



# Do renewable energy and natural gas consumption mitigate CO<sub>2</sub> emissions in the USA? New insights from NARDL approach

Ferhat Çıtak<sup>1</sup> · Hakan Uslu<sup>2</sup> · Oğuzhan Batmaz<sup>3</sup> · Safa Hoş<sup>1</sup>

Received: 17 July 2020 / Accepted: 1 October 2020 / Published online: 13 October 2020  
© Springer-Verlag GmbH Germany, part of Springer Nature 2020

## Abstract

This article attempts to explore the asymmetric impact of renewable energy and natural gas consumptions on CO<sub>2</sub> emissions for the selected ten most populous states in the USA over the period from 1997 to 2017. For that purpose, the nonlinear autoregressive distributed lag (NARDL) estimation technique, developed by Shin et al. (2014), decomposes the consumption of renewable energy and natural gas into positive and negative changes. The cointegration test results indicate that renewable energy and natural gas consumptions have a long-run connection with CO<sub>2</sub> emissions in the eight of states used in the study. Moreover, the results reveal that the long-run asymmetric impact of renewable energy and natural gas consumptions on CO<sub>2</sub> emissions differs from state to state. Finally, the study provides several important policy suggestions, including reducing the CO<sub>2</sub> emissions in the atmosphere.

**Keywords** CO<sub>2</sub> emissions · Renewable energy · Natural gas · NARDL · USA

## Introduction

Energy plays many vital roles in the modern society from the sustainability of human life to the economic growth of a country. is the USA is one of the energy-based growing countries that produce and consume different types of energy sources. The USA consumes 17% of the total global energy consumption of 582 btu (British Thermal Units) although it has less than 5% of the world's population in 2017. In comparison, the

European Union, which includes 27 countries, consumes only 12% of the world's energy consumption at the same year. However, the USA has also a large amount of contribution to world energy production with the production of 12% of the total global energy production of 576 btu ([www.eia.gov](http://www.eia.gov)). Total energy consumption in the USA in 2019 was about 100.2 quadrillion btu. The amount of energy production has exceeded the consumption amount for the first time since 1957 and has approached to 101 quadrillion btu. A large part of all this energy production and consumption depends on traditional non-renewable energy sources including coal, oil, and natural gas. In addition, renewable energy sources have an important place in this consumption.

Between 1950 and 2019, total energy consumption has increased by 190% in the country, as a result of this increase there has been a sharp rise in the CO<sub>2</sub> emissions in the atmosphere, which is considered as the main source of the greenhouse gas effect causing environmental pollution. Problems such as environmental pollution, climate change, and global warming, which occur as a result of energy consumption, have made it necessary to take various social and political measures in the USA as well as all over the world. Accordingly, the use of energy sources such as renewable energy and natural gas, which led to less CO<sub>2</sub> emissions, has increased in the country. During the same period, consumption of renewable energy and natural gas has increased by 389%, while energy

---

Responsible Editor: Nicholas Apergis

✉ Ferhat Çıtak  
ferhatcitak@hitit.edu.tr

Hakan Uslu  
huslu@adiyaman.edu.tr

Oğuzhan Batmaz  
obatmaz@coloradocollege.edu

Safa Hoş  
safahos@hitit.edu.tr

<sup>1</sup> School of Economics and Administrative Sciences, Hitit University, Corum, Turkey

<sup>2</sup> School of Economics and Administrative Sciences, Adiyaman University, Adiyaman, Turkey

<sup>3</sup> Colorado College, Colorado Springs, CO, USA

consumption based on fossil fuels (coal and petroleum) has increased by 119.5%<sup>1</sup>. Hence, it is worth for a scientific investigation to examine the relationship between the use of renewable and non-renewable energy sources and the differences in the amount of CO<sub>2</sub> they release into the atmosphere.

The purpose of this particular study is to empirically investigate the asymmetric impact of the consumption of natural gas and renewable energy on CO<sub>2</sub> emissions in the ten most populous states of the USA. The study employs a well-known econometric estimation method called the nonlinear autoregressive distributed lag (NARDL) using a quarterly dataset from the ten states covering almost 55% of the US population for the time period between 1997 and 2017. There are numerous studies in the relevant literature using different methods and approaches to deal with the relationship between energy consumption and CO<sub>2</sub> emissions in different countries, and they have no consensus on this relationship. In addition, only a few studies have examined how increasing and decreasing periods in consumption of renewable energy and natural gas have an effect on CO<sub>2</sub> emissions. Therefore, the main purpose of this study is to contribute to this literature by examining how increasing and decreasing periods in renewable energy and natural gas consumption influence CO<sub>2</sub> emissions in the atmosphere using a new dataset and new approach.

The rest of the study is organized as follows: Following section provides a brief literature review on the relationship between energy consumption and carbon dioxide emissions. Data and methodology section gives details on the econometric models and how the dataset is obtained. The last two sections include the empirical results and conclusions-discussion and policy recommendations.

## Literature review

The importance of the relationship among renewable energy, natural gas, and CO<sub>2</sub> emission has been going up in the relevant literature due to rising air pollutions especially in the urban areas. Polluted atmosphere forces countries to find not only alternative ways but also clean ways to use energy sources. According to Ouyang and Li (2018), economic growth needs use of more energy, so it causes a global warming crisis. To deal with this crisis, Bhattacharya et al. (2017) pointed that countries need to find clean and sustainable energy sources including natural gas and renewable energy. In the literature, the nexus of above has been mostly studied using linear methods. However, here in this study, we aim to find the nonlinear relationship between renewable energy, natural gas, and CO<sub>2</sub> emission.

In the relevant literature, several numbers of studies have been conducted to show the impact of natural gas and renewable energy on CO<sub>2</sub> emissions. Many have concluded that increase in consumption of natural gas and renewable energy reduces CO<sub>2</sub> emissions. For example, Johnson and Keith (2014) found that low natural gas prices trigger to use more natural gas, which lead to a reduction in CO<sub>2</sub> emissions up to 40% in electricity market. Podesta and Wirth (2009) concluded a significant reduction in CO<sub>2</sub> emissions because of more usage of natural gas. Joskow (2013) also showed a great potential of natural gas to reduce GHG emissions in the USA. Shearer et al. (2014) investigated natural gas supply and its impacts on renewable energy and CO<sub>2</sub> emissions. They pointed an interesting result that with firm climate policies, coal use will gradually decline so do CO<sub>2</sub> emissions; otherwise, use of natural gas will only delay renewable energy use and not reduce the emissions significantly.

Moreover, in one study Dogan and Ozturk (2017) stressed the importance of this fact which has stated in the first paragraph and they concluded that for the USA, consuming more renewable energy reduces environmental pollution while consuming more non-sustainable energy increases CO<sub>2</sub> emissions using ARDL approach and EKC hypothesis. In another study, Isik et al. (2019) investigated the nexus between economic growth/development and environmental pollution using EKC hypothesis as state based in the USA. Their results are both valid and invalid in terms of EKC hypothesis; however, they reached a consensus to use renewable energy to reduce CO<sub>2</sub> emissions. In addition to these studies, there is another valuable article studied by Xu (2016), which focused on both linear and nonlinear relationship of renewable energy and CO<sub>2</sub> emissions in the USA. Although the results are complex in that study, but the author concluded a unidirectional significant relationship between economic growth and renewable energy consumption.

In addition to the US-based studies, there are other important studies, which show the impact of natural gas and renewable energy consumption on CO<sub>2</sub> emissions. Dong et al. (2017a) stated every 1% increase in consumption of natural gas and renewable energy will decrease CO<sub>2</sub> emissions by 0.16% and 0.26%, respectively, in BRICS countries. Dong et al. (2017b) found that every 1% increase in natural gas consumption lowers CO<sub>2</sub> emissions by 0.033 to 0.054% depending on the method they used. Dong et al. (2018) also showed similar results for 14 Asia-Pacific countries. Solarin and Lean (2016) addressed the long-run relationship between natural gas consumption and CO<sub>2</sub> emissions and concluded that natural gas consumption lowers CO<sub>2</sub> emissions for almost the past 50 years in China and India. Ummalla and Samal (2019) studied the long-run impact of natural gas and renewable energy consumption on CO<sub>2</sub> emissions and economic growth. Their results contradict with Solarin and Lean (2016) for China that no causality exists between

<sup>1</sup> <https://www.eia.gov/totalenergy/data/monthly/pdf/sec1.pdf>

variables, but consistent for India especially in the short run. Mahmood et al. (2019) concluded the importance of renewable energy consumption as reducing CO<sub>2</sub> emissions in Pakistan from 1980 to 2014. Lastly, Ergun et al. (2019) exhibited a different perspective that there is a negative relationship between social and economic factors including per capita GDP/human development index and renewable energy and a positive relationship between foreign direct investment and renewable energy in 21 African countries between 1990 and 2013. Hence, they recommend improvements in policies to use more renewable energy because it has positive impacts on environments.

In another study, Shafiei and Salim (2014) found a significant negative relationship between renewable energy and CO<sub>2</sub> emissions in OECD countries from 1980 to 2011. Using different approaches, Bilgili et al. (2016) supported the previous studies by concluding a negative and significant relationship between renewable energy and CO<sub>2</sub> emissions in OECD countries. Jaforullah and King (2015) found a negative relationship between renewable energy consumption and CO<sub>2</sub> emission in the USA. Aslan and Ocal (2016) also emphasized the significant characteristic of renewable energy as reducing CO<sub>2</sub> emissions. In contrast, Menyah and Wolde-Rufael (2010) and Apergis et al. (2010) concluded insignificant results of renewable energy on CO<sub>2</sub> emission in both the USA and a group of 19 developed and developing countries.

Again, to the best of our knowledge, there are no ample studies that focusing on the state base analyses for the USA to explain the nexus of renewable energy, natural gas, and CO<sub>2</sub> emissions. Therefore, the current paper fills the gap in the existing literature as targeting to find the state based non-linear relationship between renewable energy, natural gas, and CO<sub>2</sub> emissions. In addition, the study makes the USA government aware of this fact, so imposing policies to find and use clean and sustainable energy sources.

## Data and methodology

### Data

The data set contains yearly observations of CO<sub>2</sub> emissions, renewable energy, natural gas, and population over the period from 1997 to 2017 for ten most populous states<sup>23</sup> in the USA. As in previous relevant studies (Romero (2005), McDermott and McMenamin (2008), Sbia et al. (2014), Shahbaz (2017)), we have applied the quadratic match-sum method to transform

<sup>2</sup> According to World Population Reviews, the most ten populous states in the USA are ranked as follows: (1) California, (2) Texas, (3) Florida, (4) New York, (5) Pennsylvania, (6) Illinois, (7) Ohio, (8) Georgia, (9) North Carolina, and (10) Michigan.

<sup>3</sup> We excluded North Carolina and New Jersey from the analysis because of heteroscedasticity problem, and Washington is substituted.

the annual data to quarterly in order to increase the number of observations. The data for CO<sub>2</sub> emissions, renewable energy (hereafter, REN), and natural gas (hereafter, NGAS) were obtained from the USA Energy Information Administration (EIA). Population data (hereafter, POP) has been acquired from the USA Census Bureau, Population Division. All series are converted into the logarithmic form to remove the potential heteroscedasticity problem and to have unbiased and efficient estimators.

### Methodology

Given the aims of this study, the nonlinear autoregressive distributed lag (NARDL) methodology is applied to test asymmetric effect of renewable energy and natural gas consumption on CO<sub>2</sub> emissions. The NARDL approach, which is proposed by Shin et al. (2014), has various advantages over the conventional ARDL model. First, it permits us to investigate asymmetries nonlinearly thus violates linearity assumption. Second, the NARDL model checks for the possibility of asymmetric impact of positive and negative influences of the explanatory variable(s) on the dependent variable in the long and short-runs. Third, the NARDL model also allows to capture cointegration for single equation framework as compared with the linear ARDL model.

To investigate the long-run relationship between CO<sub>2</sub> emissions, REN, NGAS, and POP, the following linear equation framework can be modeled:

$$CO_{2t} = \beta_0 + \beta_1 POP_t + \beta_2 REN_t + \beta_3 NGAS_t + \varepsilon_t \quad (1)$$

where CO<sub>2</sub>, REN, NGAS, and POP represent the carbon dioxide emissions, renewable energy consumption, natural gas consumption, and population in each study state of the USA in given time period *t*, respectively.  $\beta_i$  represents the long-run coefficients, and  $\varepsilon_t$  is an error term. Following the approaches used in relevant studies, such as Katrakilidis and Trachanas (2012), Koutroulis et al. (2016), Ahmad et al. (2018), Khan et al. (2019), Ahmad et al. (2020), Ullah et al. (2020), we can rewrite Eq. (1) to express the asymmetric long-run regression of CO<sub>2</sub> as follows:

$$CO_{2t} = \delta_0 + \delta_1 (POP_t) + \delta_2 (REN_t^+) + \delta_3 (REN_t^-) + \delta_4 (NGAS_t^+) + \delta_5 (NGAS_t^-) + \varepsilon_t \quad (2)$$

where  $\delta_i$  indicates coefficients vector for long-run parameters to be estimated and  $REN_t^+$ ,  $REN_t^-$ ,  $NGAS_t^+$ , and  $NGAS_t^-$  denote the positive and negative partial sum process variation in REN and NGAS, respectively. Following Shin et al. (2014), the values of  $REN_t^+$ ,  $REN_t^-$ ,  $NGAS_t^+$ , and  $NGAS_t^-$  can be framed through the equations below (2a, 2b, 2c, and 2d):

$$REN^+ = \sum_{i=1}^t \Delta REN_i^+ = \sum_{i=1}^t \max(\Delta REN_i, 0) \quad (2a)$$

$$REN^- = \sum_{i=1}^t \Delta REN_i^- = \sum_{i=1}^t \min(\Delta REN_i, 0) \quad (2b)$$

$$NGAS^+ = \sum_{i=1}^t \Delta NGAS_i^+ = \sum_{i=1}^t \max(\Delta NGAS_i, 0) \quad (2c)$$

$$NGAS^- = \sum_{i=1}^t \Delta NGAS_i^- = \sum_{i=1}^t \min(\Delta NGAS_i, 0) \quad (2d)$$

As set out in Shin et al. (2014) and Pesaran et al. (2001), we substitute Eq. (2) into Eq. (1) to obtain the asymmetric ARDL model setting by distinguishing the long-run and short-run asymmetric relationships can be formulated as follows:

$$\begin{aligned} \Delta CO_{2t} = & \vartheta_0 + \vartheta_1 CO_{2t-1} + \vartheta_2 (POP_{t-1}) + \vartheta_3^+ (REN_{t-1}^+) \\ & + \vartheta_4^- (REN_{t-1}^-) + \vartheta_5^+ (NGAS_{t-1}^+) \\ & + \vartheta_6^- (NGAS_{t-1}^-) + \sum_{i=1}^k \omega_i \Delta CO_{2t-i} + \sum_{i=0}^m \sigma_{2i} \Delta POP_{t-i} \\ & + \sum_{i=0}^n \zeta_{3i}^+ \Delta REN_{t-i}^+ \\ & + \sum_{i=0}^p \zeta_{4i}^- \Delta REN_{t-i}^- + \sum_{i=0}^m \zeta_{5i}^+ \Delta NGAS_{t-i}^+ + \sum_{i=0}^s \zeta_{6i}^- \Delta NGAS_{t-i}^- + e_t \end{aligned} \quad (3)$$

where  $\Delta$ 's present the differenced variables in period  $t$ ,  $k$ ,  $m$ ,  $n$ ,  $p$ , and  $s$  denote the respective lags orders.  $\vartheta = (\vartheta_1, \vartheta_2, \vartheta_3^+, \vartheta_4^-, \vartheta_5^+, \text{ and } \vartheta_6^-)$  indicate the coefficients of the long-run positive and negative changes of REN and NGAS on CO<sub>2</sub> emissions. While  $\sum_{i=0}^n \zeta_{3i}^+ \Delta REN_{t-i}^+$  and  $\sum_{i=0}^p \zeta_{4i}^- \Delta REN_{t-i}^-$  express the short-run positive and negative effects of renewable energy on CO<sub>2</sub> emission,  $\sum_{i=0}^m \zeta_{5i}^+ \Delta NGAS_{t-i}^+$  and  $\sum_{i=0}^s \zeta_{6i}^- \Delta NGAS_{t-i}^-$  capture the short-run positive and negative effects of natural on CO<sub>2</sub> emissions, respectively. Furthermore, the long-run effect of positive and negative changes on the CO<sub>2</sub> emissions can be calculated as  $\lambda_1 = -\vartheta_3^+/\vartheta_1$ ,  $\lambda_2 = -\vartheta_4^-/\vartheta_1$ ,  $\lambda_3 = -\vartheta_5^+/\vartheta_1$ , and  $\lambda_4 = -\vartheta_6^-/\vartheta_1$ .

Building non-linear ARDL technique entails various steps. First, it is essential and pre-requisite to verify that none of the variables is integrated at  $I(2)$  or beyond in time series studies. According to Ouattara (2004), having a variable with order of  $I(2)$  yields meaningless results. Second, we estimate Eq. (3) by using standard ordinary least squares (OLS) approach. Then, we apply the general-to-specific procedure suggested by Katrakilidis and Trachanas (2012) to reach the final specification of the NARDL model employing the Akaike Information Criterion (AIC). Third, after eliminating insignificant lags, we check the possible existence of a long-run cointegration among the variables by testing the following hypotheses: the null hypothesis,  $H_0 : \vartheta_1 = \vartheta_2 = \vartheta_3^+ = \vartheta_4^- = \vartheta_5^+ = \vartheta_6^-$ , claims that there is no long-run association existence against the alternative hypothesis,  $H_1 : \vartheta_1 \neq \vartheta_2 \neq \vartheta_3^+ \neq \vartheta_4^- \neq \vartheta_5^+ \neq \vartheta_6^-$ . Fourth, after confirming the presence of the long-run cointegration between the variables, we control the long-run and short-run asymmetric effect of REN and NGAS on CO<sub>2</sub> emissions. Finally, we apply several robustness tests including residual independence (autocorrelation), residuals

heteroscedasticity (Breusch–Pagan) and residuals normality (Jarque-Berra) to check the validity of our results.

## Empirical findings

### Test of stationarity

As a preliminary step in empirical analysis, all variables should be tested for unit root. We implement Phillips and Perron (PP) unit root test to detect the stationarity of the variables. Table 1 reports the unit root results. According to the results, all variables for each state, except NGAS for Illinois and REN for Washington, are not stationary in their levels. After taking their first differences, all variables are integrated at order one, i.e.,  $I(1)$  at the 5% level of significance.

### Cointegration analysis

The next step is to test whether a long-run equilibrium relations exists among the variables. For that, we employ the bound  $F$  statistic based on the Wald test approach. Table 2 reports the cointegration test results in the nonlinear estimation. Following Narayan (2005), we compare the  $F$  test results with the critical values, which reports critical values for the upper and the lower bounds for the small sample cases. As per computed  $F$  statistic value of the long-run for California, Texas, Florida, New York, Pennsylvania, Ohio, Georgia, and Michigan lie above the upper critical bound values at 10% level of significance, which indicates nonlinear cointegration among the variables.

### NARDL results

Once cointegration is confirmed for NARDL model, the next step is to examine the long-run asymmetries for the purposed variables. Table 3 tabulates the long-run asymmetry findings for NGAS ( $W_{LRNGAS}$ ) and REN ( $W_{LRREN}$ ) based on the Wald test. Here, the null hypothesis of nonlinear ARDL is that there exists asymmetric effect of REN and NGAS on CO<sub>2</sub> emissions for long-run equilibrium. As noted in the Table 3, we observe that 5 cases exhibit a long-term asymmetry (except for Florida, Ohio, and Georgia) for NGAS, while all cases (except Florida and New York) show a long-run asymmetry for REN at 5% significance level. The existence of long-run asymmetrical results allows us to interpret both positive and negative effects of NGAS and REN shocks on CO<sub>2</sub> emissions.

As we observe the estimated coefficients for the individual states, we conclude that the findings are mixed and differ from each other. The results for each state are as follows: For example, in California, the estimated coefficients of long-run model indicate that both partial sum of positive and negative changes in REN and NGAS are significant at 5% significance

**Table 1** Unit root test results

|                 | PP (levels)                    | PP (1st differences)           |
|-----------------|--------------------------------|--------------------------------|
| California      |                                |                                |
| CO <sub>2</sub> | - 2.621 (5) c + t              | - 4.874 <sup>a</sup> (4) c + t |
| NGAS            | - 3.209 (5) c + t              | - 4.967 <sup>a</sup> (4) c + t |
| REN             | - 1.549 (5) c + t              | - 4.754 <sup>a</sup> (4) c + t |
| POP             | - 2.175 (5) c + t              | - 3.931 <sup>a</sup> (5) c + t |
| Texas           |                                |                                |
| CO <sub>2</sub> | - 1.474 (5) c + t              | - 4.976 <sup>a</sup> (4) c + t |
| NGAS            | - 1.468 (4) c + t              | - 5.078 <sup>a</sup> (4) c + t |
| REN             | - 2.792 (5) c + t              | - 4.402 <sup>a</sup> (5) c + t |
| POP             | - 1.562 (4) c + t              | - 5.105 <sup>a</sup> (4) c + t |
| Florida         |                                |                                |
| CO <sub>2</sub> | - 2.871 (5) c + t              | - 4.908 <sup>a</sup> (4) c + t |
| NGAS            | - 2.223 (4) c + t              | - 5.103 <sup>a</sup> (4) c + t |
| REN             | - 2.824 (5) c + t              | - 4.351 <sup>a</sup> (4) c + t |
| POP             | - 1.650 (5) c + t              | - 4.854 <sup>a</sup> (4) c + t |
| New York        |                                |                                |
| CO <sub>2</sub> | - 2.090 (5) c + t              | - 4.976 <sup>a</sup> (4) c + t |
| NGAS            | - 2.676 (5) c + t              | - 4.643 <sup>a</sup> (4) c + t |
| REN             | - 2.194 (2) c + t              | - 4.781 <sup>a</sup> (3) c + t |
| POP             | - 1.802 (5) c + t              | - 4.903 <sup>a</sup> (4) c + t |
| Pennsylvania    |                                |                                |
| CO <sub>2</sub> | - 1.795 (4) c + t              | - 4.983 <sup>a</sup> (4) c + t |
| NGAS            | - 2.698 (4) c + t              | - 5.138 <sup>a</sup> (4) c + t |
| REN             | - 2.486 (5) c + t              | - 4.837 <sup>a</sup> (4) c + t |
| POP             | - 1.227 (4) c + t              | - 5.179 <sup>a</sup> (4) c + t |
| Illinois        |                                |                                |
| CO <sub>2</sub> | - 1.532 (5) c + t              | - 4.893 <sup>a</sup> (4) c + t |
| NGAS            | - 3.955 <sup>a</sup> (4) c + t | - 5.510 <sup>a</sup> (3) c + t |
| REN             | - 2.266 (6) c + t              | - 4.988 <sup>a</sup> (4) c + t |
| POP             | - 2.685 (5) c + t              | - 4.518 <sup>a</sup> (4) c + t |
| Ohio            |                                |                                |
| CO <sub>2</sub> | - 1.992 (4) c + t              | - 5.448 <sup>a</sup> (3) c + t |
| NGAS            | - 2.512 (5) c + t              | - 5.022 <sup>a</sup> (4) c + t |
| REN             | - 1.948 (5) c + t              | - 4.345 <sup>a</sup> (5) c + t |
| POP             | - 2.152 (4) c + t              | - 4.934 <sup>a</sup> (4) c + t |
| Georgia         |                                |                                |
| CO <sub>2</sub> | - 1.579 (5) c + t              | - 4.638 <sup>a</sup> (4) c + t |
| NGAS            | - 2.648 (2) c + t              | - 6.100 <sup>a</sup> (3) c + t |
| REN             | - 2.562 (3) c + t              | - 5.925 <sup>a</sup> (3) c + t |
| POP             | - 1.131 (5) c + t              | - 4.884 <sup>a</sup> (4) c + t |
| Michigan        |                                |                                |
| CO <sub>2</sub> | - 2.485 (4) c + t              | - 4.971 <sup>a</sup> (4) c + t |
| NGAS            | - 2.267 (5) c + t              | - 5.067 <sup>a</sup> (3) c + t |
| REN             | - 2.948 (4) c + t              | - 5.051 <sup>a</sup> (4) c + t |
| POP             | - 2.157 (6) c + t              | - 4.887 <sup>a</sup> (5) c + t |
| Washington      |                                |                                |
| CO <sub>2</sub> | - 2.099 (4) c + t              | - 5.044 <sup>a</sup> (4) c + t |
| NGAS            | - 2.856 (4) c + t              | - 5.051 <sup>a</sup> (4) c + t |
| REN             | - 3.923 <sup>a</sup> (4) c + t | - 5.468 <sup>a</sup> (3) c + t |

**Table 1** (continued)

|     | PP (levels)       | PP (1st differences)           |
|-----|-------------------|--------------------------------|
| POP | - 2.244 (5) c + t | - 4.528 <sup>a</sup> (5) c + t |

Lag order is indicated in parentheses. Barlett kernel is used as the spectral estimation method. The bandwidth is selected using the Newey–West method

<sup>a</sup> 5% level of significance

level. Findings suggest that an increase in natural gas consumption causes to an increase in CO<sub>2</sub> emissions, while a decrease in natural gas consumption tends to depress CO<sub>2</sub> emissions. However, while a positive shock in renewable energy consumption reduces CO<sub>2</sub> emissions, a negative shock in renewable energy consumption adds to CO<sub>2</sub> emissions in California. Moreover, the results also suggest the effect of population on CO<sub>2</sub> emissions is statistically insignificant.

For Texas, we find that only positive component of natural gas consumption has positive and statistically significant impact on CO<sub>2</sub> emissions. Based on the results, a one percent increase in natural gas consumption leads to 0.808% increases in CO<sub>2</sub> emissions. On the other hand, only negative component of renewable energy consumption has negative and significant impact on CO<sub>2</sub> emissions. In other words, the results show that a 1% decline in renewable energy consumption triggers a rise of 0.437% in CO<sub>2</sub> emissions, holding everything else is constant. More so, as expected, the coefficient of population was found to be positive and significant at 10%

**Table 2** Bound test for nonlinear ARDL model

| State                   | F stat             | P value | Decision          |
|-------------------------|--------------------|---------|-------------------|
| California              | 4.384 <sup>a</sup> | 0.000   | Cointegration     |
| Texas                   | 4.933 <sup>a</sup> | 0.000   | Cointegration     |
| Florida                 | 3.961 <sup>a</sup> | 0.005   | Cointegration     |
| New York                | 5.360 <sup>a</sup> | 0.000   | Co-integration    |
| Pennsylvania            | 7.052 <sup>a</sup> | 0.000   | Cointegration     |
| Illinois <sup>b</sup>   | 1.926              | 0.189   | No co-integration |
| Ohio                    | 4.669 <sup>a</sup> | 0.000   | Cointegration     |
| Georgia                 | 8.458 <sup>a</sup> | 0.000   | Cointegration     |
| Michigan                | 8.480 <sup>a</sup> | 0.000   | Cointegration     |
| Washington <sup>b</sup> | 1.518              | 0.1849  | No cointegration  |

F critical values are cited from Narayan (2005) for  $k = 3$  and  $n = 84$ . The upper bound critical values for F statistic with unrestricted intercept and no trend at the 10% critical value bounds for  $I(0) = 2.823$  and  $I(1) = 3.885$

<sup>b</sup> Since the Wald test results for long-run co-integration for Illinois and Washington are found below the lower and upper critical value bounds, we conclude that there is no long-cointegration. Thus, we did not report both long-run and short-run estimates for these two states

**Table 3** Nonlinear ARDL estimation results for each state

| Dependent variable : CO <sub>2</sub>              |                      |                |                      |                |                      |                |                      |                |
|---|----------------------|----------------|----------------------|----------------|----------------------|----------------|----------------------|----------------|
| Variables   | California           |                | Texas                |                | Florida              |                | New York             |                |
|   | Coef.                | <i>P</i> value | Coef.                | <i>P</i> value | Coef.                | <i>P</i> value | Coef.                | <i>P</i> value |
| <b>Long-run analysis</b>                          |                      |                |                      |                |                      |                |                      |                |
| Constant  | 0.296 <sup>a</sup>   | 0.002          | 0.458 <sup>b</sup>   | 0.011          | 0.506 <sup>a</sup>   | 0.004          | 0.163                | 0.137          |
| CO <sub>2</sub> (-1)                              | - 0.064 <sup>a</sup> | 0.001          | - 0.087 <sup>b</sup> | 0.012          | - 0.129 <sup>a</sup> | 0.003          | - 0.043              | 0.123          |
| NGAS <sup>+</sup> (-1)                            | 0.086 <sup>b</sup>   | 0.022          | 0.808 <sup>a</sup>   | 0.000          | - 0.032              | 0.308          | 0.149                | 0.928          |
| NGAS <sup>-</sup> (-1)                            | - 0.102 <sup>b</sup> | 0.021          | 0.316                | 0.186          | - 0.022              | 0.674          | - 2.598              | 0.260          |
| REN <sup>+</sup> (-1)                             | - 0.028 <sup>b</sup> | 0.024          | - 0.025              | 0.610          | 0.003                | 0.911          | 0.769                | 0.526          |
| REN <sup>-</sup> (-1)                             | 0.061 <sup>b</sup>   | 0.007          | 0.437 <sup>b</sup>   | 0.029          | - 0.064 <sup>b</sup> | 0.011          | 1.870                | 0.165          |
| POP   | - 0.403              | 0.501          | 12.732 <sup>c</sup>  | 0.076          | 0.820                | 0.076          | - 39.402             | 0.182          |
| <b>Short-run analysis</b>                         |                      |                |                      |                |                      |                |                      |                |
| $\Delta$ CO <sub>2</sub>                          |                      |                |                      |                |                      |                |                      |                |
| $\Delta$ CO <sub>2</sub> (-1)                     | 0.360 <sup>a</sup>   | 0.000          | 0.484 <sup>a</sup>   | 0.000          | 0.435 <sup>a</sup>   | 0.000          | 0.270 <sup>a</sup>   | 0.004          |
| $\Delta$ CO <sub>2</sub> (-2)                     | 0.254 <sup>a</sup>   | 0.010          | 0.150 <sup>c</sup>   | 0.068          |                      |                |                      |                |
| $\Delta$ CO <sub>2</sub> (-3)                     |                      |                | 0.177 <sup>b</sup>   | 0.048          |                      |                |                      |                |
| $\Delta$ CO <sub>2</sub> (-4)                     | - 0.442 <sup>a</sup> | 0.000          | - 0.203 <sup>b</sup> | 0.027          |                      |                |                      |                |
| $\Delta$ NGAS <sup>+</sup>                        | 0.333 <sup>a</sup>   | 0.000          | 0.307 <sup>a</sup>   | 0.001          |                      |                | 0.873 <sup>a</sup>   | 0.000          |
| $\Delta$ NGAS <sup>+</sup> (-1)                   | - 0.201 <sup>a</sup> | 0.004          | - 0.191 <sup>a</sup> | 0.008          |                      |                |                      |                |
| $\Delta$ NGAS <sup>+</sup> (-2)                   | - 0.188 <sup>b</sup> | 0.010          |                      |                |                      |                |                      |                |
| $\Delta$ NGAS <sup>+</sup> (-3)                   |                      |                |                      |                |                      |                |                      |                |
| $\Delta$ NGAS <sup>+</sup> (-4)                   |                      |                |                      |                | 0.225 <sup>b</sup>   | 0.010          | 0.337 <sup>b</sup>   | 0.030          |
| $\Delta$ NGAS <sup>-</sup>                        | 0.175 <sup>b</sup>   | 0.010          | 0.346 <sup>a</sup>   | 0.000          | 0.355 <sup>b</sup>   | 0.014          |                      |                |
| $\Delta$ NGAS <sup>-</sup> (-1)                   |                      |                | - 0.281 <sup>a</sup> | 0.000          |                      |                | - 0.398 <sup>a</sup> | 0.006          |
| $\Delta$ NGAS <sup>-</sup> (-2)                   |                      |                | - 0.122 <sup>c</sup> | 0.092          |                      |                |                      |                |
| $\Delta$ NGAS <sup>-</sup> (-3)                   |                      |                | - 0.163 <sup>b</sup> | 0.024          |                      |                |                      |                |
| $\Delta$ NGAS <sup>-</sup> (-4)                   | 0.318 <sup>a</sup>   | 0.000          |                      |                | - 0.333 <sup>b</sup> | 0.015          | - 0.432 <sup>a</sup> | 0.006          |
| $\Delta$ RENG <sup>+</sup>                        |                      |                |                      |                |                      |                | - 0.350 <sup>a</sup> | 0.004          |
| $\Delta$ RENG <sup>+</sup> (-1)                   |                      |                |                      |                |                      |                |                      |                |
| $\Delta$ RENG <sup>+</sup> (-2)                   |                      |                |                      |                |                      |                |                      |                |
| $\Delta$ RENG <sup>+</sup> (-3)                   |                      |                | - 0.048 <sup>c</sup> | 0.076          |                      |                |                      |                |
| $\Delta$ RENG <sup>+</sup> (-4)                   |                      |                | 0.077 <sup>b</sup>   | 0.011          | - 0.172 <sup>c</sup> | 0.082          |                      |                |
| $\Delta$ RENG <sup>-</sup>                        |                      |                | 0.223 <sup>a</sup>   | 0.001          |                      |                |                      |                |
| $\Delta$ RENG <sup>-</sup> (-1)                   |                      |                |                      |                |                      |                | 0.184 <sup>a</sup>   | 0.005          |
| $\Delta$ RENG <sup>-</sup> (-2)                   | - 0.042              | 0.106          |                      |                |                      |                |                      |                |
| $\Delta$ RENG <sup>-</sup> (-3)                   |                      |                |                      |                |                      |                |                      |                |
| $\Delta$ RENG <sup>-</sup> (-4)                   | - 0.050              | 0.050          | - 0.211 <sup>a</sup> | 0.000          | 0.177 <sup>b</sup>   | 0.038          | 0.300 <sup>a</sup>   | 0.005          |
| <b>Asymmetric relationship</b>                    |                      |                |                      |                |                      |                |                      |                |
| Long-run asymmetry ( <i>W</i> <sub>LRNGAS</sub> ) | 3.863 (0.007)        |                | 6.732 (0.000)        |                | 2.707 (0.375)        |                | 2.928 (0.027)        |                |
| Long-run asymmetry ( <i>W</i> <sub>LRREN</sub> )  | 2.506 (0.019)        |                | 5.141 (0.000)        |                | 1.512 (0.208)        |                | 1.045 (0.404)        |                |
| <b>Diagnostic tests</b>                           |                      |                |                      |                |                      |                |                      |                |
| J-B normality test (Prob.)                        | 0.071                |                | 0.002                |                | 0.000                |                | 0.000                |                |
| Serial correlation (Prob.)                        | 0.181                |                | 0.548                |                | 0.541                |                | 0.284                |                |
| Breusch/Pagan heteros. (Prob.)                    | 0.065                |                | 0.253                |                | 0.287                |                | 0.926                |                |
| <i>R</i> <sup>2</sup>                             | 0.788                |                | 0.883                |                | 0.515                |                | 0.705                |                |
| <i>F</i> stat (prob.)                             | 14.424 (0.000)       |                | 22.085 (0.000)       |                | 5.842 (0.000)        |                | 10.933 (0.000)       |                |
| AIC   | - 7.828              |                | - 7.095              |                | - 6.348              |                | - 6.594              |                |
| D-W stat  | 1.698                |                | 1.786                |                | 1.989                |                | 1.772                |                |
| Dependent variable : CO <sub>2</sub>              |                      |                |                      |                |                      |                |                      |                |
| Variables   | Pennsylvania         |                | Ohio                 |                | Georgia              |                | Michigan             |                |

**Table 3** (continued)

|   | Coef.                | <i>P</i> value | Coef.                | <i>P</i> value | Coef.                | <i>P</i> value | Coef.                 | <i>P</i> value |
|---|----------------------|----------------|----------------------|----------------|----------------------|----------------|-----------------------|----------------|
| Long-run analysis                                 |                      |                |                      |                |                      |                |                       |                |
| Constant  | 0.707 <sup>a</sup>   | 0.000          | 0.270 <sup>b</sup>   | 0.023          | 0.322 <sup>a</sup>   | 0.002          | 0.740 <sup>a</sup>    | 0.000          |
| CO <sub>2</sub> (-1)                              | - 0.162 <sup>a</sup> | 0.000          | - 0.063 <sup>b</sup> | 0.026          | - 0.087 <sup>a</sup> | 0.002          | - 0.182 <sup>a</sup>  | 0.000          |
| NGAS <sup>+</sup> (-1)                            | - 0.087 <sup>a</sup> | 0.001          | - 0.021              | 0.288          | - 0.038 <sup>b</sup> | 0.020          | 0.450 <sup>b</sup>    | 0.028          |
| NGAS <sup>-</sup> (-1)                            | 0.240 <sup>a</sup>   | 0.007          | 0.119 <sup>c</sup>   | 0.051          | - 0.056              | 0.246          | 0.421 <sup>b</sup>    | 0.033          |
| REN <sup>+</sup> (-1)                             | 0.015                | 0.401          | 0.021                | 0.166          | - 0.018              | 0.430          | - 0.071               | 0.369          |
| REN <sup>-</sup> (-1)                             | - 0.165 <sup>a</sup> | 0.001          | - 0.035 <sup>b</sup> | 0.012          | - 0.010              | 0.636          | 0.443 <sup>a</sup>    | 0.002          |
| POP   | 0.677                | 0.362          | 4.940 <sup>c</sup>   | 0.097          | 1.589 <sup>b</sup>   | 0.044          | - 24.659 <sup>a</sup> | 0.002          |
| Short-run analysis                                |                      |                |                      |                |                      |                |                       |                |
| ΔCO <sub>2</sub>                                  |                      |                |                      |                |                      |                |                       |                |
| ΔCO <sub>2</sub> (-1)                             | 0.442 <sup>a</sup>   | 0.000          | 0.271 <sup>a</sup>   | 0.000          | 0.545 <sup>a</sup>   | 0.000          | 0.387 <sup>a</sup>    | 0.000          |
| ΔCO <sub>2</sub> (-2)                             |                      |                |                      |                |                      |                |                       |                |
| ΔCO <sub>2</sub> (-3)                             |                      |                |                      |                |                      |                |                       |                |
| ΔCO <sub>2</sub> (-4)                             |                      |                |                      |                |                      |                |                       |                |
| ΔNGAS <sup>+</sup>                                | 0.352 <sup>a</sup>   | 0.002          | 0.562 <sup>a</sup>   | 0.000          | 0.285 <sup>a</sup>   | 0.004          |                       |                |
| ΔNGAS <sup>+</sup> (-1)                           |                      |                |                      |                | - 0.181 <sup>a</sup> | 0.003          | - 0.154 <sup>b</sup>  | 0.039          |
| ΔNGAS <sup>+</sup> (-2)                           |                      |                |                      |                |                      |                |                       |                |
| ΔNGAS <sup>+</sup> (-3)                           |                      |                |                      |                |                      |                |                       |                |
| ΔNGAS <sup>+</sup> (-4)                           | 0.260 <sup>b</sup>   | 0.013          | - 0.493 <sup>a</sup> | 0.000          | - 0.139 <sup>c</sup> | 0.094          | - 0.480 <sup>a</sup>  | 0.000          |
| ΔNGAS <sup>-</sup>                                | 0.533 <sup>a</sup>   | 0.000          |                      |                |                      |                |                       |                |
| ΔNGAS <sup>-</sup> (-1)                           | - 0.262 <sup>b</sup> | 0.027          | - 0.221 <sup>b</sup> | 0.016          |                      |                |                       |                |
| ΔNGAS <sup>-</sup> (-2)                           |                      |                |                      |                | 0.176 <sup>b</sup>   | 0.015          |                       |                |
| ΔNGAS <sup>-</sup> (-3)                           |                      |                |                      |                | 0.178 <sup>a</sup>   | 0.009          |                       |                |
| ΔNGAS <sup>-</sup> (-4)                           | 0.449 <sup>a</sup>   | 0.001          |                      |                | 0.746 <sup>a</sup>   | 0.000          |                       |                |
| ΔRENG <sup>+</sup>                                |                      |                | 0.237 <sup>a</sup>   | 0.000          | 0.299 <sup>a</sup>   | 0.000          | 0.349 <sup>a</sup>    | 0.000          |
| ΔRENG <sup>+</sup> (-1)                           |                      |                |                      |                |                      |                |                       |                |
| ΔRENG <sup>+</sup> (-2)                           |                      |                |                      |                |                      |                |                       |                |
| ΔRENG <sup>+</sup> (-3)                           |                      |                |                      |                |                      |                |                       |                |
| ΔRENG <sup>+</sup> (-4)                           |                      |                | - 0.183 <sup>a</sup> | 0.000          | 0.152 <sup>a</sup>   | 0.004          |                       |                |
| ΔRENG <sup>-</sup>                                |                      |                |                      |                | 0.143 <sup>c</sup>   | 0.073          | 0.266 <sup>a</sup>    | 0.000          |
| ΔRENG <sup>-</sup> (-1)                           |                      |                |                      |                |                      |                | - 0.151 <sup>a</sup>  | 0.008          |
| ΔRENG <sup>-</sup> (-2)                           |                      |                |                      |                |                      |                | - 0.135 <sup>a</sup>  | 0.009          |
| ΔRENG <sup>-</sup> (-3)                           |                      |                |                      |                |                      |                |                       |                |
| ΔRENG <sup>-</sup> (-4)                           | - 0.208 <sup>b</sup> | 0.014          |                      |                |                      |                |                       |                |
| Asymmetric relationship                           |                      |                |                      |                |                      |                |                       |                |
| Long-run asymmetry ( <i>W</i> <sub>LRNGAS</sub> ) | 2.796 (0.033)        | 1.492 (0.216)  | 1.113 (0.358)        | 36.135 (0.000) |                      |                |                       |                |
| Long-run asymmetry ( <i>W</i> <sub>LRREN</sub> )  | 2.457 (0.042)        | 3.072 (0.022)  | 2.706 (0.012)        | 3.673 (0.005)  |                      |                |                       |                |
| Diagnostic tests                                  |                      |                |                      |                |                      |                |                       |                |
| J-B normality test (Prob.)                        | 0.018                | 0.000          | 0.311                | 0.000          |                      |                |                       |                |
| Serial correlation (Prob.)                        | 0.365                | 0.995          | 0.621                | 0.313          |                      |                |                       |                |
| Breusch/Pagan heteros. (Prob.)                    | 0.046                | 0.744          | 0.000                | 0.436          |                      |                |                       |                |
| <i>R</i> <sup>2</sup>                             | 0.840                | 0.791          | 0.755                | 0.755          |                      |                |                       |                |
| <i>F</i> stat (prob.)                             | 24.399 (0.000)       | 20.925 (0.000) | 11.96927 (0.000)     | 14.413 (0.000) |                      |                |                       |                |
| AIC   | - 7.271              | - 6.633        | - 6.368              | - 7.106        |                      |                |                       |                |
| D-W stat  | 2.248                | 1.865          | 2.166                | 1.775          |                      |                |                       |                |

CO<sub>2</sub> is carbon emissions, NGAS is natural gas, REN is renewable energy, and POP is population. The superscript “+” and “-” indicate the positive and negative cumulative sums, respectively. NGAS<sup>+</sup>, NGAS<sup>-</sup>, REN<sup>+</sup>, and REN<sup>-</sup> are the estimated long-run coefficient related to positive and negative changes in the natural gas and renewable energy, respectively. The symbols (a), (b), and (c) show that the parameter is significant at 1%, 5%, and 10% levels of significance respectively.

significance level, indicating 1% increase in population would rise CO<sub>2</sub> emissions by 12.732% in the long-run.

When analyzing New York, we find that the estimation results of positive and negative component of natural gas and renewable energy consumptions are statistically insignificant in the long-run. Additionally, the effect of population on CO<sub>2</sub> emissions is also found to be statistically insignificant at any significance level.

For Pennsylvania, a statistically significant long-run effect is found only from positive change in natural gas and negative change in renewable energy has statistically significant effect on CO<sub>2</sub> emissions. The estimated long-run coefficient of NGAS<sup>+</sup> is  $-0.087$ , indicating that a 1% positive shock in natural gas consumption is expected to decrease CO<sub>2</sub> emissions by 0.087%. NGAS<sup>-</sup> estimation is also found statistically significant, which suggest that a 1% decrease in natural gas consumption causes a 0.24% increase in CO<sub>2</sub> emissions. On the other hand, it is found that the decrease in renewable energy consumption REN<sup>-</sup> has a negative impact on CO<sub>2</sub> emissions in the long-run. This particular result indicates that a 1% percent change in renewable energy consumption would lead to a decrease in CO<sub>2</sub> emissions by 0.165%.

For the case of Michigan, all results are statistically significant in the long run at 1% and 5%, except the REN<sup>+</sup>. According to the estimation parameters, both a 1% positive and a 1% negative shock of natural gas have a positive impact on CO<sub>2</sub> emissions, respectively, by 0.45% and 0.421%. Furthermore, renewable energy consumption has not only positive but also negative estimation results. The results indicate that a 1% increase in renewable energy consumption causes 0.071% reduction in CO<sub>2</sub> emissions, whereas a 1% decrease in renewable energy consumption results in a 0.443% rise in CO<sub>2</sub> emissions. Lastly, population has a strong and significant estimation result, which points 24.659% increase in emissions if population goes up by 1%.

## Robustness checks

To confirm the validity of our results, we apply several statistical tests on the dataset, including the Breusch–Godfrey LM test for serial correlation, the Breusch–Pagan–Godfrey for heteroskedasticity problem, and Jarque–Bera normality test for normality assumption in error terms. All the diagnostic test statistics for each State are presented in the bottom part of the Table 3. The results reveal that there is no evidence of model misspecification.

In addition, we employed the CUSUM and CUSUMQ tests to investigate the constancy of parameters as suggested by Brown et al. (1975) and Pesaran and Pesaran (1999). The findings of the CUSUM and CUSUMQ tests are displayed in Fig. 1. Based on the findings, the estimated parameters are stable over the sample period since the CUSUM or

CUSUMQ blue line stays inside the 5% percent critical lines, which indicates the stability of parameters.

## Conclusions, discussion and policy recommendations

The current study aims to explore the determinants of CO<sub>2</sub> emissions in the selected most populous states in the USA using an estimation model based on a statistical method, non-ARDL, over the period from 1997 to 2017. The empirical analyses compare the effects of increasing and decreasing shocks in natural gas and renewable energy consumptions on CO<sub>2</sub> emissions in the long- and short-run.

The empirical results of the study indicate that there is an existence of long-run positive causality between renewable energy/natural gas consumption and carbon dioxide emissions in the study states. Regarding specifically to the results for the natural gas consumption, increasing natural gas consumption positively affects carbon dioxide emissions in California, Texas and Michigan states, while it only decreases the emissions in Pennsylvania. Moreover, the periods, in which natural gas consumption decreased, carbon dioxide emissions decrease only in California yet increase in Pennsylvania and Michigan. Therefore, adoption of policies designed to discourage natural gas consumption, such as raising price of natural gas via taxes, would be more likely to contribute to future reductions in carbon dioxide emissions in California and Texas states. For the state of Pennsylvania, the results suggest that substitution from other fuel-based energy sources to natural gas is viable and effective effort to decrease carbon dioxide emissions and environmental pollution in these states.

Regarding the results for renewable energy consumption, increases in renewable energy consumption reduce carbon dioxide emissions only in the state of California. In the rest of the states examined in the study, increasing renewable energy consumption does not significantly influence carbon dioxide emissions in the atmosphere. However, during the periods when renewable energy consumption decreased, carbon dioxide emissions increase in California, Texas and Michigan states. Hence, renewable energy consumption must be promoted by the policy-makers in these states. On the other hand, the results indicate that decreasing consumption of renewable energy reduces carbon dioxide emissions only in Pennsylvania. Based on this specific result, it can be concluded that policy-makers have to get the renewable energy consumption under control in this state.

The fact that the effect of natural gas and renewable energy consumptions on carbon dioxide emission varies from state to state could be due to some social and economic characteristics of the states, such as income differences, the amount of natural gas and renewable energy consumption or the ratio of these two types of energy consumption to others in these states.



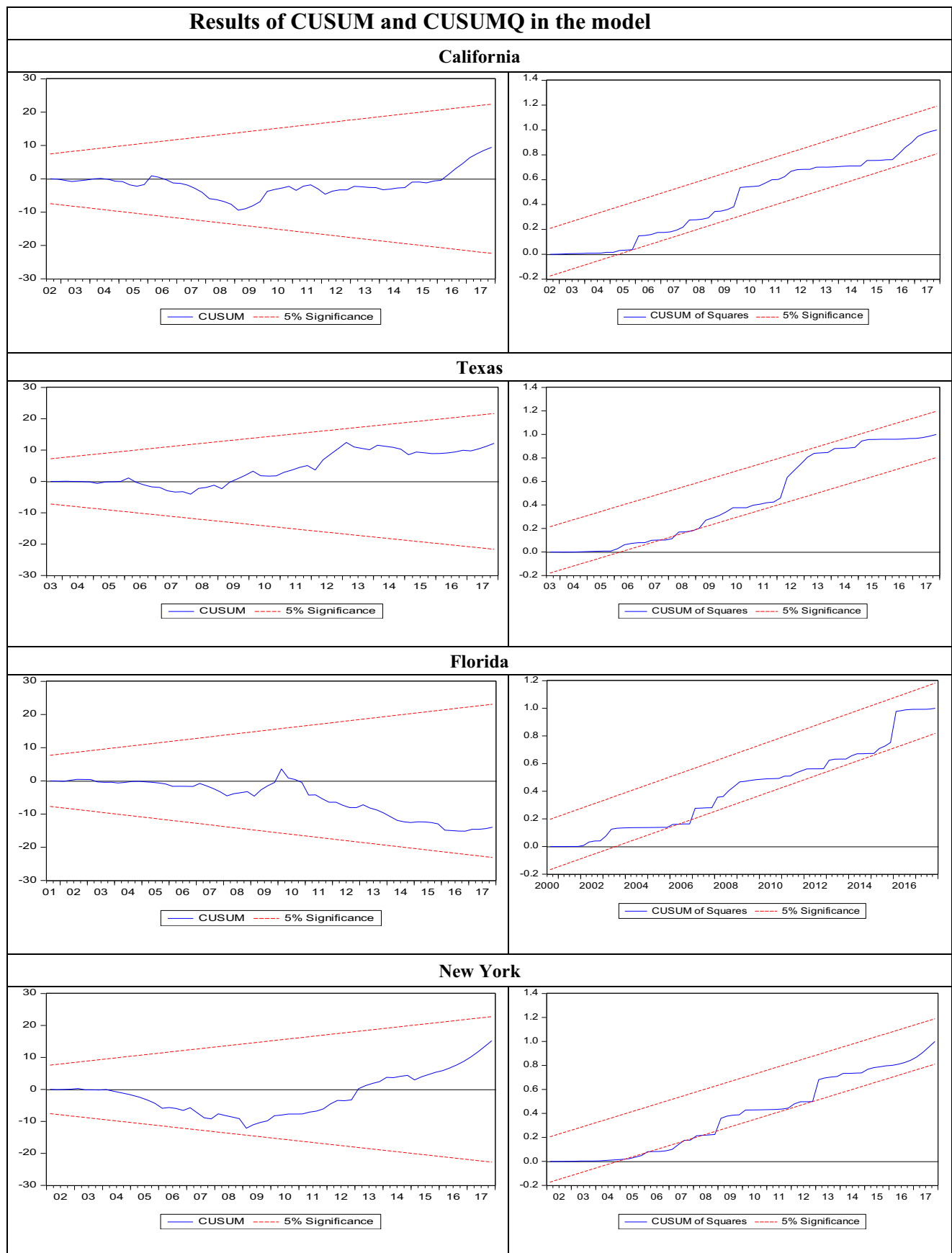


Fig. 1 Results of CUSUM and CUSUMQ in the model

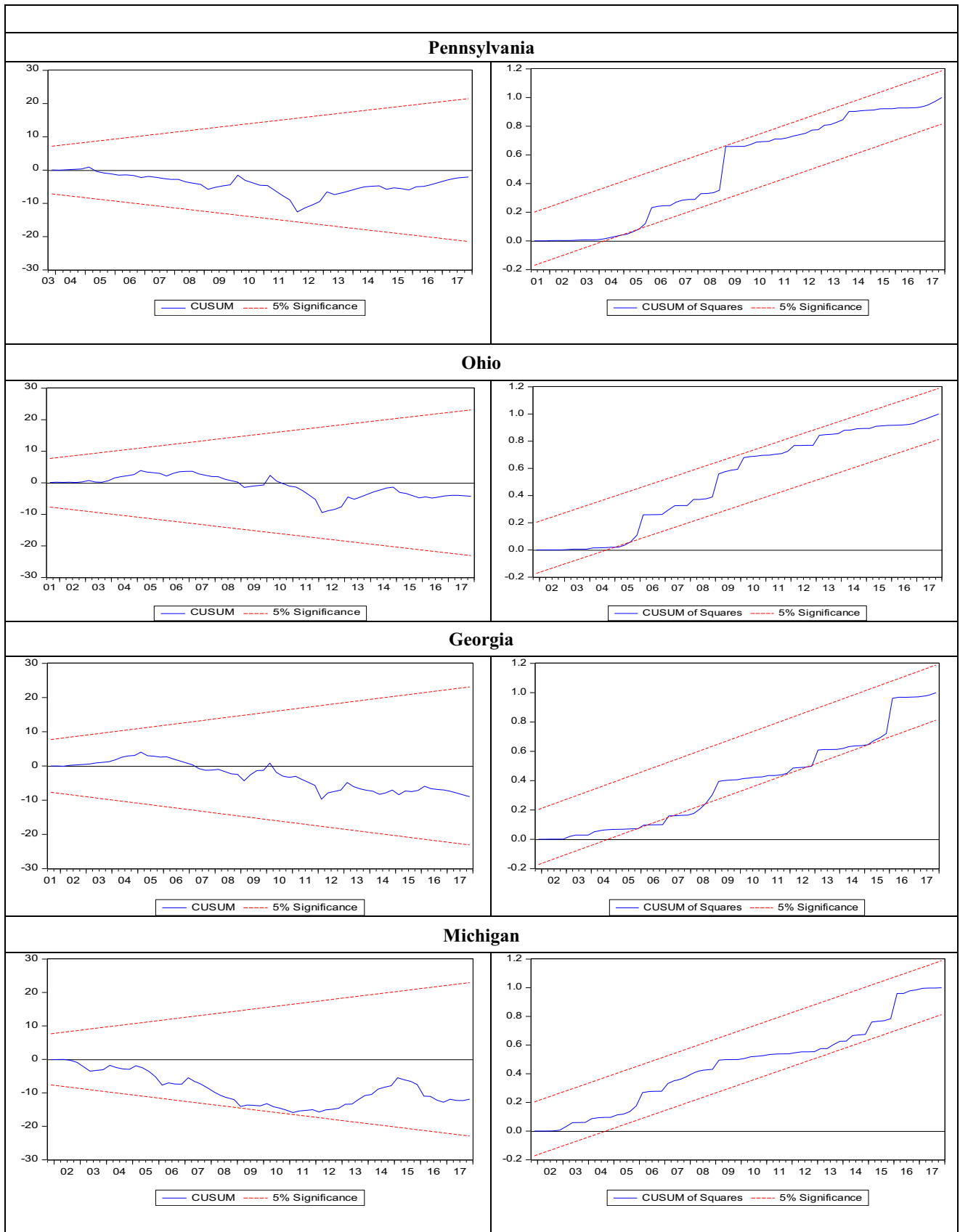


Fig. 1 (continued)

Therefore, carbon dioxide emissions impose various important responsibilities to policy-makers in these states to prevent environmental degradation and to enhance economic development. Failure to take necessary social and political measures to reduce environmental pollution will eventually slow economic growth.

In view of the results obtained from the analyses of the current study, to reduce pollutant emissions in the atmosphere, one of the most important actions that policy-makers should promote is the investments in improving the infrastructure of renewable energy. In states where renewable energy is not sufficient, the use of natural gas, in a controlled manner, should be encouraged by the state decision-makers. In addition, urban strategists should consider increasing population density as a key strategy to reduce CO<sub>2</sub> emissions since spatial density causes traffic jam and less personal vehicle use. Besides, governments should promote the usage of public transportation systems in the cities. The use of vehicles that emit less carbon dioxide in the atmospheres such as hybrid and electric vehicles, bicycles etc. should also be encouraged. In more industrialized states, producers should be promoted to switch from old technologies which emit more pollutant to environmentally friendly technologies and incentives should be given to increase the number of companies operating in the recycling sector to protect environment and reduce pollutant emissions.

Promoting the use of environmentally friendly energy in homes, transportation or industry can be through various incentive policies, or through additional taxes on the use of non-environmentally friendly fossil-based energy. However, the answers to the questions of how much tax will be applied, how these taxes will be and what their effects will be constitute the subject of future studies. Future research may also analyze the impact of the consumption of other energy types such as fossil-based or nuclear energy on CO<sub>2</sub> emissions by using additional control variables in their models. In addition, future efforts could improve this study by analyzing and comparing the relationship between energy consumption and carbon dioxide emissions in the states having more rural population.

**Acknowledgments** This paper was initially presented at the International Conference on Economics, Energy and Environment, June 25–27, 2020, Cappadocia, Nevsehir, Turkey. The authors are grateful to the editor and anonymous referees of the journal for their extremely useful suggestions to improve the quality of the article. We are solely responsible for all errors.

**Authors' contributions** Ferhat Çıtak: Supervision, writing - original draft, review and editing, validation, resources.

Hakan Uslu: writing - original draft, review and editing.

Oğuzhan Batmaz: writing - original draft, review and editing.

Safa Hoş: writing - original draft, review and editing.

## Compliance with ethical standards

**Conflict of interests** The authors declare that they have no conflict of interest.

**Research data for this article** Not applicable.

## References

- Ahmad M, Khan Z, Rahman ZU, Khan S (2018) Does financial development asymmetrically affect CO<sub>2</sub> emissions in China? An application of the nonlinear autoregressive distributed lag (NARDL) model. *Carbon Management* 9(6):631–644
- Ahmad M, Khattak SI, Khan S, Rahman ZU (2020) Do aggregate domestic consumption spending & technological innovation affect industrialization in South Africa? An application of linear & nonlinear ARDL models. *Journal of Applied Economics* 23(1):44–65
- Apergis N, Payne JE, Menyah K, Wolde-Rufael Y (2010) On the causal dynamics between emissions, nuclear energy, renewable energy, and economic growth. *Ecological Economics* 69(11):2255–2260
- Aslan A, Ocal O (2016) The role of renewable energy consumption in economic growth: evidence from asymmetric causality. *Renewable and Sustainable Energy Reviews* 60:953–959
- Bhattacharya M, Churchill SA, Paramati SR (2017) The Dynamic Impact of Renewable Energy and Institutions on Economic Output and CO<sub>2</sub> Emissions across Regions. *Renewable Energy* 111:157–167
- Bilgili F, Koçak E, Bulut Ü (2016) The dynamic impact of renewable energy consumption on CO<sub>2</sub> emissions: a revisited environmental Kuznets curve approach. *Renewable and Sustainable Energy Reviews* 54:38–845
- Brown RL, Durbin J, Evans JM (1975) Techniques for testing the constancy of regression relationships over time. *Journal of the Royal Statistical Society, Series B* 37:149–192
- Dogan E, Ozturk I (2017) The influence of renewable and non-renewable energy consumption and real income on CO emissions in the USA: evidence from structural break tests. *Environmental Science & Pollution Research* 24(11):10846–10854
- Dong K, Sun R, Hochman G (2017a) Do natural gas and renewable energy consumption lead to less CO<sub>2</sub> emission? Empirical evidence from a panel of BRICS countries. *Energy* 141:1466–1478
- Dong K, Sun R, Hochman G, Zeng X, Li H, Jiang H (2017b) Impact of natural gas consumption on CO<sub>2</sub> emissions: panel data evidence from China's provinces. *Journal of Cleaner Production* 162:400–410
- Dong K, Sun R, Li H, Liao H (2018) Does natural gas consumption mitigate CO<sub>2</sub> emissions: testing the environmental Kuznets curve hypothesis for 14 Asia-Pacific countries. *Renewable and Sustainable Energy Reviews* 94:419–429
- Ergun SJ, Owusu PA, Rivas MF (2019) Determinants of renewable energy consumption in Africa. *Environment Science and Pollution Research* 26:15390–15405
- Isik C, Serdar O, Dilek Ö (2019) The economic growth/development and environmental degradation: evidence from the US state-level EKC hypothesis. *Environmental Science and Pollution Research* 26:30772–33078
- Jaforullah M, King A (2015) Does the use of renewable energy sources mitigate CO<sub>2</sub> emissions? A reassessment of the US evidence. *Energy Economics* 49:711–717
- Johnson TL, Keith DW (2014) Fossil electricity and CO<sub>2</sub> sequestration: how natural gas prices, initial conditions and retrofits determine the cost of controlling CO<sub>2</sub> emissions. *Energy Policy* 32(3):367–382
- Joskow PL (2013) Natural gas: from shortages to abundance in the United States. *American Economic Review* 103(3):338–343

- Katrakilidis C, Trachanas E (2012) What drives housing price dynamics in Greece: new evidence from asymmetric ARDL cointegration. *Economic Modelling* 29(4):1064–1069
- Khan Z, Sisi Z, Siqun Y (2019) Environmental regulations an option: asymmetry effect of environmental regulations on carbon emissions using non-linear ARDL. *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects* 41(2):137–155
- Koutroulis A, Panagopoulos Y, Tsouma E (2016) Asymmetry in the response of unemployment to output changes in Greece: evidence from hidden co-integration. *The Journal of Economic Asymmetries* 13:81–88
- Mahmood N, Wang Z, Hassan ST (2019) Renewable energy, economic growth, human capital, CO<sub>2</sub> emission: an empirical analysis. *Environment Science and Pollution Research* 26:20619–20630
- McDermott J, McMenamin P (2008) Assessing inflation targeting in Latin America with a DSGE model. (Central Bank of Chile Working Papers, No 469). Chile: Central Bank of Chile
- Menyah K, Wolde-Rufael Y (2010) CO<sub>2</sub> emissions, nuclear energy, renewable energy and economic growth in the US. *Energy Policy* 38(6):2911–2915
- Narayan P (2005) The Saving and Investment Nexus for China: evidence from Cointegration tests. *Applied Economics* 37(17):1979–1990
- Ouattara B (2004) Foreign aid and fiscal policy in Senegal. Mimeo University of Manchester, Manchester
- Ouyang Y, Li P (2018) On the nexus of financial development, economic growth, and energy consumption in China: New perspective from a GMM panel VAR approach. *Energy Economics* 71:238–252
- Pesaran MH, Pesaran B (1999) Working with Microfit 4.0: interactive econometric analysis. Oxford University Press, Oxford.
- Pesaran MH, Shin Y, Smith RJ (2001) Bounds testing approaches to the analysis of level relationships. *J. Appl. Econometrics* 16(3):289–326
- Podesta JD, Wirth TE (2009) Natural gas: a bridge fuel for the 21st century. Center for American Progress
- Romero AM (2005) Comparative study: factors that affect foreign currency reserves in China and India. Honors projects (Paper 33). United States: Illinois Wesleyan University
- Sbia R, Shahbaz M, Hamdi H (2014) A contribution of foreign direct investment, clean energy, trade openness, carbon emissions and economic growth to energy demand in UAE. *Economic Modelling* 36:191–197
- Shafiei S, Salim RA (2014) Non-renewable and renewable energy consumption and CO<sub>2</sub> emissions in OECD countries: a comparative analysis. *Energy Policy* 66:547–556
- Shahbaz M (2017) Current issues in time-series analysis for the energy-growth nexus; asymmetries and nonlinearities case study: Pakistan. MPRA Paper 82221, University Library of Munich, Germany
- Shearer C, Bistline J, Inman M, Davis SJ (2014) The effect of natural gas supply on US renewable energy and CO<sub>2</sub> emissions. *Environmental Research Letters* 9(9):094008
- Shin Y, Yu B, Greenwood-Nimmo M (2014) Modelling asymmetric cointegration and dynamic multipliers in a nonlinear ardl framework. In: Horrace W, Sickles R (eds) *The Festschrift in Honor of Peter Schmidt: Econometric Methods and Applications*. Springer, New York, pp 281–314
- Solarin SA, Lean HH (2016) Natural gas consumption, income, urbanization, and CO<sub>2</sub> emissions in China and India. *Environ Sci Pollut Res* 23(18):18753–18765
- Ullah A, Zhao X, Kamal MA, Zheng J (2020) Modelling the relationship between military spending and stock market development (a) symmetrically in China: An empirical analysis via the NARDL approach. *Physica A: Statistical Mechanics and its Applications* 554: 124106
- Ummalla M, Samal A (2019) The impact of natural gas and renewable energy consumption on CO<sub>2</sub> emissions and economic growth in two major emerging market economies. *Environment Science and Pollution Research* 26:20893–20907
- Xu H (2016) Linear and nonlinear causality between renewable energy consumption and economic growth in the USA. *Journal of Economics and Business* 34(2):309–332

**Publisher's note** Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.