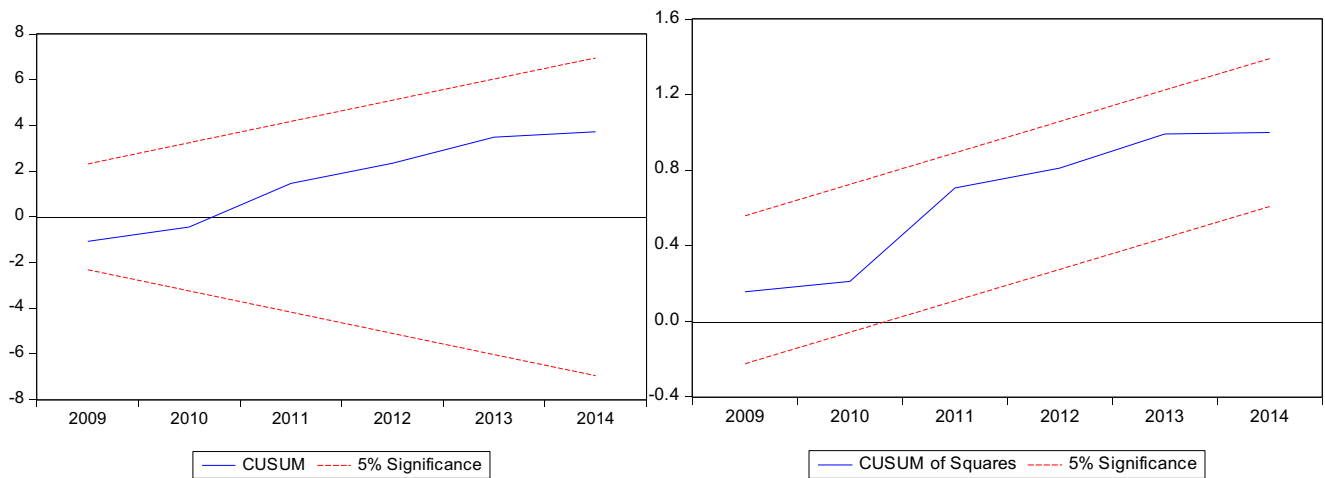


Fig. 3 CUSUM and CUSUMQ from the economic growth model

negative change in the partial function of CE decrease REC by 0.045% for a 1% change. In addition to the variable gross domestic product, the positive changes in the cumulative function of real GDP decrease REC by 0.035% for a 1% change in the long-term. Likewise, the negative changes in the cumulative function of real GDP increase REC by 0.37% for a 1% change, but in the short-run, the positive changes in the cumulative function of real GDP increase REC by 0.11% for a 1% change. The negative changes in the cumulative function of real GDP decrease REC by 0.32% for a 1% change. Furthermore, this result implies that the long- and short-term impacts of the positive shock on real GDP are not similar at the negative shock, suggesting the presence of asymmetric impacts on REC in both the short- and long-term. In addition, the CUSUM and the CUSUMSQ are stable for the real REC model (Fig. 4).

Table 7 NARDL estimation result (renewable energy is the dependent variable)

Variable	Coefficient	t-Statistic	Prob.
REC(- 1)	- 1.204022***	- 5.647801	0.0001
CE ⁺	0.094855***	4.618364	0.0005
CE ⁻	0.047266***	4.272769	0.0009
GDP ⁺	- 0.035620**	- 2.115435	0.0543
GDP ⁻	0.372609**	3.553373	0.0035
Δ (REC(- 1))	0.483839**	2.488587	0.0272
Δ (CE ⁺)	- 0.045907**	- 2.481839	0.0275
Δ (CE ⁻)	- 0.043484**	- 2.724937	0.0173
Δ (GDP ⁺)	0.111916**	2.309621	0.0380
Δ (GDP ⁻)	- 0.327800**	- 2.791051	0.0153

Δ is the first difference operator, and (+,-) represents the positive and negative changes of the cumulative function, respectively
 ** and * denote significance levels 5 and 10%, respectively

Asymmetric causality results

By testing the asymmetric causality direction among REC, CO₂ emissions, and real GDP, as well as the positive and negative components of the selected variables, we employed the Wald test. Table 8 reports the result of asymmetric causality tests for the time series data among REC, CO₂ emissions, and real GDP, as well as the positive and negative components of the three variables. First, the causality of the positive and negative components of real GDP (GDP⁺, GDP⁻) to CE is unobservable in the short- and the long-term; only a unidirectional asymmetric causality was issued from positive and negative shocks in carbon dioxide emissions (CE⁺, CE⁻) to real GDP in the long-term. Otherwise, the causality of the positive and negative component of REC (REC⁺, REC⁻) to real GDP is unobservable in both the short- and the long-term, while the joint causality of the positive and negative components of REC and CE to real GDP is observable in the long-run. Moreover, Table 8 supplies a unidirectional asymmetric causality issued from both the positive and negative changes of the carbon dioxide emissions to REC in the short and the long-run. Finally, the same result of asymmetric causality issuing from both the positive and negative shocks of the real GDP to REC arose in both the short- and the long-term periods.

Policy implications

The attainment of this study shows that policymakers in Saudi Arabia are asked to precise growth and environmental policies for long-term sustainable development goals. In this situation, the environmental grade can be upgraded at the cost of economic development or energy helpful should be promoted by the long asymmetric relationship between GDP and renewable energy in the first step and the long asymmetric relationship between carbon dioxide emissions and renewable energy in the second

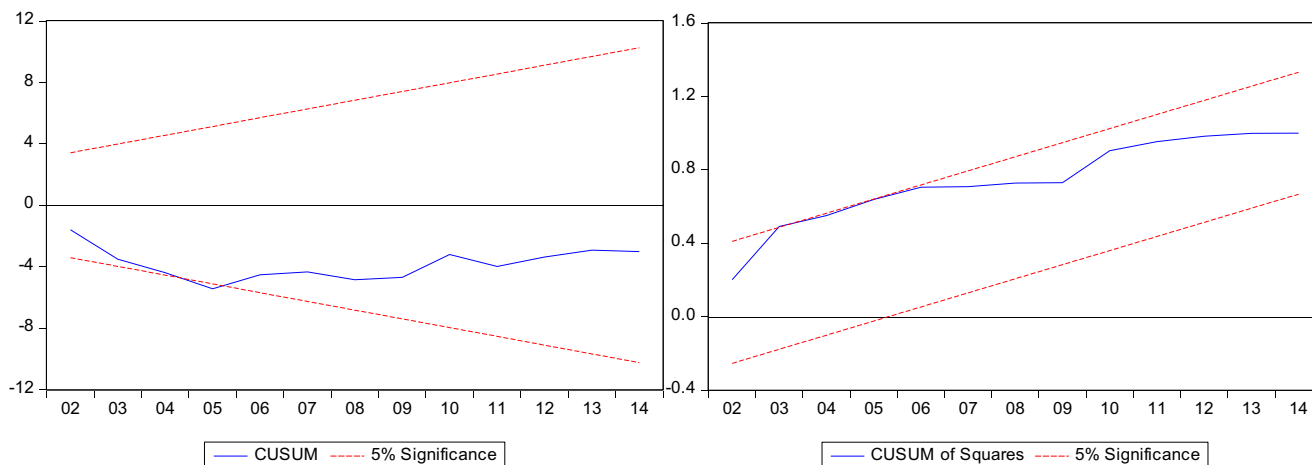


Fig. 4 CUSUM and CUSUMQ from the REC model

step. Furthermore, the measurement starting supports policymakers to build national environmental directives for the environmental sustainable development goals (SDGs).

Table 8 Asymmetric causality results

Causality	Wald test	1% Bootstrapped CV
GDP ⁺ = CE	2.463523	0.1349
GDP ⁻ = CE	2.436499	0.1374
REC ⁺ = CE	3.293454	0.0796*
REC ⁻ = CE	3.010552	0.0947*
GDP ⁺ = REC ⁺ = CE	3.190859	0.0848*
GDP ⁻ = REC ⁻ = CE	2.111662	0.1623
Δ (REC ⁺) = Δ (REC ⁻) = CE	4.034898	0.0404**
Δ (GDP ⁺) = Δ (GDP ⁻) = CE	1.010433	0.4281
CE ⁺ = GDP	8.124790	0.0196**
CE ⁻ = GDP	6.898650	0.0278**
REC ⁺ = GDP	0.022187	0.9781
REC ⁻ = GDP	1.554305	0.2858
CE ⁺ = REC ⁺ = GDP	5.452133	0.0378**
CE ⁻ = REC ⁻ = GDP	5.452133	0.0378**
Δ (CE ⁺) = Δ (CE ⁻) = GDP	2.431332	0.1549
Δ (REC ⁺) = Δ (REC ⁻) = GDP	2.879954	0.1194
CE ⁺ = REC	16.02630	0.0003***
CE ⁻ = REC	16.08045	0.0003***
GDP ⁺ = REC	16.87584	0.0002***
GDP ⁻ = REC	19.89124	0.0001***
CE ⁺ = GDP ⁺ = REC	12.95976	0.0003***
CE ⁻ = GDP ⁻ = REC	13.53677	0.0003***
Δ (CE ⁺) = Δ (CE ⁻) = REC	9.265782	0.0032**
Δ (GDP ⁺) = Δ (GDP ⁻) = REC	3.907335	0.0469**

Δ is the first difference operator, and (+, -) represents the positive and negative changes of the cumulative function

*, **, and *** show significance at the 1%, 5%, and 10% levels, respectively

Furthermore, regarding the long-term asymmetric nexus between real GDP and renewable energy, policymakers are invited to augmented per capita financial investment in green energy, beyond the estimated threshold to achieve the required effect on reducing carbon dioxide emissions. In order to reach the objectives of the 2030 vision for sustainable development goals, Saudi Arabia will need to assume really strong actions in all prospect, in which renewable energy consumption is well-respected to be a “multi-target way” for 2030 action plan.

Now, regarding the effect of renewable energy on carbon dioxide emissions in the long-term, policymakers can practically augment investment in green energy over the settled threshold to achieve sustainable development goals (SDGs) both directly and indirectly and incorporate the environmental regulation with 2030 vision in Saudi Arabia, which reduce the landing of emissions and take as well to a rise in the request for renewable energy.

Conclusions

This paper examined the asymmetric causality among renewable energy, CO₂ emissions, and real GDP using a non-linear transmission among these selected variables and using the non-linear autoregressive distributed lag model to unpack the short- and long-run asymmetries in the inconsistency of greenhouse gas emissions among the three variables and to demonstrate the asymmetric causality among them through the positive and negative shocks for time series data from the Kingdom of Saudi Arabia between 1990 and 2014, and in order to evaluate this association, we have used Granger causality test and Wald test. The positive and negative components of real GDP, carbon dioxide emissions, and renewable energy results attest the signification of asymmetric causality whereas implying policy judgment, and it has equally proved

how the causality direction should be well-respected in order to reach the sustainable development goals.

The empirical approach used in this research to survey long-term association among REC, carbon dioxide emissions, and real GDP in Saudi Arabia is based on NARDL bounds testing approach on the presence of asymmetries. The non-linear model confirms the existence of long-term asymmetry between carbon dioxide emissions and renewable energy in KSA. Indeed, positive and negative shocks in the partial sum of renewable energy consumption reduce the emissions of carbon dioxide in the long-term. It is necessary to adopt new strategies that contribute to the action plan, which also respect sustainable development goals.

The asymmetric causal relationship is neutral from carbon dioxide emissions to renewable energy in the long-term. Both positive and negative shocks on REC had a consistently adverse impact on CE. This improvement is substantial; indicating that reducing the CE in KSA will improve real GDP in the long-term and substitute renewable energy use for traditional power. It also maintains the asymmetrical causal dealings between real GDP and REC in the first step, and carbon dioxide emissions and green energy in the second step with the action plan in mind, as this vision can progressively establish a new renewable industry by reducing CO₂ emissions and decreasing the cost of electricity production.

Finally, in accordance with the results of this survey, recommendations and policy implications have been treated in accordance with the SDGs in KSA. These proposals are assumed to orientate policymakers for more and more fossil energy taxation and grant for green energy in the KSA. In addition, equilibrium between environmental guard policy and investment-hearty policy will be found such that sustainable development goals will be attained.

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