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RESEARCH ARTICLE

# An asymmetric analysis of the impacts of energy use on carbon dioxide emissions in the G7 countries

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## Abstract

The foremost theme of the paper is to explore the asymmetric/symmetric impact of energy consumption on the carbon dioxide emission of G7 countries (Germany, Canada, USA, Italy, France, Italy, UK, and Japan). The nonlinear autoregressive distributed lag is used to measure asymmetric/symmetric cointegration by using annual data of G7 countries from 1965 to 2019. The augmented Dickey-Fuller and structural break unit root test is employed to measure the stationarity in variables while the Brock, Dechert, and Scheinkman test is used for measuring nonlinearity and the Wald test is used to figure out short- and long-run asymmetries/symmetries, respectively. The estimated findings of the nonlinear autoregressive distribution lag model show a significant effect of energy use on the ecological footprint. The asymmetric causality test provides evidence of unidirectional, bidirectional, and asymmetrical/symmetrical causality among the variables of G7 nations. The finding of the study suggested policy for the government of Canada and France to use coal instead of oil and gas while the USA, Germany, Italy, UK, and Japan are required to consume gas as compared to oil and coal. Similarly, the study also suggests using modern technology, renewable energy, and preventive measurement for ensuring environmental betterment.

**Keywords** G7 · Cointegration · Stationarity · Energy · Causality · Symmetries

## Introduction

The human lifestyle and standards are uplifted due to the expansion of technology, but it causes many environmental challenges such as emission of greenhouse gases (GHG) and depletion of the ozone layer (Sapovadia and Vrajlal 2020; Fang et al. 2019). In the present time, reducing the risk of environmental hazard along with economic growth is the current global agenda. Therefore, the world economies assured the United Nations' Sustainable Development Goals (UNDP 2018) agenda to protect the environmental quality (Chirambo 2018). These policies exposed the traditional economic development policy which was considered as a blunder with environmental sustainability (Murshed 2020a, b). The race in economic growth among the economies has worsened the global environment which causes a serious risk to maintaining the performance of economic growth (Murshed 2018). The environmental economist considers the emission of greenhouse gases during economic activity a major factor responsible for the environmental degradation worldwide. Therefore, during the Paris Agreement conference under the United Nations Framework Convention on Climate Change (UNFCCC), most of the countries are agreeing to adopt a friendly environment policy to reduce the GHG emission and retain the temperature below the pre-industrial level (Horton et al. 2016). The World Development Indicators (WDI 2017) reported a tremendous increase in GHG from the last decades. Globally, the carbon dioxide emission during 1980 was observed to be 19.35 million kilotons which are raised to 35.84 million kilotons during 2017 showing about an 84% increase along this period. Such increase in emission is due to the use of fossil fuel in various sectors of the economy. Transportation, agricultural production, power generator, etc., are responsible for the emission of GHG (Naseem et al. 2020; Alola and Joshua 2020; Nasrullah et al. 2021).

The modern challenges and harmful properties of global warming attracted and forced researchers to focus on the

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association among energy use, economic growth, and carbon dioxide ($CO_2$) emission (Cai et al. 2018; Bekun et al. 2018; Roinioti and Koroneos 2017). It is even a big challenge for the policymakers and environmental economists in the modern world to consume energy for sustainable development without harming the environment (Luqman et al. 2019). Hence, the attention of researchers toward energy consumption, GDP, and environmental protection increased significantly in the world to deal with this global hazard (Akadiri et al. 2019; Baz et al. 2019; Ozcan et al. 2019). Therefore, the increases in energy demand and climatic issues due to the massive use of fossil fuels forced many economies to move toward renewable energy to decrease ecological footprint and improve air quality (Kuriqi et al. 2019; Baz et al. 2020). Not only other human activities that substantially ruined the natural ecosystem and atmosphere, but the growth in demand for energy also substantially pressurized the ecological footprint (Nathaniel and Rehman Khan 2020; Baz et al. 2020; Nathaniel et al. 2019). This environmental concern is related to the worldwide policymakers, environmentalists, and energy economists to design environmental policies linked to the use of energy and implement it globally (Khan et al. 2019a, b). Though the association between energy consumption and economic growth is important for sustainable growth, this nexus of energy consumption is also responsible for environmental degradation due to GHG emission, which is emitted from the combustion of fossil fuel in various sectors of the economy (Baz et al. 2020). Still, it is expected that energy consumption has a direct relation with the environment but a strong bond also exists between GDP and the environment (Ali et al. 2019).

The energy consumption and $CO_2$ emission increase much faster than real growth which is a considerable challenge to handle the association among economic growth, energy consumption, and environmental quality (Ozcan et al. 2019; Akadiri et al. 2019; Jafari et al. 2012). Previous studies employed the autoregressive distribution lag (ARDL) model to measure the relation between economic growth, environmental degradation, and energy consumption (Ali et al. 2020; Koengkan 2018; Javid and Sharif 2016). Hence, most of the studies ignored the asymmetries that exist among environmental quality, energy use, economic growth, and gross capital formation of G7 countries. World Bank (2018) reported that the G7 countries emit 27.3% (95 billion tons) of the total world carbon emission due to which these countries are facing a huge risk of environmental degradation. This study covers the gap of asymmetries that exist in the fossil fuel among fossil fuel and environmental quality of G7 economies. The study also highlights the positive and negative shocks of the oil, coal, and gas of G7 countries and also focuses on the shipment of energy source which are missing in the existing literature. The previous study mostly used renewable energy and nonrenewable energy in their study, but this study covers the impact of oil, coal, and gas on $CO_2$ emission. Therefore, the current study added to the existing literature by using the nonlinear ARDL model to measure:

a) The role of fossil fuel on the mitigation of carbon emission in G7 countries
b) The asymmetric/symmetric positive and negative shocks of fossil fuel on carbon emission of G7 economies
c) If there is any asymmetric/symmetric causality among the variables
d) The robustness of our findings by using the different diagnostic techniques

The paper is classified as follows: “Literature reviews” describe the previous literature, while “Data and variables” shows the data and variables used in the study. “Methodology and model specification” highlights the methods and model specification, while “Results and discussion” presents the estimated result with discussion, and finally, the “Conclusion and suggestion” shows the conclusion with the crucial suggestion.

## Literature reviews

Simon Kuznets (1955) proposed the environmental Kuznets curve (EKC) hypothesis which assumes the nonlinear inverted-U-shaped association between income inequality and economic growth. In his study, he observed that the EKC hypothesis replaces the inequality of income and finds the changes in environmental quality and GHG emission with the increase in national income level. Grossman and Krueger (1991) first time check the validity of the EKC hypothesis for Mexico by using sulfur and smoke emission to measure the environmental quality in EKC analysis. The finding of their results verifies the presence of the EKC hypothesis in Mexico. Later, many researchers have followed the EKC hypothesis such as Murshed et al. (2020, 2021), Murshed et al. (2021), Murshed and Dao (2020), Adedoyin et al. (2020), Sun et al. (2019), Ozcan et al. (2018), Asongu et al. (2018), Apergis and Ozturk (2015), Nasrullah et al. (2019, 2020), and Zulfiqar et al. (2020).

Several studies are conducted to measure the impact of various factors responsible for the degradation of environmental quality (Bello et al. 2018; Işik et al. 2017; Acar and Lindmark 2017). Işık et al. (2019) measure the impact of fossil fuel, GDP, population growth, and renewable energy on $CO_2$ emission using the EKC hypothesis of 10 states of the USA. Azam et al. (2016) utilize panel data of China, India, Japan, and the USA by using the fully modified ordinary least square (FMOLS) model for measuring the influence of $CO_2$ emission, trade, energy use, and economic growth. Similarly, Lee et al. (2016) and Al-Mulali et al. (2015) find the unidirectional causality from economic growth and $CO_2$ emission. Hanif (2018) measured the impact of urban sprawling, fossil fuel, and economic growth on $CO_2$ emission using the generalized method of moments (GMM) model, while Saboori et al. (2017) measured the cointegration between $CO_2$ emission, oil consumption, and GDP of three Asian countries using the Johansen cointegration test. Similarly, Baloch et al. (2019) and Saboori et al. (2012) publicized the causal nexus between economic growth and $CO_2$ emission of 59 countries using panel data.

Lei and Zhou (2012) affirmed that inefficient energy and population are the major factors for environmental degradation of 17 countries while Sarkodie and Strezov (2018a, 2018b) analyzed data from 1974 to 2013 of the Australian economy by using the FMOLS model and concluded that nonrenewable energy consumption (NREC) increases the emission factor (EF) by increased $CO_2$ emission while the consumption of renewable energy promotes environmental stability by reducing emission. Remarkably, the economies utilizing high renewable energy have a clean environment and low emission factor. Acheampong et al. (2019) figured out the nexus of EF and NREC of 46 SSA studies and confirmed that the economy's growth increases from the NREC can generate high emission factor which directly increases the level of $CO_2$ emission. Liu et al. (2017a) find the relation of energy consumption and emission factor of Southeast Asian economies (ASEAN-4 countries: Philippines, Malaysia, Thailand, and Indonesia) covering the period from 1970 to 2013. The study ascertains that renewable energy consumption and agriculture decline the level of $CO_2$ emission while nonrenewable energy consumption deteriorates the emission factor. Liu et al. (2017a, 2017b) also measure the agricultural industry of BRICS economies which emits $CO_2$.

The previous study of Wesseh and Lin (2016) measures the renewable and nonrenewable energy consumption impact on the economic performance of 34 African countries using a dynamic panel data analysis. Their study provides evidence of a rapid increase in economic performance with the utilization of nonrenewable energy consumption as compared to renewable energy. On the other hand, Shahbaz et al. (2015) show that the economic performance is also high with the consumption of renewable energy in Pakistan. Boontome et al. (2017) detected that from 1971 to 2013, the race of economic growth forces the Thailand economy to upsurge the nonrenewable energy consumption level which directly increases the emission factor, while Nathaniel et al. (2019) stated that economic growth and emission factor have unidirectional causality, which implies that the environmental worsen is still connected with the increase in the utilization of nonrenewable energy consumption during the period of under review. The literature of Hanif et al. (2019) studied the 25 middle-income economies of the globe and found the shocking effect of nonrenewable energy on environmental sustainability.

In Latin America, Al-Mulali et al. (2014) figure out that the performance of renewable energy performance is better in encouraging the economies of Latin America than nonrenewable energy due to its efficiency issues. To endure better growth and prosperity, it is recommended to strengthen renewable energy by investment and reduce the dependency on fossil fuel in addition to ensure energy security. In the same manner, Feng et al. (2018) and Long et al. (2015) reinforce China that high economic growth is related to the ecosystem service deficit. The existing literature of Ozcan et al. (2019) which studied 35 OECD countries by using the GMM-panel vector autoregression (PVAR) model covering data from 2000 to 2014 fully supports the literature of Feng et al. (2018). The authors also proved that the rise in the economic growth of the economies worsens the ecological indices due to the dependency on fossil fuel and nonrenewable energy consumption.

Westerlund and Edgerton (2007) carried out a deep study of 74 countries using Pedroni cointegration, FMOLS, bootstrap cointegration, and panel causality technique, while Sharif et al. (2019) proved that renewable energy and nonrenewable energy consumption has a positive and negative impact on the environmental degradation. Relatively, Jorgenson and Clark (2011) studied 65 economies around the world and opined that economic growth has no relation with emission factors. Similarly, 24 North African (MENA) and Middle East countries are studied by Charfeddine and Kahia (2019) from 1980 to 2015 using the PVAR model. Their study provides evidence that renewable energy causes a positive shock on the economic growth while its contribution to $CO_2$ emission is a little weak.

## Data and variables

The study employed annual data of G7 countries (Canada, USA, France, Germany, Italy, UK, and Japan) from 1965 to 2019 with a total observation of 55 years except for France. Due to the presence of unit root at the first difference I (1) in Gross Capital Formation of France, the time was chosen from 1985 to 2019 with a total observation of 35 years. The selected independent variable of the study is the consumption of three energy sources (oil [million tons], gas [million tons of oil equivalent], coal [million tons of oil equivalent]), gross domestic products (million US dollar), and gross capital formation (constant local currency unit). The dependent variable is the $CO_2$ emission in million tons emitted by each G7 country. The selected data are obtained from World Development

Indicators and British Petroleum Energy Statistical review. The descriptive statistics of the selected variables are shown in Table 1. The estimated results of Jarque-Bera statistics show that all the variables follow a normal distribution. Figures 1, 2, 3, and 4 in the Appendix show the trend of $CO_2$ emission and oil, coal, and gas consumption of G7

**Table 1** Description of the variables of the G7 nations

| Country | Variables | Mean | Std. Dev. | Skewness | Kurtosis | Jarque-Bera |
|---|---|---|---|---|---|---|
| Canada | $CO_2$ | 6.098 | 0.196 | −0.852 | 3.220 | 6.759 |
| | Oil | 4.435 | 0.163 | −0.648 | 2.929 | 3.855 |
| | Gas | 4.001 | 0.430 | −0.662 | 2.740 | 4.173 |
| | Coal | 3.110 | 0.256 | −0.358 | 1.766 | 4.667 |
| | GDP | 26.886 | 1.041 | −0.481 | 2.2089 | 3.554 |
| | GCF | 26.175 | 0.520 | 0.051 | 1.735 | 3.692 |
| USA | $CO_2$ | 6.098 | 0.196 | −0.852 | 3.220 | 6.759 |
| | Oil | 4.435 | 0.163 | −0.648 | 2.929 | 3.855 |
| | Gas | 4.001 | 0.430 | −0.662 | 2.740 | 4.173 |
| | Coal | 3.110 | 0.256 | −0.358 | 1.766 | 4.667 |
| | GDP | 26.886 | 1.041 | −0.481 | 2.209 | 3.554 |
| | GCF | 26.175 | 0.520 | 0.051 | 1.735 | 3.691 |
| France | $CO_2$ | 5.879 | 0.081 | −0.961 | 2.678 | 5.542 |
| | Oil | 4.453 | 0.094 | −0.731 | 2.111 | 4.269 |
| | Gas | 3.510 | 0.176 | −0.592 | 1.943 | 3.673 |
| | Coal | 2.578 | 0.303 | −0.234 | 2.678 | 0.470 |
| | GDP | 28.191 | 0.428 | −0.630 | 2.770 | 2.390 |
| | GCF | 26.717 | 0.221 | −0.372 | 1.962 | 2.379 |
| Germany | $CO_2$ | 6.819 | 0.130 | −0.258 | 1.915 | 3.3059 |
| | Oil | 4.833 | 0.136 | −0.253 | 2.838 | 0.645 |
| | Gas | 3.808 | 0.816 | −2.233 | 7.156 | 85.291 |
| | Coal | 4.672 | 0.287 | −0.185 | 1.601 | 4.802 |
| | GDP | 27.925 | 0.912 | −0.551 | 1.997 | 5.095 |
| | GCF | 26.896 | 0.219 | −0.127 | 1.456 | 5.610 |
| Italy | $CO_2$ | 5.909 | 0.167 | −1.493 | 5.814 | 38.591 |
| | Oil | 4.414 | 0.196 | −0.999 | 2.542 | 9.627 |
| | Gas | 3.485 | 0.697 | −0.801 | 2.525 | 6.401 |
| | Coal | 2.485 | 0.210 | −0.246 | 2.097 | 2.425 |
| | GDP | 27.271 | 1.095 | −0.737 | 2.240 | 6.301 |
| | GCF | 26.292 | 0.259 | −0.1649 | 1.824 | 3.417 |
| UK | $CO_2$ | 6.353 | 0.148 | −0.840 | 3.695 | 7.570 |
| | Oil | 4.411 | 0.119 | 0.937 | 3.368 | 8.351 |
| | Gas | 3.651 | 1.137 | −2.374 | 8.022 | 109.461 |
| | Coal | 3.866 | 0.633 | −1.393 | 5.208 | 28.954 |
| | GDP | 27.447 | 1.124 | −0.528 | 1.926 | 5.202 |
| | GCF | 25.943 | 0.403 | 0.061 | 1.455 | 5.506 |
| Japan | $CO_2$ | 6.931 | 0.237 | −1.618 | 5.744 | 41.257 |
| | Oil | 5.381 | 0.232 | −2.082 | 7.796 | 92.442 |
| | Gas | 3.348 | 1.311 | −1.039 | 2.781 | 10.011 |
| | Coal | 4.378 | 0.308 | −0.015 | 1.600 | 4.492 |
| | GDP | 28.249 | 1.257 | −1.033 | 2.762 | 9.919 |
| | GCF | 32.290 | 0.264 | −0.486 | 1.724 | 5.898 |

$CO_2$ represents carbon dioxide emissions; Oil represents oil consumption; Gas represents gas consumption; Coal represents coal consumption

*GDP* gross domestic product, *GCF* gross capital formation countries which shows that $CO_2$ emission and oil, coal, and gas consumption increase each year after 1965 but, after 2010, the $CO_2$ emission and oil and coal consumption show a decline while gas consumption inclines up to 2019.

## Methodology and model specification

The study used nonlinear autoregressive distribution lag (NARDL) pioneered by Shin et al. (2014) to notice that asymmetries arise due to the positive and negative shocks of energy (oil, gas, and coal) consumption. To measure the asymmetries due to positive and negative shocks, Shin et al. (2014) extend the ARDL technique of Pesaran et al. (2001). NARDL technique composes an error correction description that allows capturing the asymmetries which originate from the shocks in time series both short and long run (Mensi et al. 2017). The NARDL model can be applied, when the series is stationary at level, at the first difference and mixed order of integration even if the sample is small (Ahmad et al. 2018a, b). Additionally, the NARDL model also detects the hidden cointegration which is proposed by Granger and Yoon (2002). Hence, this cointegration approach covers all the linkages in macroeconomic variables that a simple ARDL cannot be detected. Due to nonlinear ARDL, it becomes possible to differentiate between the linear and nonlinear cointegration. Many researchers use this technique in the field of applied and theoretical economics due to its multiple functions and advantages (Mensi et al. 2017; Uddin et al. 2018; Rahman and Ahmad 2019). Generally, the relation among the variable can be presented in the following linear equation form:

$$\begin{aligned}\mathrm{CO}_{2t} = {} & \delta_0 + \delta_1 \mathrm{Oil}_t + \delta_2 \mathrm{Gas}_t + \delta_3 \mathrm{Coal}_t + \delta_4 \mathrm{GDP}_t \\ & + \delta_5 \mathrm{GCF}_t + \mu_t \end{aligned} \tag{1}$$

where $\mathrm{CO}_{2t}$ is the total carbon dioxide emission in time $t$, Oil represents the total consumption of oil in time $t$, Gas represents the total consumption of gas in time $t$, Coal represents the total consumption of coal in time $t$, GDP is the gross domestic product in time $t$, GCF is the gross capital formation in time $t$, $\mu_t$ represents the residual, $\delta_0$ is constant, and $\delta_1$, $\delta_2$, $\delta_3$, $\delta_4$, and $\delta_5$ are the coefficients. The asymmetric cointegration equation is as follows:

$$\begin{aligned}\mathrm{CO}_{2t} = {} & \delta_0 + \delta_1 \mathrm{Oil}_t^+ + \delta_2 \mathrm{Oil}_t^- + \delta_3 \mathrm{Gas}_t^+ + \delta_4 \mathrm{Gas}_t^- \\ & + \delta_5 \mathrm{Coal}_t^+ + \delta_6 \mathrm{Coal}_t^- + \delta_7 \mathrm{GDP}_t + \delta_8 \mathrm{GCF}_t \\ & + \mu_t \end{aligned} \tag{2}$$

The modified version of Eq. (2) for the NARDL model can be written as

$$\begin{aligned}\Delta \mathrm{CO}_{2t} = {} & \eta_0 + \textstyle\sum_{k=0}^{p} \eta_1 \Delta \mathrm{CO}_{2t-k} + \sum_{k=0}^{p} \eta_2 \Delta \mathrm{Oil}_{t-k}^+ \\ & + \textstyle\sum_{k=0}^{p} \eta_3 \Delta \mathrm{Oil}_{t-k}^- + \sum_{k=0}^{p} \eta_4 \Delta \mathrm{Gas}_{t-k}^+ \\ & + \textstyle\sum_{k=0}^{p} \eta_5 \Delta \mathrm{Gas}_{t-k}^- + \sum_{k=0}^{p} \eta_6 \Delta \mathrm{Coal}_{t-k}^+ \\ & + \textstyle\sum_{k=0}^{p} \eta_7 \Delta \mathrm{Coal}_{t-k}^- + \sum_{k=0}^{p} \eta_8 \Delta \mathrm{GDP}_{t-k} \\ & + \textstyle\sum_{k=0}^{p} \eta_9 \Delta \mathrm{GCF}_{t-k} + \varsigma_1 \mathrm{CO}_{2t-1} + \varsigma_2 \mathrm{Oil}_{t-1}^+ \\ & + \varsigma_3 \mathrm{Oil}_{t-1}^- + \varsigma_4 \mathrm{Gas}_{t-1}^+ + \varsigma_5 \mathrm{Gas}_{t-1}^- + \varsigma_6 \mathrm{Coal}_{t-1}^+ \\ & + \varsigma_7 \mathrm{Coal}_{t-1}^- + \varsigma_8 \mathrm{GDP}_{t-1} + \varsigma_9 \mathrm{GCF}_{t-1} + \mu_t \end{aligned} \tag{3}$$

Keep in mind that the main objective of the study is to measure whether oil, gas, and coal consumption symmetrically or asymmetrically affects the $CO_2$ emission of G7 countries. Therefore, the study follows the methodology of Shin et al. (2014) to capture the symmetric or asymmetric effect. The oil, gas, and coal consumption will be decomposed into two new variables which will capture the positive and negative shocks in oil, gas, and coal as follows:

$$\mathrm{Oil}_t^+ = \textstyle\sum_{j=1}^{t} \Delta \mathrm{Oil}_j^+ = \sum_{j=1}^{t} \max\left(\Delta \mathrm{Oil}_j^+, 0\right) \tag{4}$$

$$\mathrm{Oil}_t^- = \textstyle\sum_{j=1}^{t} \Delta \mathrm{Oil}_j^- = \sum_{j=1}^{t} \max\left(\Delta \mathrm{Oil}_j^-, 0\right) \tag{5}$$

$$\mathrm{Gas}_t^+ = \textstyle\sum_{j=1}^{t} \Delta \mathrm{Gas}_j^+ = \sum_{j=1}^{t} \max\left(\Delta \mathrm{Gas}_j^+, 0\right) \tag{6}$$

$$\mathrm{Gas}_t^- = \textstyle\sum_{j=1}^{t} \Delta \mathrm{Gas}_j^- = \sum_{j=1}^{t} \max\left(\Delta \mathrm{Gas}_j^-, 0\right) \tag{7}$$

$$\mathrm{Coal}_t^+ = \textstyle\sum_{j=1}^{t} \Delta \mathrm{Coal}_j^+ = \sum_{j=1}^{t} \max\left(\Delta \mathrm{Coal}_j^+, 0\right) \tag{8}$$

$$\mathrm{Coal}_t^- = \textstyle\sum_{j=1}^{t} \Delta \mathrm{Coal}_j^- = \sum_{j=1}^{t} \max\left(\Delta \mathrm{Coal}_j^-, 0\right) \tag{9}$$

The error correction mechanism (ECM) can be developed to measure the short-term effect and also to check the consistency of long-term parameters as follows:

$$\begin{aligned}\Delta \mathrm{CO}_{2t} = {} & \eta_0 + \textstyle\sum_{k=0}^{p} \eta_1 \Delta \mathrm{CO}_{2t-k} + \sum_{k=0}^{p} \eta_2 \Delta \mathrm{Oil}_{t-k}^+ \\ & + \textstyle\sum_{k=0}^{p} \eta_3 \Delta \mathrm{Oil}_{t-k}^- + \sum_{k=0}^{p} \eta_4 \Delta \mathrm{Gas}_{t-k}^+ \\ & + \textstyle\sum_{k=0}^{p} \eta_5 \Delta \mathrm{Gas}_{t-k}^- + \sum_{k=0}^{\mathrm{P}} \eta_6 \Delta \mathrm{Coal}_{t-k}^+ \\ & + \textstyle\sum_{k=0}^{p} \eta_7 \Delta \mathrm{Coal}_{t-k}^- + \sum_{k=0}^{p} \eta_8 \Delta \mathrm{GDP}_{t-k} \\ & + \textstyle\sum_{k=0}^{p} \eta_9 \Delta \mathrm{GCF}_{t-k} + \tau_0 \mathrm{ECT}_{t-1} + \mu_t \end{aligned} \tag{10}$$

$\Delta \mathrm{CO}_{2t}$ is the first difference of carbon dioxide emission in time $t$; $\Delta \mathrm{Oil}_{t-k}$, $\Delta \mathrm{Gas}_{t-k}$, and $\Delta \mathrm{Coal}_{t-k}$ are the first difference of oil, gas, and coal consumption in time $t$ with a lagged value of $k$, respectively; $\eta_1$–$\eta_9$ are the short-term elasticity whereas $\varsigma_1$–$\varsigma_9$ are the long-term elasticity; $\tau_0$ represents the elasticity of lag error correction term (ECT); and $\mu_t$ is the error correction term.

The presence of long-term cointegration among the selected variables in Eq. (3) is determined by checking the association by using a standard $F$-test. Precisely, the null hypothesis of $\varsigma_1 = \varsigma_2 = \varsigma_3 = \varsigma_4 = \varsigma_5 = \varsigma_6 = \varsigma_7 = \varsigma_8 = \varsigma_9 = 0$ is tested. The $F$-statistics has a lack of normal standard $F$-distribution due to which the critical value below the null hypothesis cannot be used. Therefore, Pesaran et al. (2001) used upper and lower bound critical values to deal with this problem. The null hypothesis can be accepted in the case where the estimated $F$-statistics is less than the upper bound critical value. If there is evidence of cointegration, then Eq. (3) can be used to find the response of $CO_2$ emission with a change in oil, gas, and coal consumption both in the long and short run. The estimated result of Eq. (3) can be checked through the Wald test to identify the possible asymmetric effect of oil, gas, and coal consumption on $CO_2$ emission. The null hypothesis of the symmetrical effect of oil, gas, and coal on $CO_2$ emission for the short and long run can be identified if the null hypothesis of the short run ($\frac{\eta_2}{\eta_1} = \frac{\eta_3}{\eta_1}$, $\frac{\eta_4}{\eta_1} = \frac{\eta_5}{\eta_1}$, and $\frac{\eta_6}{\eta_1} = \frac{\eta_7}{\eta_1}$) and long run ($\frac{\varsigma_2}{\varsigma_1} = \frac{\varsigma_3}{\varsigma_1}$, $\frac{\varsigma_4}{\varsigma_1} = \frac{\varsigma_5}{\varsigma_1}$, and $\frac{\varsigma_6}{\varsigma_1} = \frac{\varsigma_7}{\varsigma_1}$) is rejected.

## Results and discussion

### Unit root test

To measure the possible stationarity level in a series, the augmented Dickey-Fuller (ADF) unit root test is considered the most suitable approach. The estimated results of ADF are shown in Table 2 which demonstrates that some of the variables are stationary at level, but at first difference, all the variables of G7 countries are stationary.

### Structural break unit root test

The traditional unit root used in various studies does not figure out multiple breaks in the series due to various macroeconomic shifts and policy which cause spurious results for policymaking. Therefore, Narayan and Popp (2010) proposed a structural break unit root test at unknown time intervals with two breaks at slope and level. The estimated results in Table 3 show that the Narayan and Popp (2010) test has the correct size and stable power and detects structural break more accurately as compared to various other tests that are used in previous studies (Mishra and Smyth 2014; Salisu et al. 2016)

**Table 2** Traditional unit root test

| Country | Variables | I (0) | I (1) | Conclusion ADF |
|---|---|---|---|---|
| Canada | $CO_2$ | −3.392 [a] | −5.201 [a] | I (0) |
| | Oil | −2.400 | −4.573 [a] | I (1) |
| | Gas | −3.397 [a] | −4.793 [a] | I (0) |
| | Coal | −0.844 | −6.774 [a] | I (1) |
| | GDP | −3.443 [a] | −4.656 [a] | I (0) |
| | GCF | −0.979 | −7.929 [a] | I (1) |
| USA | $CO_2$ | −3.605 [a] | −5.819 [a] | I (0) |
| | Oil | −3.272 [b] | −4.116 [a] | I (0) |
| | Gas | −0.481 | −5.807 [a] | I (1) |
| | Coal | −1.634 | −4.394 [a] | I (1) |
| | GDP | −7.141 [a] | −3.257 [b] | I (0) |
| | GCF | −0.486 | −6.313 [a] | I (1) |
| France | $CO_2$ | −0.394 | −6.491 [a] | I (1) |
| | Oil | 0.206 | −3.757 [a] | I (1) |
| | Gas | −1.721 | −7.368 [a] | I (1) |
| | Coal | −0.758 | −6.704 [a] | I (1) |
| | GDP | −3.519 [a] | −5.144 [a] | I (0) |
| | GCF | −1.579 | −4.450 [a] | I (1) |
| Germany | $CO_2$ | 0.568 | −6.974 [a] | I (1) |
| | Oil | −2.673 [c] | −5.599 [a] | I (0) |
| | Gas | −10.482 [a] | −2.674 [c] | I (0) |
| | Coal | 0.618 | −4.595 [a] | I (1) |
| | GDP | −1.756 | −6.433 [a] | I (1) |
| | GCF | −0.748 | −7.064 [a] | I (1) |
| Italy | $CO_2$ | −4.984 [a] | −4.037 [a] | I (0) |
| | Oil | −1.535 | −3.555 [a] | I (1) |
| | Gas | −4.539 [a] | −4.764 [a] | I (0) |
| | Coal | −1.172 | −5.078 [a] | I (1) |
| | GDP | −3.213 [b] | −4.975 [a] | I (0) |
| | GCF | −1.521 | −7.542 [a] | I (1) |
| UK | $CO_2$ | 0.769 | −7.562 [a] | I (1) |
| | Oil | −1.628 | −7.075 [a] | I (1) |
| | Gas | −8.177 [a] | −2.449 | I (1) |
| | Coal | 1.996 | −5.467 [a] | I (1) |
| | GDP | −1.838 | −4.516 [a] | I (1) |
| | GCF | −0.402 | −6.590 [a] | I (1) |
| Japan | $CO_2$ | −5.778 [a] | −5.199 [a] | I (0) |
| | Oil | −5.622 [a] | −3.660 [a] | I (0) |
| | Gas | −4.503 [a] | −1.370 | I (0) |
| | Coal | −1.067 | −7.234 [a] | I (1) |
| | GDP | −5.025 [a] | −4.347 [a] | I (0) |
| | GCF | −1.818 | −5.089 [a] | I (1) |

Superscript lowercase letters a, b, and c signify 1%, 5%, and 10% significance levels. $CO_2$ represents carbon dioxide emissions; Oil represents oil consumption; Gas represents gas consumption; Coal represents coal consumption

*ADF* augmented Dickey-Fuller, *GDP* gross domestic product, *GCF* gross capital formation

**Table 3** Narayan and Popp unit root test with two structural breaks

| Country | Variables | Break in intercept (M1) | | | Break in intercept and trend (M2) | | |
|---|---|---|---|---|---|---|---|
| | | *t*-statistics | TB1 | TB2 | *t*-statistics | TB1 | TB2 |
| Canada | $CO_2$ | 0.200 | 1987 | 2006 | −0.073 | 1983 | 2008 |
| | Oil | −4.172 | 1981 | 2008 | −3.087 | 1981 | 2008 |
| | Gas | −4.067 | 1982 | 2000 | −1.802 | 1983 | 2000 |
| | Coal | −0.240 | 1976 | 1979 | −2.047 | 1977 | 2008 |
| | GDP | −0.572 | 2002 | 2008 | −3.449 | 1976 | 2008 |
| | GCF | −2.948 | 1981 | 2008 | −3.578 | 1981 | 2008 |
| USA | $CO_2$ | −2.306 | 1981 | 2008 | −2.259 | 1981 | 2008 |
| | Oil | −4.191 | 1975 | 2007 | −3.470 | 1975 | 2007 |
| | Gas | −1.386 | 1981 | 1983 | −2.997 | 1983 | 2000 |
| | Coal | −0.124 | 2008 | 2010 | −3.946 | 1978 | 2008 |
| | GDP | 2.723 | 1981 | 2008 | −3.601 | 1981 | 2008 |
| | GCF | −4.014 | 1981 | 2008 | −4.031 | 1983 | 2008 |
| France | $CO_2$ | −3.238 | 1997 | 2010 | −3.508 | 1997 | 2010 |
| | Oil | −2.963 | 1997 | 2008 | −2.628 | 1992 | 2001 |
| | Gas | −3.372 | 1995 | 2010 | −4.527 | 2006 | 2010 |
| | Coal | −4.932 | 1997 | 2004 | −5.702 | 1992 | 2010 |
| | GDP | −3.819 | 1994 | 2002 | −3.787 | 1996 | 2002 |
| | GCF | −2.713 | 1992 | 2008 | −3.543 | 1997 | 2008 |
| Germany | $CO_2$ | −3.534 | 1975 | 2008 | −2.998 | 1991 | 2008 |
| | Oil | −4.084 | 1980 | 2006 | −3.441 | 1979 | 2006 |
| | Gas | −7.606 | 1980 | 1995 | −3.033 | 1986 | 1996 |
| | Coal | −2.074 | 1990 | 2008 | −2.332 | 1990 | 2008 |
| | GDP | −3.355 | 1977 | 1985 | −2.980 | 1985 | 1999 |
| | GCF | −2.827 | 1980 | 2008 | −3.998 | 1989 | 2008 |
| Italy | $CO_2$ | −4.964 | 1982 | 2008 | −4.193 | 1988 | 2008 |
| | Oil | −2.975 | 1975 | 1977 | −1027 | 1975 | 1979 |
| | Gas | −2.739 | 1983 | 2008 | −1.478 | 1977 | 1983 |
| | Coal | 0.301 | 1979 | 2008 | −3.233 | 1991 | 2008 |
| | GDP | −1.457 | 1985 | 1992 | −2.936 | 1980 | 1992 |
| | GCF | −3.802 | 1992 | 2008 | −5.449 | 1975 | 2008 |
| UK | $CO_2$ | −1.335 | 1979 | 1984 | −4.073 | 1984 | 2008 |
| | Oil | −3.713 | 1979 | 1984 | −3.383 | 1979 | 1983 |
| | Gas | −10.780 | 1992 | 1995 | −9.793 | 1992 | 1996 |
| | Coal | −0.005 | 1984 | 1999 | −0.864 | 1984 | 1999 |
| | GDP | −2.859 | 1977 | 2008 | −4.937 | 1992 | 2008 |
| | GCF | −2.600 | 1979 | 2008 | −3.167 | 1987 | 2008 |
| Japan | $CO_2$ | −4.569 | 1981 | 2008 | −3.781 | 1983 | 2008 |
| | Oil | −4.595 | 1079 | 2008 | −5.222 | 1987 | 2008 |
| | Gas | 1.381 | 1980 | 1983 | −3.508 | 1980 | 1984 |
| | Coal | −2.704 | 2008 | 2010 | −5.187 | 1980 | 2008 |
| | GDP | −1.523 | 1977 | 1985 | −4.513 | 1981 | 1995 |
| | GCF | −2.957 | 1987 | 2008 | −5.688 | 1987 | 2008 |

Note the critical values for both M1 (−4.958, −4.316, −3.980) and M2 (−5.576, −4.937, −4.596). $CO_2$ represents carbon dioxide emissions; Oil represents oil consumption; Gas represents gas consumption; Coal represents coal consumption

*M1* first model, *M2* second model, *TB1* first time break, *TB2* second time break, *GDP* gross domestic product, *GCF* gross capital formation

**Table 4** BDS nonlinearity test results

| Country | Variables | Dimension 2 | Dimension 3 | Dimension 4 | Dimension 5 | Dimension 6 |
|---|---|---|---|---|---|---|
| Canada | $CO_2$ | 0.1782 [a] | 0.3000 [a] | 0.3841 [a] | 0.4416 [a] | 0.4746 [a] |
| | Oil | 0.1712 [a] | 0.2807 [a] | 0.3578 [a] | 0.4044 [a] | 0.4305 [a] |
| | Gas | 0.1957 [a] | 0.3296 [a] | 0.4255 [a] | 0.4946 [a] | 0.5437 [a] |
| | Coal | 0.1425 [a] | 0.2447 [a] | 0.3251 [a] | 0.3778 [a] | 0.4186 [a] |
| | GDP | 0.2043 [a] | 0.3468 [a] | 0.4476 [a] | 0.5187 [a] | 0.5694 [a] |
| | GCF | 0.1809 [a] | 0.3020 [a] | 0.3814 [a] | 0.4368 [a] | 0.4766 [a] |
| USA | $CO_2$ | 0.1830 [a] | 0.3129 [a] | 0.3973 [a] | 0.4487 [a] | 0.4748 [a] |
| | Oil | 0.1690 [a] | 0.2779 [a] | 0.3439 [a] | 0.3805 [a] | 0.3939 [a] |
| | Gas | 0.1453 [a] | 0.2280 [a] | 0.2892 [a] | 0.3185 [a] | 0.3313 [a] |
| | Coal | 0.1637 [a] | 0.2829 [a] | 0.3687 [a] | 0.4247 [a] | 0.4680 [a] |
| | GDP | 0.2064 [a] | 0.3504 [a] | 0.4529 [a] | 0.5260 [a] | 0.5789 [a] |
| | GCF | 0.1848 [a] | 0.3090 [a] | 0.3959 [a] | 0.4574 [a] | 0.4994 [a] |
| France | $CO_2$ | 0.1298 [a] | 0.1983 [a] | 0.2406 [a] | 0.2231 [a] | 0.1488 [a] |
| | Oil | 0.1467 [a] | 0.2308 [a] | 0.2648 [a] | 0.2587 [a] | 0.2099 [a] |
| | Gas | 0.1736 [a] | 0.3031 [a] | 0.3862 [a] | 0.4402 [a] | 0.4823 [a] |
| | Coal | 0.1166 [a] | 0.1980 [a] | 0.2746 [a] | 0.2934 [a] | 0.3075 [a] |
| | GDP | 0.1587 [a] | 0.2639 [a] | 0.3411 [a] | 0.3931 [a] | 0.4214 [a] |
| | GCF | 0.1659 [a] | 0.2732 [a] | 0.3495 [a] | 0.3955 [a] | 0.4293 [a] |
| Germany | $CO_2$ | 0.1450 [a] | 0.2441 [a] | 0.3124 [a] | 0.3609 [a] | 0.3918 [a] |
| | Oil | 0.1393 [a] | 0.2187 [a] | 0.2679 [a] | 0.2883 [a] | 0.3003 [a] |
| | Gas | 0.2092 [a] | 0.3582 [a] | 0.4621 [a] | 0.5332 [a] | 0.5805 [a] |
| | Coal | 0.1616 [a] | 0.2732 [a] | 0.3477 [a] | 0.3971 [a] | 0.4299 [a] |
| | GDP | 0.1910 [a] | 0.3192 [a] | 0.4101 [a] | 0.4736 [a] | 0.5174 [a] |
| | GCF | 0.1342 [a] | 0.2273 [a] | 0.2932 [a] | 0.3413 [a] | 0.3785 [a] |
| Italy | $CO_2$ | 0.1722 [a] | 0.2887 [a] | 0.3611 [a] | 0.4028 [a] | 0.4241 [a] |
| | Oil | 0.1702 [a] | 0.2725 [a] | 0.3317 [a] | 0.3611 [a] | 0.3719 [a] |
| | Gas | 0.2022 [a] | 0.3448 [a] | 0.4442 [a] | 0.5109 [a] | 0.5548 [a] |
| | Coal | 0.1301 [a] | 0.2185 [a] | 0.2711 [a] | 0.3078 [a] | 0.3317 [a] |
| | GDP | 0.1996 [a] | 0.3402 [a] | 0.4384 [a] | 0.5072 [a] | 0.5538 [a] |
| | GCF | 0.1560 [a] | 0.2651 [a] | 0.3518 [a] | 0.4135 [a] | 0.4530 [a] |
| UK | $CO_2$ | 0.1326 [a] | 0.2037 [a] | 0.2373 [a] | 0.2419 [a] | 0.2350 [a] |
| | Oil | 0.1336 [a] | 0.2121 [a] | 0.2559 [a] | 0.2783 [a] | 0.3024 [a] |
| | Gas | 0.1270 [a] | 0.2379 [a] | 0.3338 [a] | 0.4163 [a] | 0.4866 [a] |
| | Coal | 0.1508 [a] | 0.2322 [a] | 0.2739 [a] | 0.2846 [a] | 0.3126 [a] |
| | GDP | 0.1950 [a] | 0.3268 [a] | 0.4181 [a] | 0.4826 [a] | 0.5307 [a] |
| | GCF | 0.1771 [a] | 0.3029 [a] | 0.3859 [a] | 0.4412 [a] | 0.4767 [a] |
| Japan | $CO_2$ | 0.1726 [a] | 0.2908 [a] | 0.3697 [a] | 0.4230 [a] | 0.4528 [a] |
| | Oil | 0.1621 [a] | 0.2596 [a] | 0.3178 [a] | 0.3577 [a] | 0.3863 [a] |
| | Gas | 0.2067 [a] | 0.3517 [a] | 0.4533 [a] | 0.5237 [a] | 0.5724 [a] |
| | Coal | 0.1816 [a] | 0.3046 [a] | 0.3867 [a] | 0.4411 [a] | 0.4764 [a] |
| | GDP | 0.2071 [a] | 0.3543 [a] | 0.4568 [a] | 0.5283 [a] | 0.5773 [a] |
| | GCF | 0.1810 [a] | 0.3079 [a] | 0.3934 [a] | 0.4502 [a] | 0.4860 [a] |

$CO_2$ represents carbon dioxide emissions; Oil represents oil consumption; Gas represents gas consumption; Coal represents coal consumption

*GDP* gross domestic product, *GCF* gross capital formation

[a] One percent significance levels

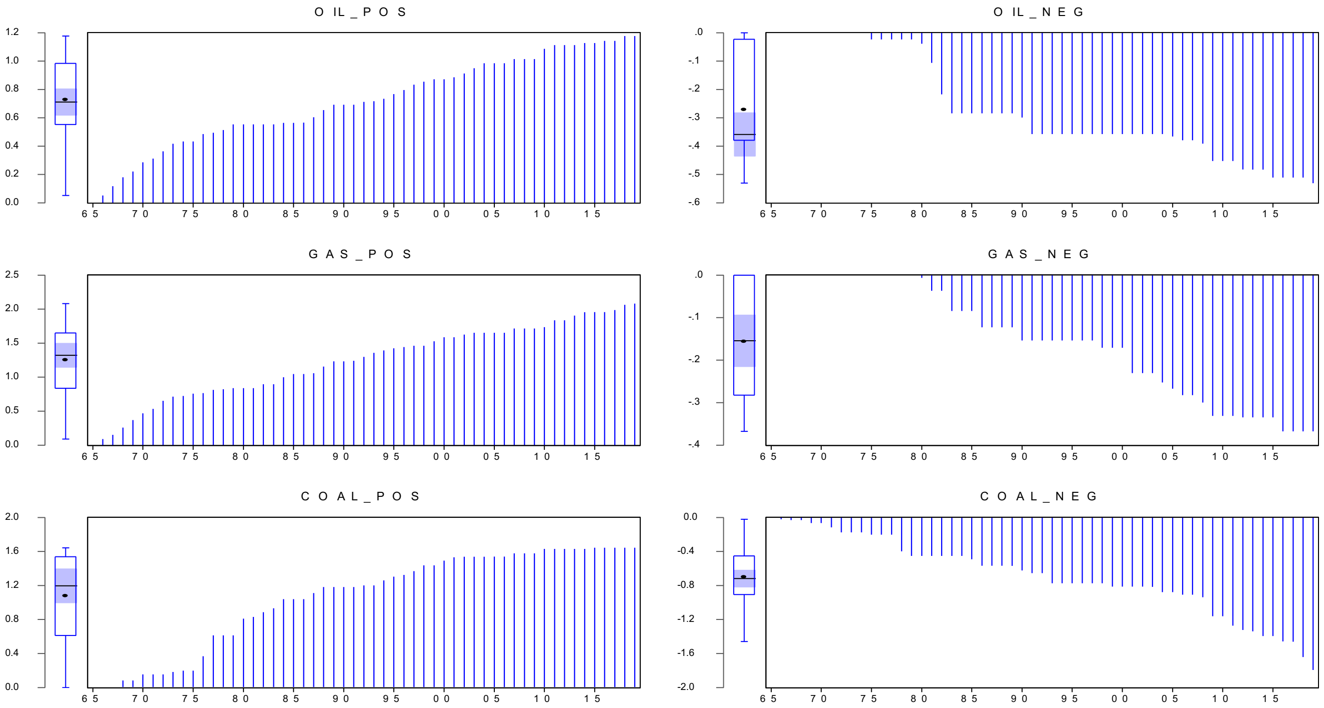

**Fig. 1** Positive and negative component of oil, gas, and coal, Canada

## Brock, Dechert, and Scheinkman test

After confirming the presence of structural breaks in macroeconomic variables, the study applies the Brock-Dechert-Scheinkman (BDS) test proposed by Broock et al. (1996) to detect the nonlinearity dependencies in the time series. The estimated results of the BDS independence test shown in Table 4 demonstrate that the data

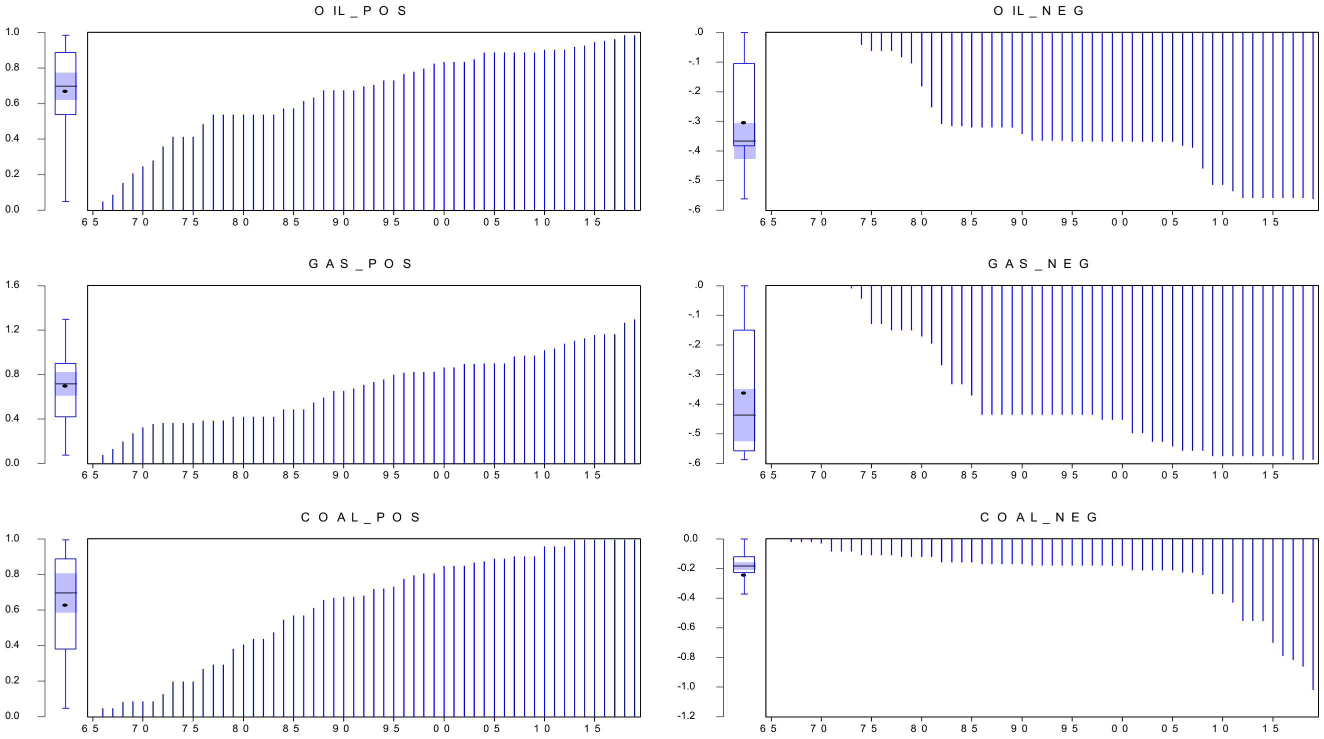

**Fig. 2** Positive and negative component of oil, gas, and coal, USA

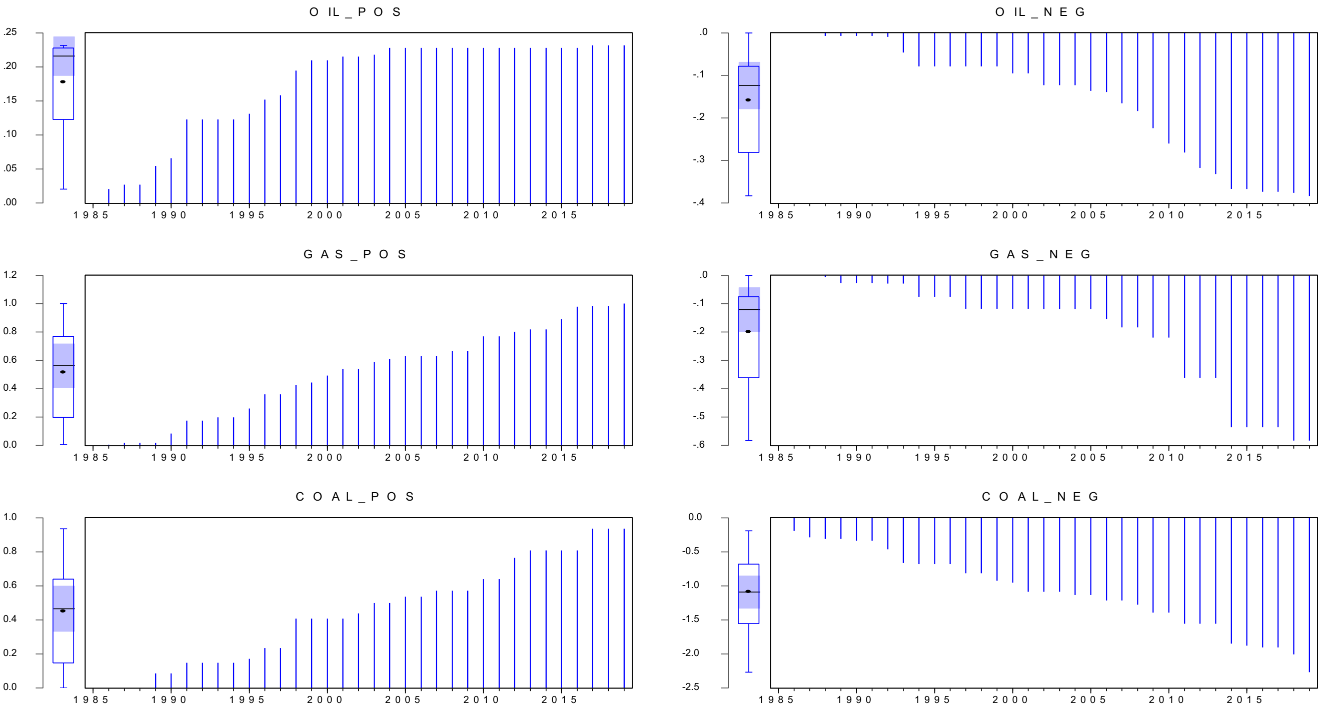

**Fig. 3** Positive and negative component of oil, gas, and coal, France

series are not identically and independently distributed (iid) and reject the null hypothesis of linearity. Therefore, an asymmetric analysis is important to detect the structural shift and nonlinear association in energy consumption (oil, gas, and coal) and $CO_2$ emission. Figures 1, 2, 3, 4, 5, 6, and 7 show the positive and negative shocks of oil, gas, and coal consumption and their effects on carbon dioxide emission.

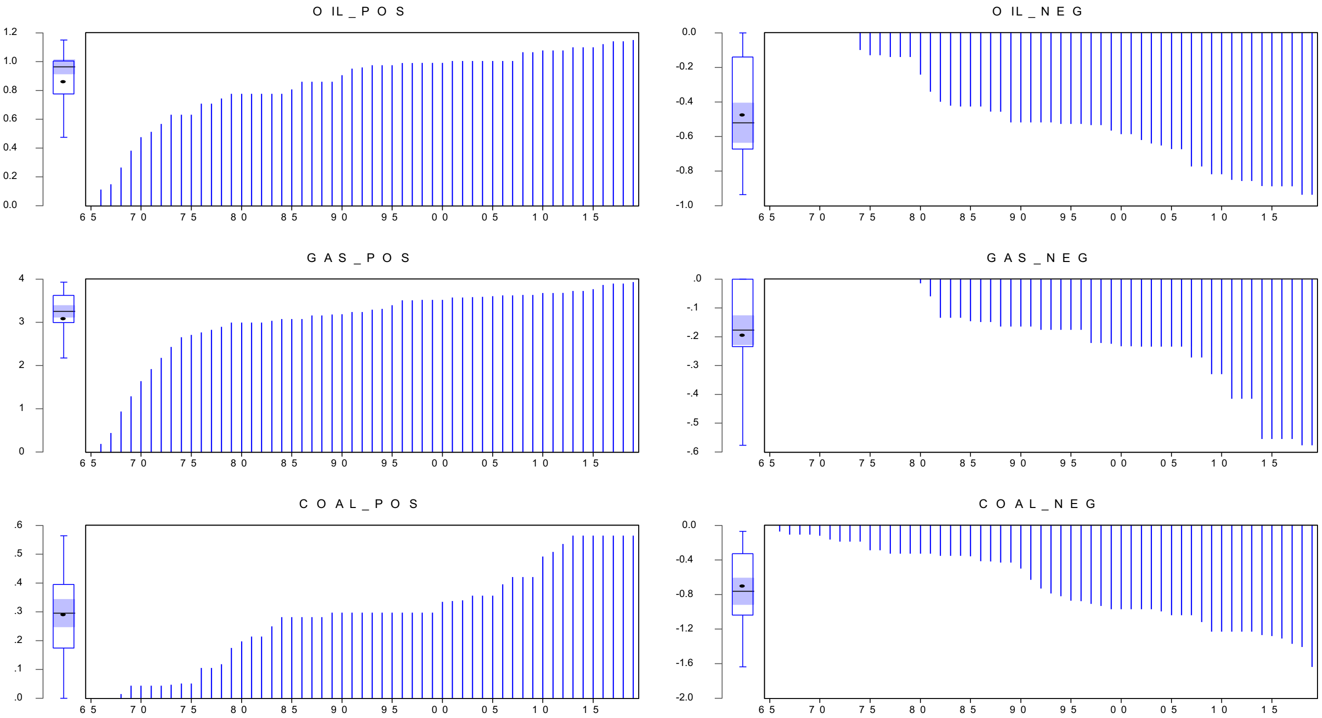

**Fig. 4** Positive and negative component of oil, gas, and coal, Germany

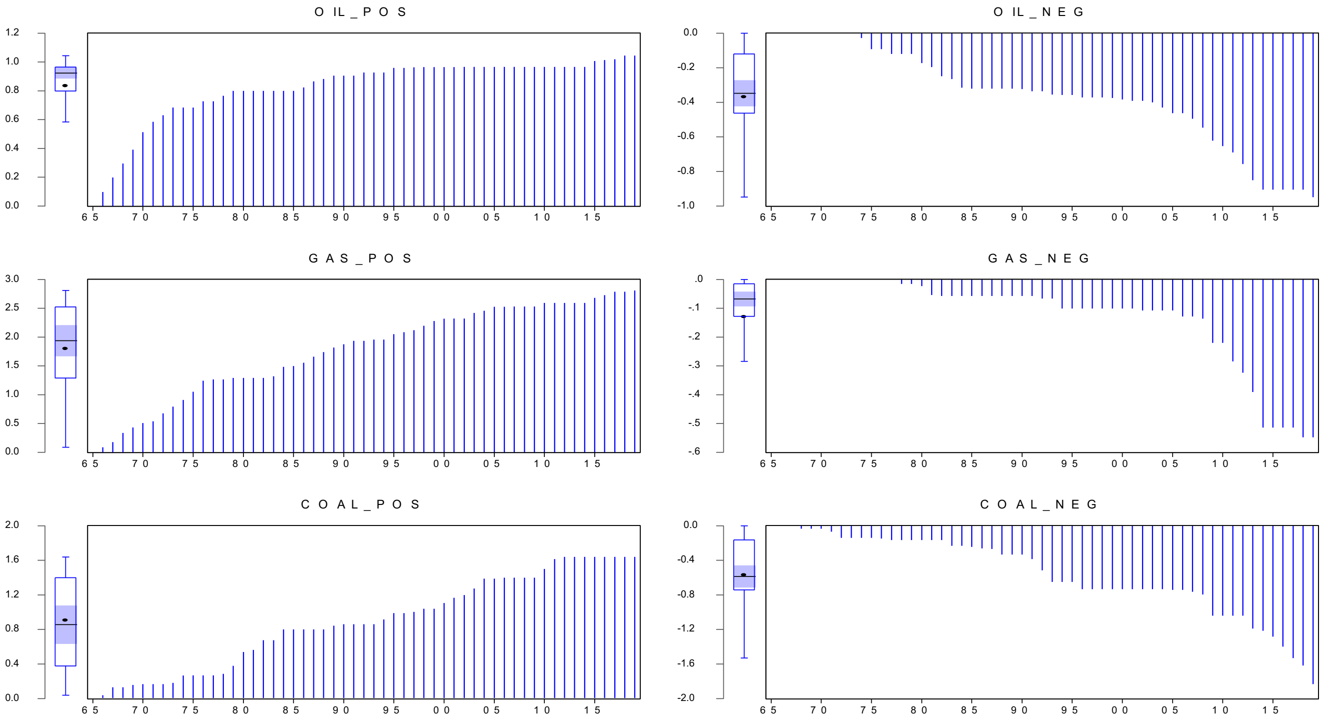

**Fig. 5** Positive and negative component of oil, gas, and coal, Italy

## Testing for asymmetries hypothesis

After the estimation of Eq. (3) for possible cointegration among the series, the study uses the standard Wald test to measure the possible short- and long-run asymmetries in the series. The estimated results of the Wald test in Table 5 show that there is a short-term asymmetry in oil and coal consumption of Canada, gas consumption of the USA, oil and coal

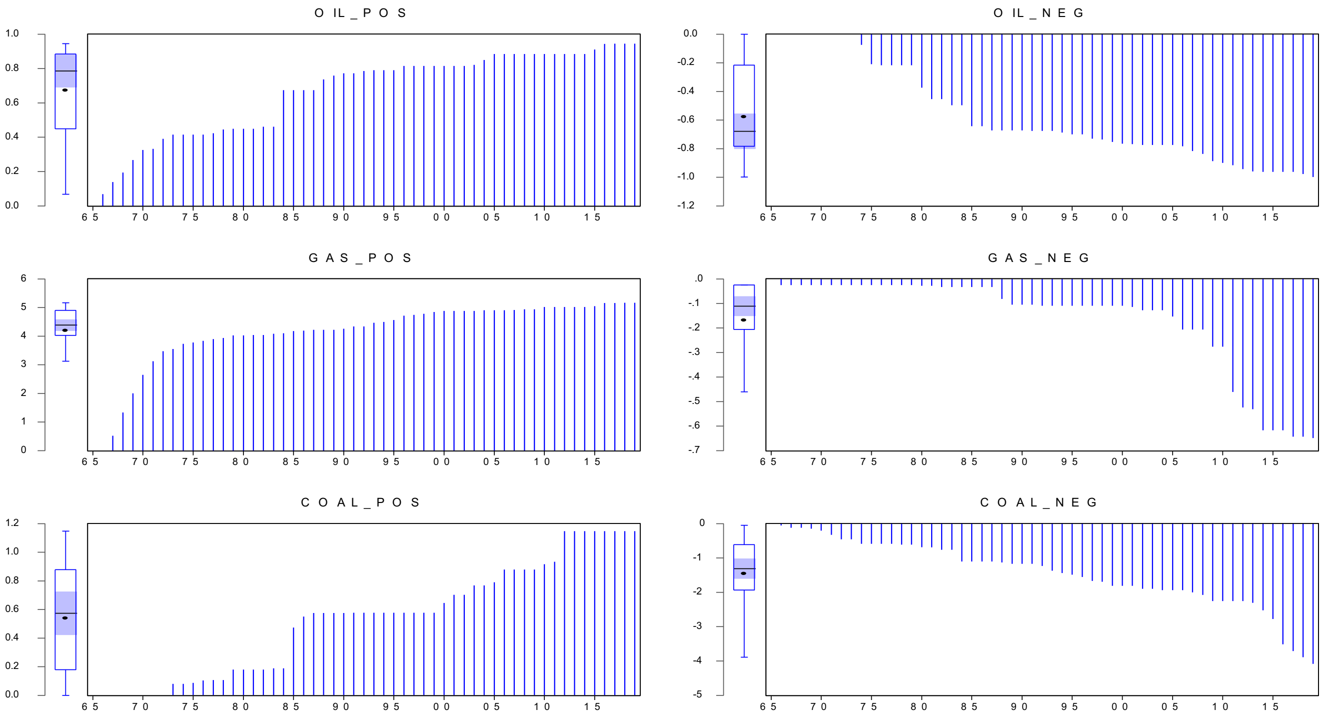

**Fig. 6** Positive and negative component of oil, gas, and coal, UK

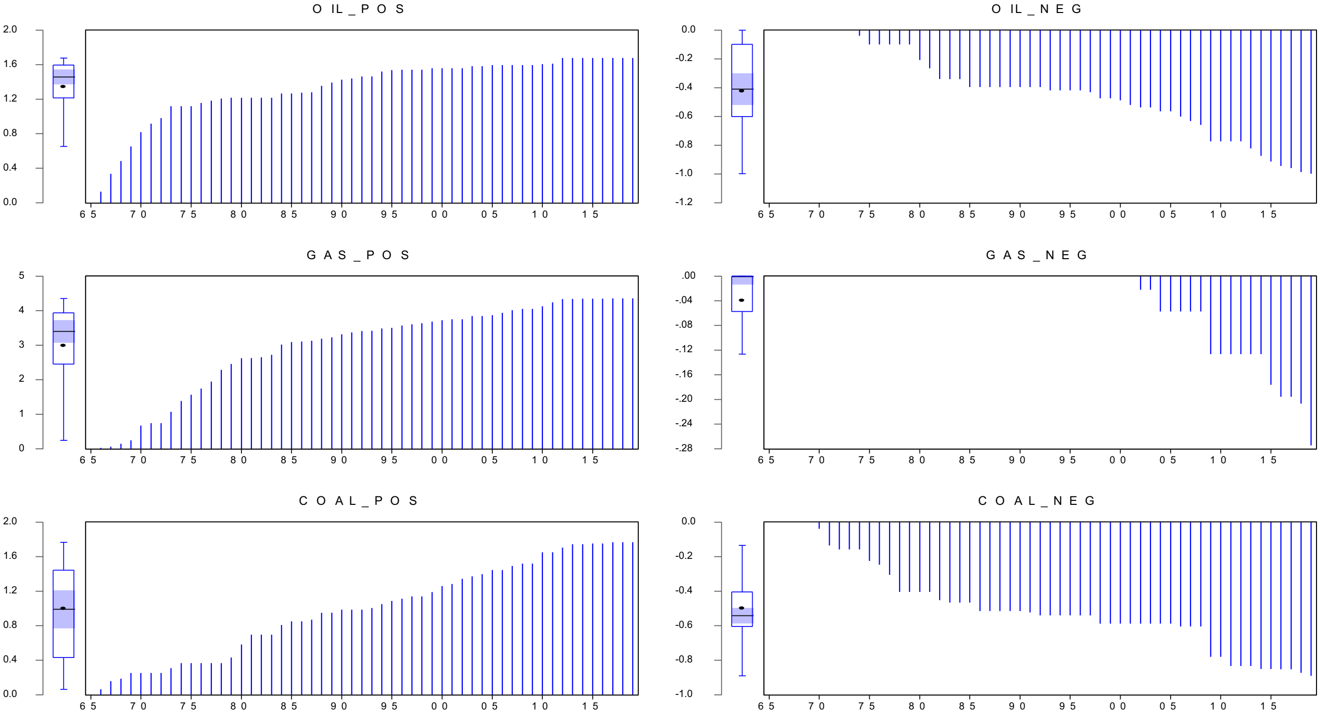

**Fig. 7** Positive and negative component of oil, gas, and coal, Japan

consumption of Italy, and oil, coal, and gas consumption of the UK. Similarly, it is also reported that there is a long-term asymmetry in coal consumption of Canada; oil and coal consumption of the USA and France; oil, gas, and coal consumption of Italy; and oil and gas consumption of the UK. The estimated results also show that there is short-term symmetry in gas consumption of Canada, oil and coal of the USA, gas consumption of Italy, and oil, coal, and gas consumption of France, Germany, and Japan. Likewise, there is also long-term symmetry in the oil and gas consumption of Canada, gas consumption of the USA and France, oil and coal consumption of Germany, coal consumption of the UK, and oil, coal, and gas consumption of Japan.

## Cointegration bound test

After the confirmation of structural break, the study compares the critical *F*-statistics with lower and upper bound values (Pesaran et al. 2001). The estimated results of the bound test shown in Table 6 demonstrate the presence of a long-term cointegration association between oil, gas, and coal consumption; GDP; GFC; and $CO_2$ emission. The *F*-statistics estimate ($CO_2$ = f(Oil,Gas,Coal,GDP,GCF) for all G7 countries is greater than the upper bound value.

## Short-term and long-term estimates of NARDL

The estimated elasticity of the nonlinear ARDL for the short run is shown in Table 7. The estimated coefficient of NARDL indicates that the positive shock and negative shock of oil, gas, and coal consumption increase the $CO_2$ emission of G7 economies. The results imply that the estimated coefficient is positive for oil, gas, and coal consumption, which increases the $CO_2$ emission, and negative for oil, gas, and coal consumption, which decreases the $CO_2$ emission. For instance, the estimated coefficient of oil consumption shows that an increase (decrease) of 1% in oil consumption can significantly increase (decrease) the $CO_2$ emission by 0.422% (−0.487%), 0.430% (−0.436%), 0.806% (−0.367%), 0.377% (−0.292%), 0.871% (−0.388%), 0.092% (−0.546%), and 0.780% (−0.694%) of Canada, USA, France, Germany, Italy, UK, and Japan, respectively. Similarly, the estimated elasticity for the positive and negative shocks of gas consumption is also significant for the G7 countries. The estimated elasticity shows that an increase (decrease) of 1% in gas consumption can increase (decrease) the $CO_2$ emission by 0.398% (−0.201%), 0.178% (−0.167%), 0.188% (−0.452%), 0.060% (−0.223%), 0.147% (−0.383%), and 0.093% (−0.315%) of Canada, USA, France, Germany, Italy, and UK, respectively; the positive shock of gas consumption has no effect, while the negative shock can decrease $CO_2$ emission by 0.384%. Likewise, the estimated results of coal consumption show that an increase (decrease) of 1% coal consumption can significantly upsurge (drop) the $CO_2$ emission by 0.195% (−0.176%), 0.299% (−0.276%), 0.108% (−0.082%), 0.278% (−0.341%), 0.148% (−0.132%), 0.382% (−0.163%), and 0.357% (−0.252%) of Canada, USA, France, Germany, Italy, UK, and Japan, respectively. The coefficient of

**Table 5** Long- and short-term asymmetry results

| Country | Variables | Test | *F*-statistic | Probability | Conclusion |
|---|---|---|---|---|---|
| Canada | Oil | $W_{SR}$ | $5.334^{b}$ | 0.026 | SR asymmetry |
| | | $W_{LR}$ | 0.183 | 0.671 | Symmetry |
| | Coal | $W_{SR}$ | $4.207^{b}$ | 0.047 | SR asymmetry |
| | | $W_{LR}$ | $39.797^{a}$ | 0.000 | LR asymmetry |
| | Gas | $W_{SR}$ | 1.918 | 0.174 | Symmetry |
| | | $W_{LR}$ | 0.015 | 0.904 | Symmetry |
| USA | Oil | $W_{SR}$ | 0.329 | 0.570 | Symmetry |
| | | $W_{LR}$ | $14.691^{a}$ | 0.000 | LR asymmetry |
| | Coal | $W_{SR}$ | 1.226 | 0.275 | Symmetry |
| | | $W_{LR}$ | $7.730^{a}$ | 0.008 | LR asymmetry |
| | Gas | $W_{SR}$ | $3.930^{b}$ | 0.055 | SR asymmetry |
| | | $W_{LR}$ | 1.113 | 0.298 | Symmetry |
| France | Oil | $W_{SR}$ | 0.104 | 0.750 | Symmetry |
| | | $W_{LR}$ | $5.760^{b}$ | 0.027 | LR asymmetry |
| | Coal | $W_{SR}$ | 0.456 | 0.507 | Symmetry |
| | | $W_{LR}$ | $15.035^{a}$ | 0.001 | LR asymmetry |
| | Gas | $W_{SR}$ | 2.178 | 0.156 | Symmetry |
| | | $W_{LR}$ | 0.594 | 0.450 | Symmetry |
| Germany | Oil | $W_{SR}$ | 0.885 | 0.353 | Symmetry |
| | | $W_{LR}$ | 0.005 | 0.943 | Symmetry |
| | Coal | $W_{SR}$ | 0.375 | 0.544 | Symmetry |
| | | $W_{LR}$ | 1.463 | 0.234 | Symmetry |
| | Gas | $W_{SR}$ | 0.030 | 0.864 | Symmetry |
| | | $W_{LR}$ | $7.035^{a}$ | 0.012 | LR asymmetry |
| Italy | Oil | $W_{SR}$ | $2.866^{c}$ | 0.099 | SR asymmetry |
| | | $W_{LR}$ | $6.329^{a}$ | 0.016 | LR asymmetry |
| | Coal | $W_{SR}$ | $5.791^{b}$ | 0.021 | SR asymmetry |
| | | $W_{LR}$ | $30.520^{a}$ | 0.000 | LR asymmetry |
| | Gas | $W_{SR}$ | 1.241 | 0.272 | Symmetry |
| | | $W_{LR}$ | $6.318^{a}$ | 0.016 | LR asymmetry |
| UK | Oil | $W_{SR}$ | $10.589^{a}$ | 0.002 | SR asymmetry |
| | | $W_{LR}$ | $21.685^{a}$ | 0.000 | LR asymmetry |
| | Coal | $W_{SR}$ | $12.154^{a}$ | 0.001 | SR asymmetry |
| | | $W_{LR}$ | 0.080 | 0.779 | Symmetry |
| | Gas | $W_{SR}$ | $19.431^{a}$ | 0.000 | SR asymmetry |
| | | $W_{LR}$ | $12.351^{a}$ | 0.001 | LR asymmetry |
| Japan | Oil | $W_{SR}$ | 1.384 | 0.246 | Symmetry |
| | | $W_{LR}$ | 0.648 | 0.426 | Symmetry |
| | Coal | $W_{SR}$ | 1.264 | 0.268 | Symmetry |
| | | $W_{LR}$ | 1.256 | 0.269 | Symmetry |
| | Gas | $W_{SR}$ | 0.354 | 0.555 | Symmetry |
| | | $W_{LR}$ | 0.156 | 0.591 | Symmetry |

Superscript lowercase letters a, b, and c signify 1%, 5%, and 10% significance levels, respectively. $W_{SR}$ is the Wald test for a short run, and $W_{LR}$ is the Wald test for the long run

economic growth shows that in G7 countries, only France and Japan have a significant negative impact on $CO_2$ emission. This implies that a partial sum of 1% increase in the economic growth of France and Japan decreases the environmental degradation and pollution by 0.029% and 0.020%. Similarly, the finding also shows that among the G7 countries, only the gross capital formation of France can increase the air pollution by 0.073% with a 1% increase in France GCF. Furthermore, the estimated results of ΔECT are significant with a negative coefficient implying the existence of cointegration among variables of G7 countries.

The estimated results of NARDL for the long run shown in Table 8 imply that an increase (decrease) of 1% in oil consumption in the long run can significantly increase (decrease) the $CO_2$ emission by 0.498% (−0.505%), 0.224% (−0.308%), 0.547% (−1.643%), 0.128% (−0.566%), and 0.911% (−0.583%) of the USA, Germany, Italy, UK, and Japan, respectively. The rise in consumption of oil can increase the air pollution of France by 0.247% while a decrease in oil consumption decreases the air pollution of Canada by 0.772%. The estimated results are coinciding with the previous study of Munir and Riaz (2020) which implies that an increase in oil consumption can significantly increase environmental degradation and air pollution. Similarly, Hossain (2011), Jebli et al. (2016), and Khan et al. (2019) also stated that an increase in oil consumption can boost environmental degradation. The empirical findings demonstrate that growth (reduction) of 1% in gas consumption can escalate (decline) the air pollution by 0.206% (−0.102%), 0.279% (−0.491%), 0.063% (−0.0.059%), 0.206% (−0.642%), and 0.023% (−0.441%) of the USA, France, Germany, Italy, and UK, respectively. The positive shock of gas consumption in Canada can increase $CO_2$ emission in the long run, but the negative shock has no impact. Similarly, the positive and negative shocks of gas consumption in Japan have no impact on environmental degradation. The estimated results are familiar to the previous study of Dong et al. (2017) which stated that consumption of natural gas increases $CO_2$ emission. Similarly, Solarin and Shahbaz et al. (2015) stated that combustion of gas induces the level of $CO_2$ emission but causes 50% less air pollution than combustion of other fossil fuels, while De Gouw et al. (2014) publicized that combustion of gas is cleaner than that of other fossil fuels which leads to lower $CO_2$ emission.

Likewise, a single positive shock in coal consumption can uplift the environmental degradation of Canada, USA, Germany, Italy, UK, and Japan by 0.124%, 0.192%, 0.293%, 0.390%, 0.375%, and 0.513%, respectively, while a negative shock in coal consumption can decrease the environmental degradation of the USA, France, Germany, and UK by 0.277%, 0122%, 0.360%, and 0.092%, respectively. Agrawal et al. (2014) stated that coal consumption is a more toxic

**Table 6** Estimated result of bound test for G7 nations

| | Equation | Lag | *F*-statistics | Conclusion |
|---|---|---|---|---|
| Canada | $CO_2$ = f(Oil,Gas,Coal,GDP,GCF) | (1,1,1,1,1,0,0,1,1) | 4.262 [a] | Cointegrated |
| USA | $CO_2$ = f(Oil,Gas,Coal,GDP,GCF) | (1,1,1,0,1,0,0,0,0) | 12.125 [a] | Cointegrated |
| France | $CO_2$ = f(Oil,Gas,Coal,GDP,GCF) | (1,1,0,0,1,0,0,1,1) | 6.611 [a] | Cointegrated |
| Germany | $CO_2$ = f(Oil,Gas,Coal,GDP,GCF) | (1,0,0,0,1,0,0,1,0) | 5.333 [a] | Cointegrated |
| Italy | $CO_2$ = f(Oil,Gas,Coal,GDP,GCF) | (1,1,1,1,1,0,0,1,0) | 4.032 [b] | Cointegrated |
| UK | $CO_2$ = f(Oil,Gas,Coal,GDP,GCF) | (1,1,1,1,0,0,0,0,1) | 5.403 [a] | Cointegrated |
| Japan | $CO_2$ = f(Oil,Gas,Coal,GDP,GCF) | (1,1,1,0,1,0,0,1,1) | 3.109 [c] | Cointegrated |
| Pesaran et al. (2001) | Critical value | I (0) | I (1) | |
| a | 1% significance | 2.79 | 4.10 | |
| b | 5% significance | 2.22 | 3.39 | |
| c | 10% significance | 1.95 | 3.06 | |

Lag selection is based on the Akaike information criterion (AIC). $CO_2$ represents carbon dioxide emissions; Oil represents oil consumption; Gas represents gas consumption; Coal represents coal consumption

*GDP* gross domestic product, *GCF* gross capital formation

pollutant and emits more $CO_2$ compared to other fuels while Wei et al. (2009) insisted that coal is a low-quality energy source and its consumption should be limited for preserving the environment. The results imply that G7 countries are developed economies and their energy consumption is more than that in developing countries. Therefore, an increase in energy consumption (oil, gas, and coal) causes environmental degradation in G7 countries and a decrease in energy consumption decreases environmental degradation and pollution in G7 countries. In the long run, the estimated results show that the GDP and GCF of France are only significant. The results imply that an increase of 1% in GDP of France can decrease the air pollution by 0.043% following the EKC hypothesis with inverted-U shape which implies that a certain amount of increase in income of France can improve the environment until stabilization point and later will decrease which is consistent to the previous study of Jardon et al. (2017) and Rahman and Ahmad (2019). Similarly, an upsurge of 1% in GCF can increase air pollution by 0.108% following the study of Althor et al. (2016) and Rahman and Ahmad (2019). The estimated findings of economic growth for Canada, USA, Germany, Italy, UK, and Japan are not supporting the EKC hypothesis as similar to Aye and Edoja (2017). The dynamic multiplier graph shows the quick response of carbon dioxide to the positive and negative shocks of oil, gas, and coal consumption of G7 countries as shown in Figs. 8, 9, 10, 11, 12, 13, and 14.

## Stability check and diagnostic tests

The study measures the cumulative sum (CUSUM) and cumulative sum of squares (CUSUMSQ) for measuring the stability of the model. The estimated results shown in Figs. 15, 16, 17, 18, 19, 20, and 21 show that the recursive residuals of the CUSUM and CUSUMSQ remain within the boundaries of 5% critical value of G7 countries. These results employed that the model used for G7 countries is stable.

Various diagnostic tests are applied to the model to check the biases as shown in Table 9. The estimated *R*-squared and adjusted *R*-squared of the G7 countries fall above 90, which is greater than 50, implying our models are good fitted. The estimated results of the diagnostic test show that there is no problem of serial correlation, abnormality, functional form, and heteroscedasticity. These results confirm the nonexistence of biases in the model.

## Symmetric and asymmetric causality test

The estimated results of Hatemi-J (2012) depicted in Table 10 show that there is asymmetric causality between $CO_2$ emission and oil consumption of Canada and UK at 10% and 1% as shown in line 1. Similarly, in line 3, the result shows that the ecological footprint can asymmetrically cause positive change in oil consumption of Canada, USA, France, Germany, Italy, and Japan, while in line 4, a positive change in oil consumption can cause the ecological footprint of France. The estimated results in line 7 show a unidirectional symmetric causality between $CO_2$ emission and gas consumption of Germany and Japan at a 5% significant level. The projected results in lines 9 and 10 show that an asymmetric unidirectional casualty between $CO_2$ emission and positive change in gas consumption of the USA, UK, and Japan exists while there is a bidirectional causality

**Table 7** Estimated results of short-run nonlinear ARDL

| Country | $\Delta\text{Oil}^{+}$ | $\Delta\text{Oil}^{-}$ | $\Delta\text{Gas}^{+}$ | $\Delta\text{Gas}^{-}$ | $\Delta\text{Coal}^{+}$ | $\Delta\text{Coal}^{-}$ | ΔGDP | ΔGCF | ΔECT |
|---|---|---|---|---|---|---|---|---|---|
| Canada | 0.442 $^{a}$ [0.065] | −0.487 $^{a}$ [0.065] | 0.398 $^{a}$ [0.040] | −0.201 $^{b}$ [0.084] | 0.195 $^{a}$ [0.022] | −0.176 $^{a}$ [0.020] | −0.006 [0.010] | 0.011 [0.012] | −0.289 $^{a}$ [0.118] |
| USA | 0.430 $^{a}$ [0.031] | −0.436 $^{a}$ [0.042] | 0.178 $^{a}$ [0.014] | −0.167 $^{a}$ [0.040] | 0.299 $^{a}$ [0.040] | −0.276 $^{a}$ [0.021] | 0.001 [0.021] | 0.003 [0.003] | −0.863 $^{a}$ [0.047] |
| France | 0.806 $^{a}$ [0.161] | −0.367 $^{a}$ [0.092] | 0.188 $^{a}$ [0.048] | −0.452 $^{a}$ [0.050] | 0.108 $^{a}$ [0.037] | −0.082 $^{a}$ [0.020] | −0.029 $^{a}$ [0.009] | 0.073 $^{a}$ [0.021] | −0.674 $^{a}$ [0.117] |
| Germany | 0.377 $^{a}$ [0.063] | −0.292 $^{a}$ [0.030] | 0.060 $^{a}$ [0.014] | −0.223 $^{a}$ [0.053] | 0.278 $^{a}$ [0.055] | −0.341 $^{a}$ [0.025] | −0.002 [0.007] | 0.011 [0.018] | −0.947 $^{a}$ [0.056] |
| Italy | 0.871 $^{a}$ [0.120] | −0.388 $^{a}$ [0.096] | 0.147 $^{a}$ [0.041] | −0.383 $^{a}$ [0.108] | 0.148 $^{a}$ [0.046] | −0.132 $^{a}$ [0.036] | 0.005 [0.013] | −0.025 [0.028] | −0.236 $^{a}$ [0.049] |
| UK | 0.092 $^{c}$ [0.051] | −0.546 $^{a}$ [0.067] | 0.093 $^{a}$ [0.025] | −0.315 $^{a}$ [0.041] | 0.382 $^{a}$ [0.047] | −0.163 $^{a}$ [0.022] | 0.017 [0.012] | 0.010 [0.022] | −0.715 $^{a}$ [0.087] |
| Japan | 0.780 $^{a}$ [0.060] | −0.694 $^{a}$ [0.067] | −0.001 [0.017] | −0.384 $^{a}$ [0.102] | 0.357 $^{a}$ [0.047] | −0.252 $^{a}$ [0.065] | −0.020 $^{c}$ [0.011] | 0.004 [0.017] | −0.219 $^{a}$ [0.087] |

Superscript lowercase letters a, b, and c signify 1%, 5%, and 10% significance levels, respectively. $CO_2$ represents carbon dioxide emissions; Oil represents oil consumption; Gas represents gas consumption; Coal represents coal consumption

*GDP* gross domestic product, *GCF* gross capital formation

**Table 8** Estimated results of long-run NARDL

| Country | $\text{Oil}^{+}$ | $\text{Oil}^{-}$ | $\text{Gas}^{+}$ | $\text{Gas}^{-}$ | $\text{Coal}^{+}$ | $\text{Coal}^{-}$ | GDP | GCF | $CO_2$ |
|---|---|---|---|---|---|---|---|---|---|
| Canada | 0.214 [0.252] | −0.772 $^{a}$ [0.173] | 0.441 $^{a}$ [0.115] | −0.268 [0.185] | 0.124 $^{a}$ [0.042] | −0.014 [0.061] | −0.022 [0.030] | 0.037 [0.046] | 5.130 $^{a}$ [1.294] |
| USA | 0.498 $^{a}$ [0.034] | −0.505 $^{a}$ [0.035] | 0.206 $^{a}$ [0.020] | −0.102 $^{a}$ [0.036] | 0.192 $^{a}$ [0.043] | −0.277 $^{a}$ [0.010] | 0.002 [0.024] | 0.004 [0.012] | 8.023 $^{a}$ [0.469] |
| France | 0.274 $^{c}$ [0.143] | −0.120 [0.199] | 0.279 $^{a}$ [0.059] | −0.491 $^{a}$ [0.073] | 0.037 [0.090] | −0.122 $^{a}$ [0.026] | −0.043 $^{a}$ [0.015] | 0.108 $^{a}$ [0.043] | 4.235 $^{a}$ [0.973] |
| Germany | 0.224 $^{a}$ [0.062] | −0.308 $^{a}$ [0.034] | 0.063 $^{a}$ [0.015] | −0.059 $^{a}$ [0.037] | 0.293 $^{a}$ [0.066] | −0.360 $^{a}$ [0.013] | −0.003 [0.007] | 0.012 [0.019] | 6.510 $^{a}$ [0.477] |
| Italy | 0.547 $^{a}$ [0.181] | −1.643 $^{a}$ [0.371] | 0.206 $^{b}$ [0.103] | −0.642 $^{c}$ [0.380] | 0.390 $^{a}$ [0.120] | −0.025 [0.096] | 0.021 [0.058] | −0.107 [0.120] | 7.496 $^{a}$ [2.796] |
| UK | 0.128 $^{c}$ [0.068] | −0.566 $^{a}$ [0.049] | 0.023 $^{b}$ [0.010] | −0.441 $^{a}$ [0.056] | 0.375 $^{a}$ [0.056] | −0.092 $^{a}$ [0.013] | 0.024 [0.017] | 0.014 [0.030] | 5.485 $^{a}$ [0.649] |
| Japan | 0.911 $^{a}$ [0.135] | −0.583 $^{b}$ [0.249] | −0.002 [0.050] | −0.195 [0.435] | 0.513 $^{a}$ [0.092] | −0.299 [0.196] | −0.091 [0.060] | 0.018 [0.078] | 7.643 $^{a}$ [2.078] |

Superscript lowercase letters a, b, and c signify 1%, 5%, and 10% significance levels, respectively. $CO_2$ represents carbon dioxide emissions; Oil represents oil consumption; Gas represents gas consumption; Coal represents coal consumption

*GDP* gross domestic product, *GCF* gross capital formation

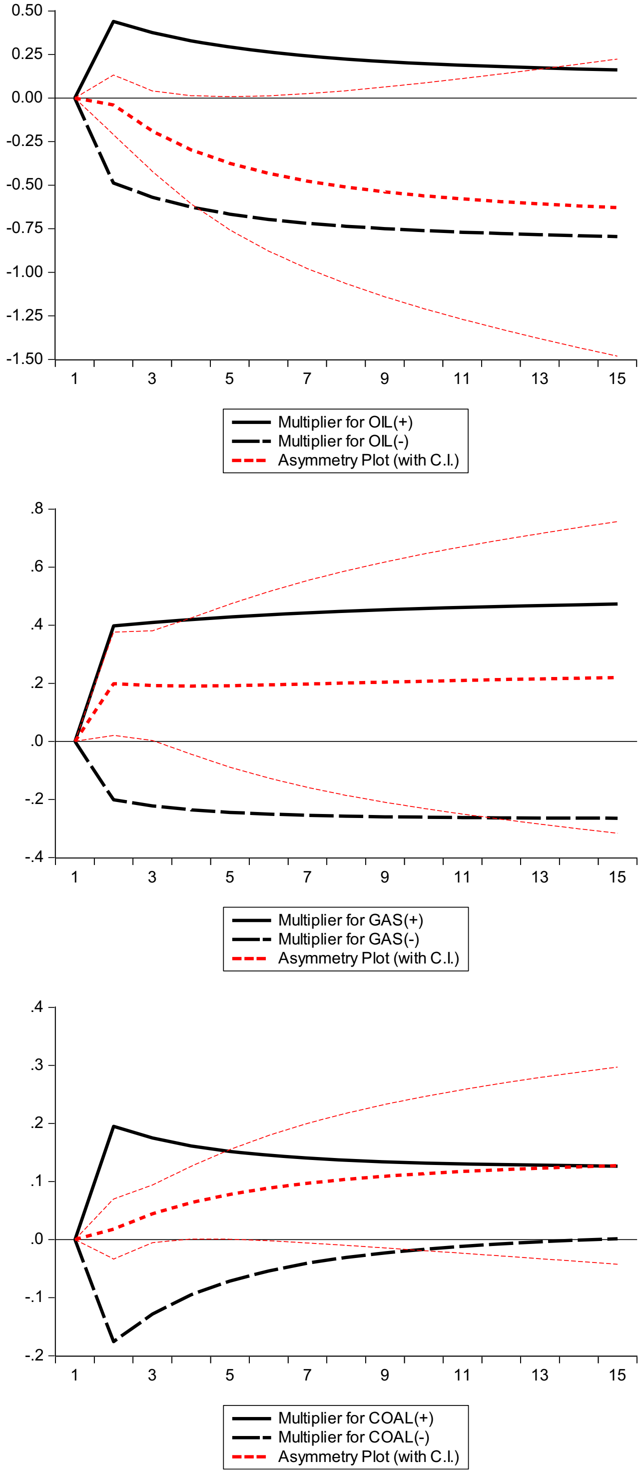

**Fig. 8** Dynamic multiplier graph for oil, gas, and coal of Canada

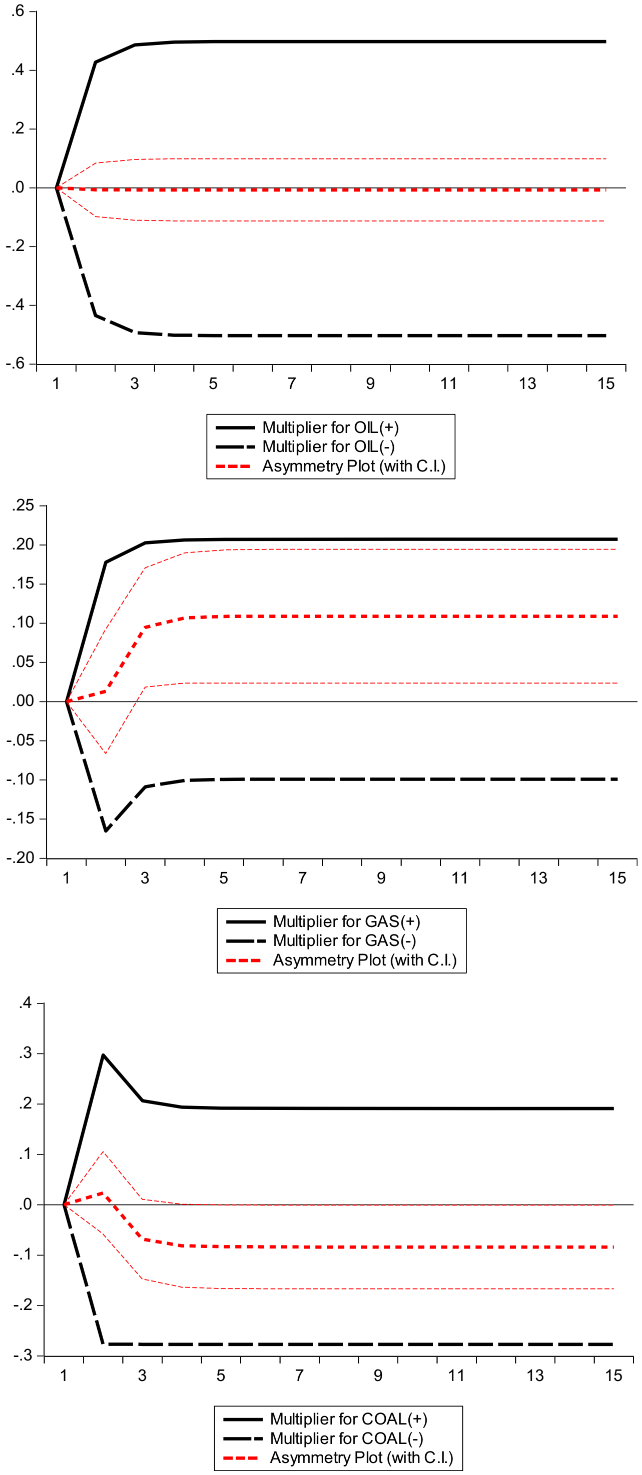

**Fig. 9** Dynamic multiplier graph for oil, gas, and coal of the USA

in the $CO_2$ emission and positive change in gas consumption of Canada and France. Lines 11 and 12 show an asymmetric unidirectional causality between ecological footprint and negative shock of the USA and UK while there is a bidirectional asymmetric causality between ecological footprint and negative shock of France. The projected results show that $CO_2$ emission symmetrically causes the coal consumption of Italy in line 13 while an asymmetrical causality exists between $CO_2$ emission with positive change and $CO_2$ emission with a negative change

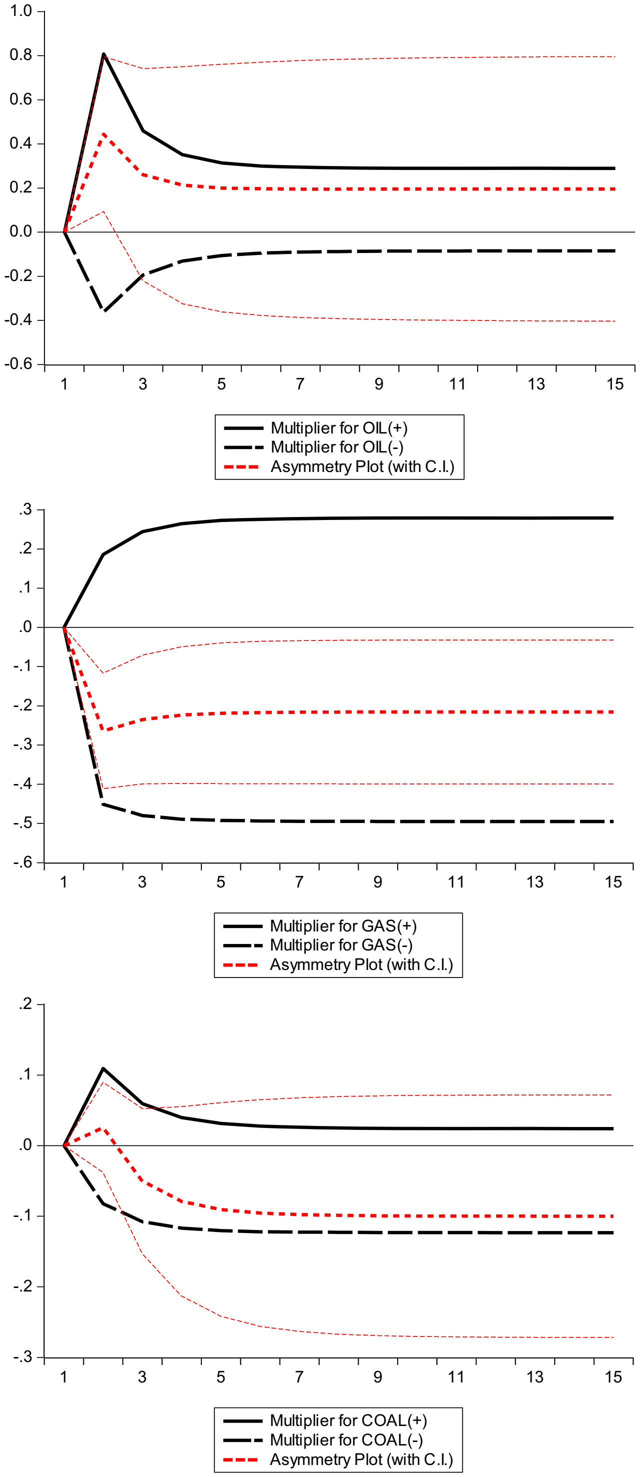

**Fig. 10** Dynamic multiplier graph for oil, gas, and coal of France

in coal consumption of the USA, France, Germany, Italy, UK, and Japan as shown in lines 15 to 17. The findings in lines 2, 5, 6, 8, 14, and 18 show that there is no causality among the variables.

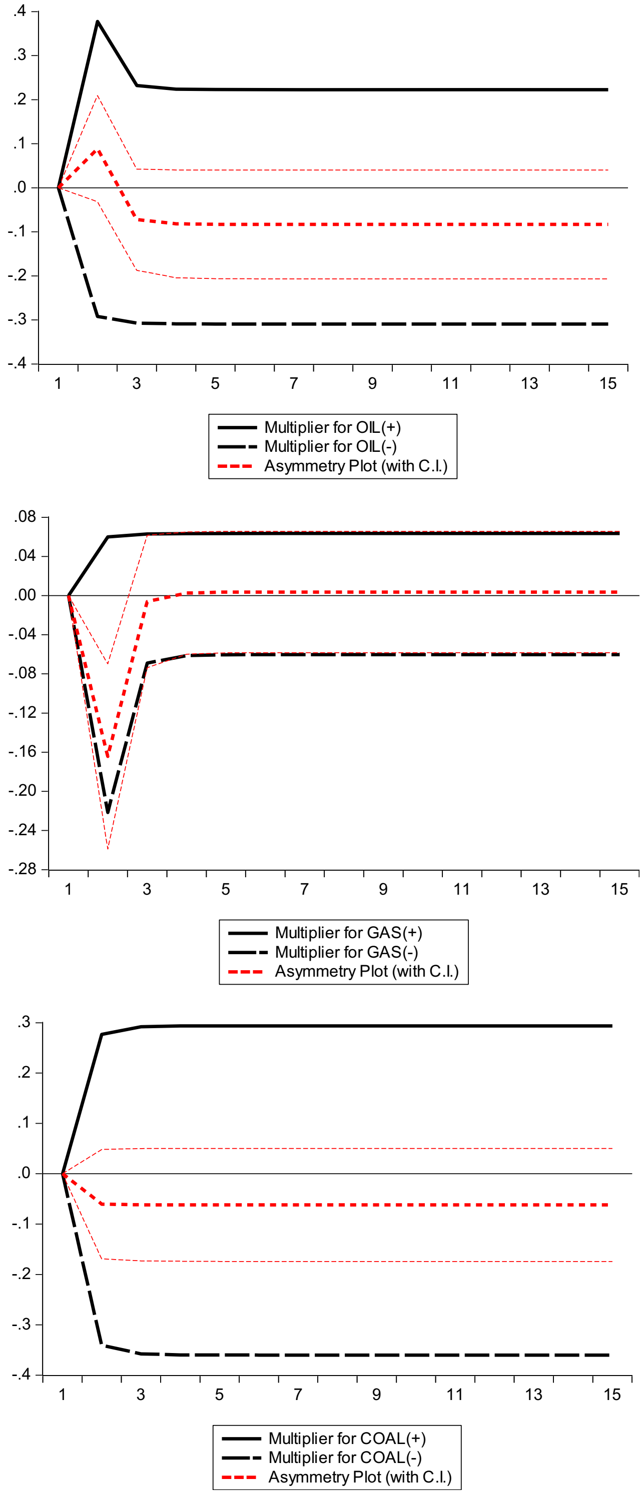

**Fig. 11** Dynamic multiplier graph for oil, gas, and coal of Germany

## Conclusion and suggestion

With the rapid increase in urbanization and industrialization after the industrial revolution, the dependencies on energy

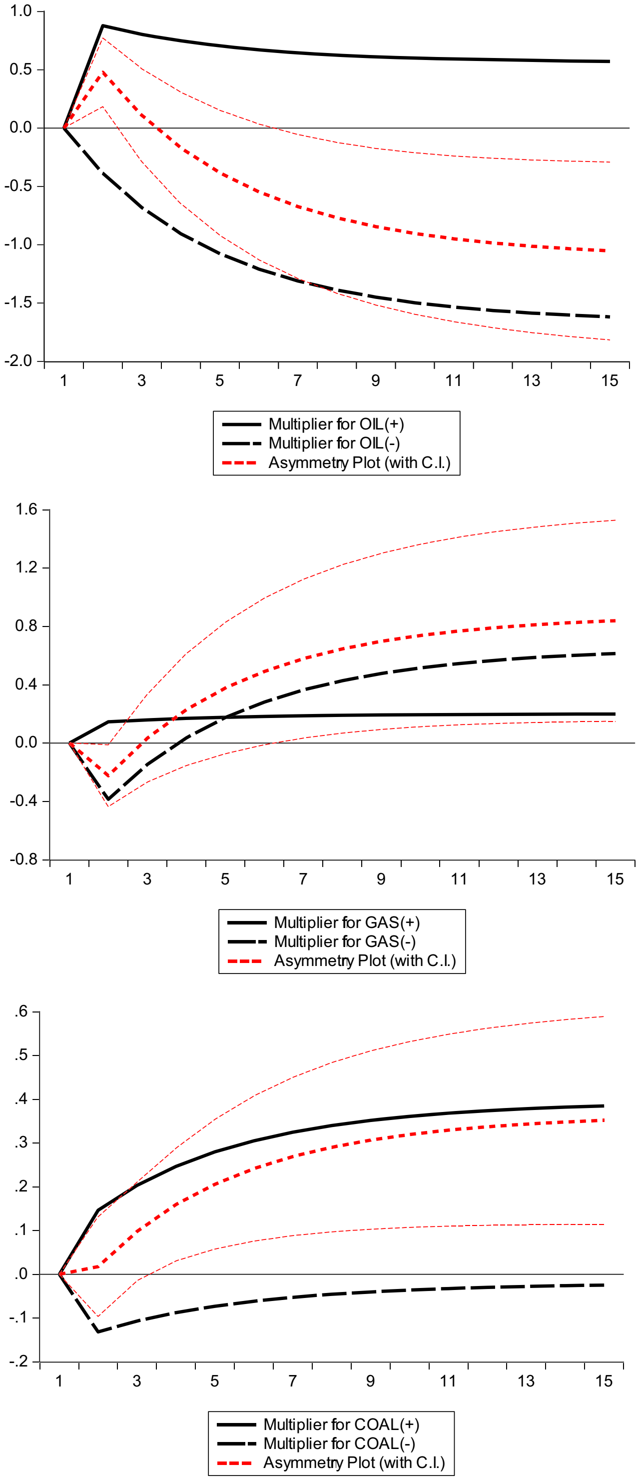

**Fig. 12** Dynamic multiplier graph for oil, gas, and coal of Italy

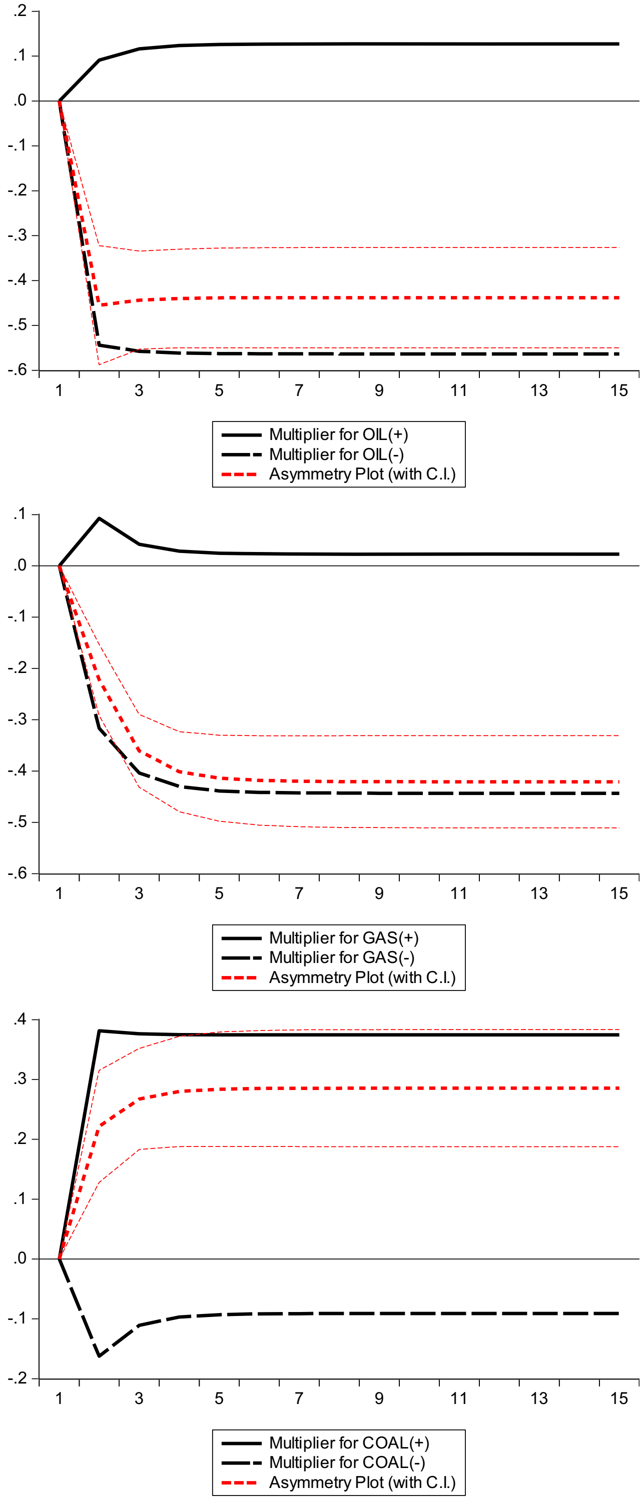

**Fig. 13** Dynamic multiplier graph for oil, gas, and coal of the UK

increase the environmental degradation in the universe. During this race of economics and sustainable development, environmental degradation and air pollution were ignored by various economies. Numerous studies are carried out to measure the impact of renewable and nonrenewable energy consumption on $CO_2$ emission, but still, the literature is missing to measure the impact of oil, coal, and gas consumption on $CO_2$ emission in G7 economies. Therefore, to cover this gap, this study was carried out to measure the asymmetric impact of oil, gas, and coal consumption on $CO_2$ emission in G7

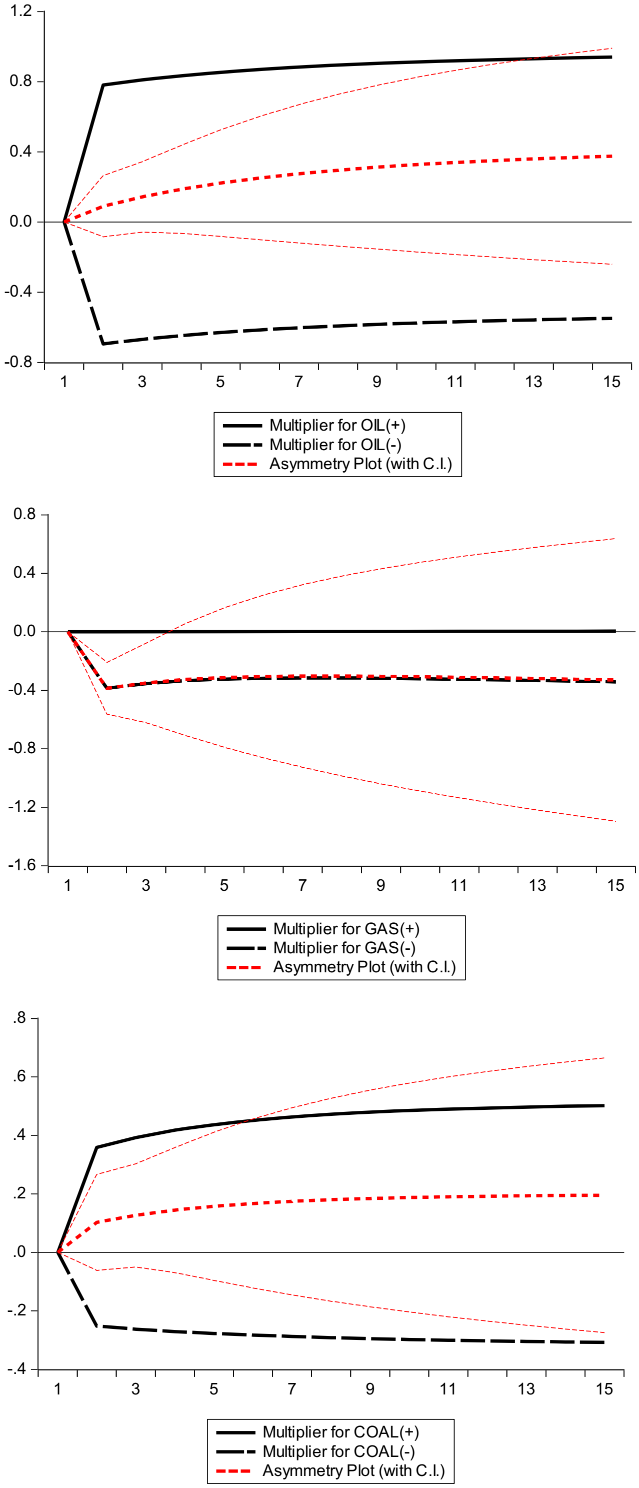

**Fig. 14** Dynamic multiplier graph for oil, gas, and coal of Japan

countries. Nonlinear ARDL is applied to the annual time series data from 1965 to 2019 (France from 1985 to 2019) of G7 countries to figure out the short- and long-run associations among variables. The ADF test demonstrates that some of the variables are stationary at level, but at first difference, all the variables of G7 countries are stationary.

The estimated results of NARDL for the long run imply that an increase in oil consumption in the long run can significantly increase the $CO_2$ emission of the USA, France, Germany, Italy, UK, and Japan while a decrease in oil consumption can decrease the air pollution of Canada, USA, Germany, Italy, UK, and Japan. On the other hand, the empirical findings demonstrate that growth in gas consumption can escalate the air pollution of Canada, USA, France, Germany, Italy, and UK while a negative shock of gas consumption can reduce the ecological footprint of the USA, France, Germany, Italy, and UK. Similarly, a single positive shock in coal consumption can uplift the environmental degradation of Canada, USA, Germany, Italy, UK, and Japan while a negative shock in coal consumption can decrease the environmental degradation of the USA, France, Germany, and UK. In the long run, the estimated results show that the GDP and GCF of France are only significant. The study concluded that a 1% movement of oil and gas consumption toward coal consumption in Canada and France can decrease the carbon emission by 1.21% and 0.64%, while a 1% movement of oil and coal consumption toward gas consumption in the USA, Germany, Italy, UK, and Japan can decrease the carbon emission by 1.48%, 1.18%, 2.58%, 1.07%, and 2.34%. It is also concluded that there is symmetric and asymmetric causality between $CO_2$ emission and oil, gas, and coal consumption of G7 countries.

It is concluded from the estimated results of Hatemi-J (2012) that there is asymmetric causality between $CO_2$ emission and oil consumption of Canada and UK, while $CO_2$ emission can asymmetrically cause positive change in oil consumption of Canada, USA, France, Germany, Italy, and Japan and the positive change in oil consumption can cause the $CO_2$ emission of France. There is also a unidirectional symmetric causality between $CO_2$ emission and gas consumption of Germany and Japan. Similarly, an asymmetric unidirectional casualty between $CO_2$ emission and positive change in gas consumption of the USA, UK, and Japan exists while there is a bidirectional causality in the $CO_2$ emission and positive change in gas consumption of Canada and France. Meanwhile, asymmetric unidirectional causality exists between the ecological footprint and negative shock of the USA and UK while there is a bidirectional asymmetric causality between the ecological footprint and negative shock of France. The projected results show that $CO_2$ emission symmetrically causes the coal consumption of Italy while an asymmetrical causality exists between $CO_2$ emission with positive change and $CO_2$ emission with a negative change in coal consumption of the USA, France, Germany, Italy, UK, and Japan. As per the results, it is concluded that there is unidirectional,

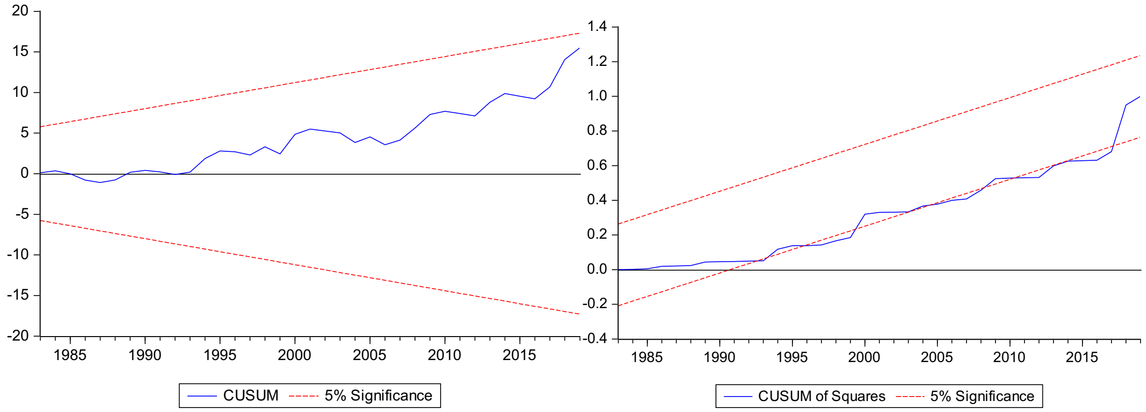

**Fig. 15** NARDL CUSUM and CUSUMSQ for Canada

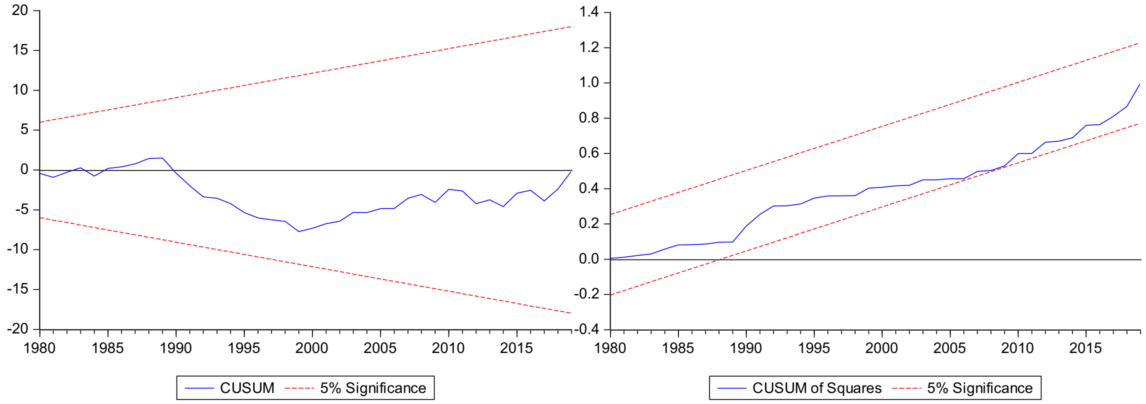

**Fig. 16** NARDL CUSUM and CUSUMSQ for USA

bidirectional causality between the consumption of oil, coal, and gas and $CO_2$ emission of G7 economies.

The results show that both in the short and long run, the consumption of oil, coal, and gas destabilizes the environment of G7 economies. Therefore, the study recommends the G7 economies to shift toward green technology to stabilize their environment. The study also recommends G7 countries to discourage the consumption of fossil fuel through various barriers and obtain their required energy from the nonrenewable energy source. For the short term, the study suggested that firstly, the government of Canada and France is required to use coal instead of oil and gas while the USA, Germany, Italy, UK, and Japan are required to consume more gas as compared to oil and coal. Secondly,

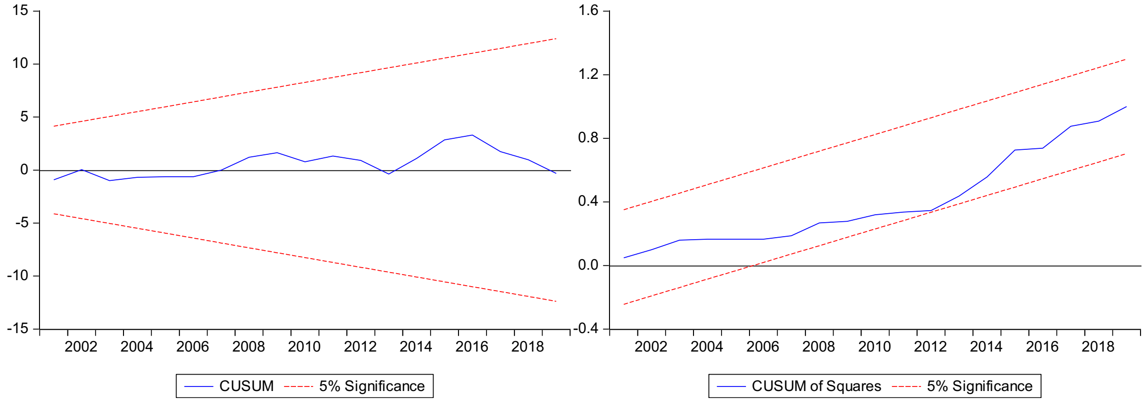

**Fig. 17** NARDL CUSUM and CUSUMSQ for France

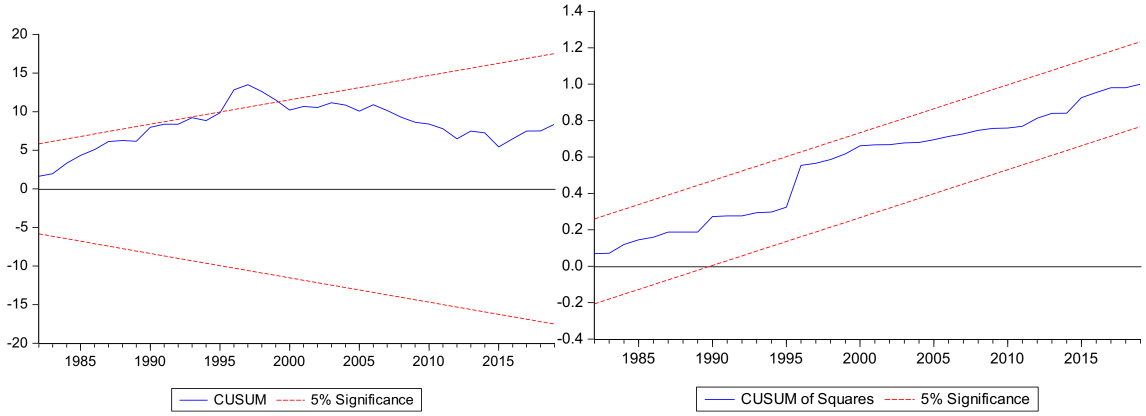

**Fig. 18** NARDL CUSUM and CUSUMSQ for Germany

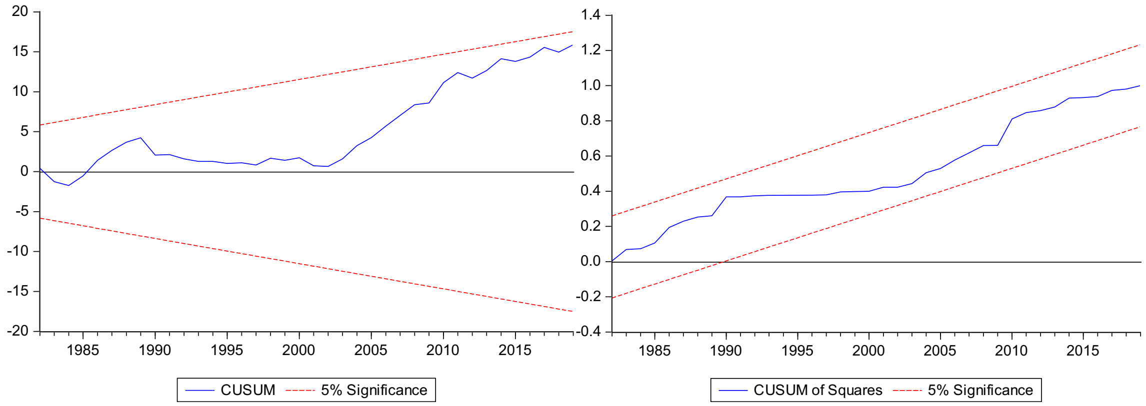

**Fig. 19** NARDL CUSUM and CUSUMSQ for Italy

international regulation and framework should be enforced to ensure sustainable development with preventive measurement of environmental degradation. Thirdly, research centers should be developed and encouraged to reduce environmental degradation by using various new technologies.

## Limitation of the study

The study is limited to measure the asymmetric cointegration and causality among $CO_2$ emission, fossil fuel consumption, GDP, and FDI of G7 economies. It is observed from the findings that further empirical studies are needed to use different

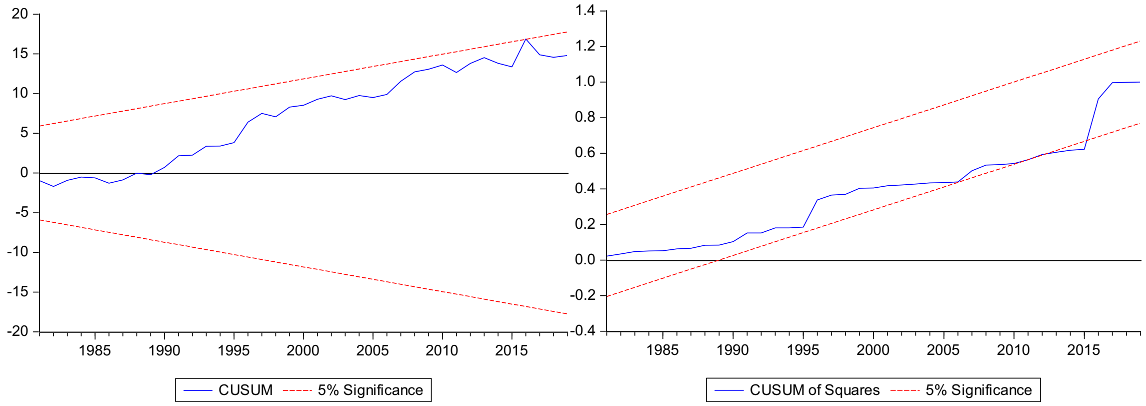

**Fig. 20** NARDL CUSUM and CUSUMSQ for UK

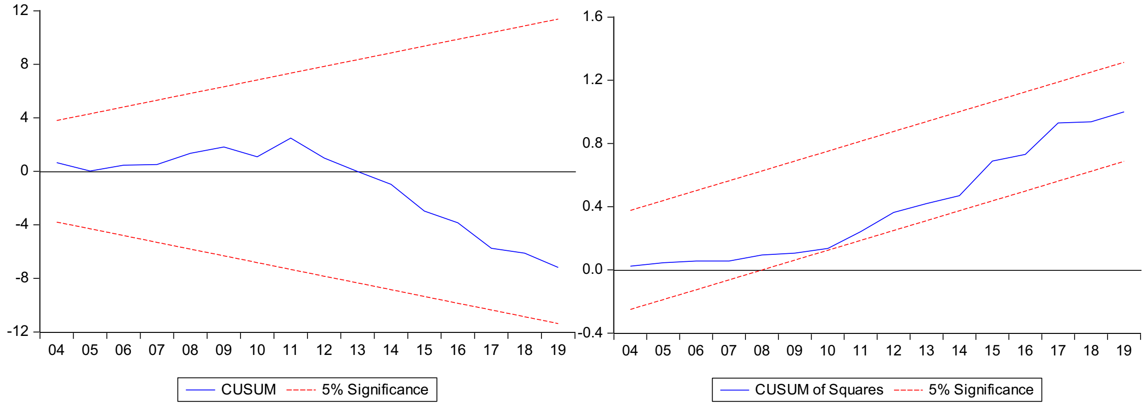

**Fig. 21** NARDL CUSUM and CUSUMSQ for Japan

**Table 9** NARDL diagnostic test for G7 countries

| Diagnostics tests | Canada | USA | France | Germany | Italy | UK | Japan |
|---|---|---|---|---|---|---|---|
| *R*-squared | 0.999 | 0.999 | 0.997 | 0.997 | 0.995 | 0.994 | 0.998 |
| Adjusted *R*-squared | 0.999 | 0.999 | 0.996 | 0.996 | 0.993 | 0.993 | 0.998 |
| Durbin-Watson | 2.082 | 1.928 | 1.882 | 2.137 | 2.057 | 2.049 | 2.101 |
| Heteroskedasticity test: Breusch-Pagan-Godfrey | 1.508<br>(0.152) | 1.542<br>(0.149) | 1.248<br>(0.322) | 1.179<br>(0.331) | 0.451<br>(0.945) | 1.598<br>(0.173) | 1.567<br>(0.127) |
| Breusch-Godfrey serial correlation LM | 0.925<br>(0.406) | 2.176<br>(0.127) | 0.051<br>(0.824) | 0.372<br>(0.545) | 0.530<br>(0.593) | 1.494<br>(0.238) | 0.286<br>(0.753) |
| Heteroskedasticity test: ARCH | 0.261<br>(0.612) | 0.025<br>(0.875) | 0.301<br>(0.588) | 1.255<br>(0.268) | 0.004<br>(0.953) | 2.169<br>(0.147) | 0.499<br>(0.483) |
| Jarque-Bera normality Ramsey RESET | 1.351<br>(0.509) | 1.327<br>(0.515) | 1.365<br>(0.505) | 1.379<br>(0.498) | 0.580<br>(0.748) | 1.626<br>(0.444) | 1.151<br>(0.563) |

**Table 10** Symmetric and asymmetric causality tests of G7 variables

| Number | G7 nations | Canada | USA | France | Germany | Italy | UK | Japan |
|---|---|---|---|---|---|---|---|---|
| 1 | $CO_2$ = Oil | 2.965 $^{c}$ | 1.162 | 0.014 | 5.085 | 1.956 | 19.911 $^{a}$ | 0.261 |
| 2 | Oil = $CO_2$ | 0.020 | 0.727 | 0.042 | 4.316 | 0.511 | 0.005 | 0.071 |
| 3 | $CO_2$ = $Oil^{+}$ | 12.077 $^{a}$ | 25.574 $^{a}$ | 284.270 $^{c}$ | 6.163 $^{b}$ | 9.105 $^{a}$ | 0.212 | 30.911 $^{a}$ |
| 4 | $Oil^{+}$ = $CO_2$ | 0.104 | 0.826 | 43.675 $^{a}$ | 0.897 | 0.645 | 0.002 | 0.824 |
| 5 | $CO_2$ = $Oil^{-}$ | 1.328 | 0.171 | 0.618 | 0.012 | 0.081 | 0.266 | 1.175 |
| 6 | $Oil^{-}$ = $CO_2$ | 1.179 | 0.179 | 3.091 | 0.024 | 4.237 | 0.001 | 0.093 |
| 7 | $CO_2$ = Gas | 0.001 | 0.297 | 2.265 | 10.283 $^{b}$ | 0.027 | 0.619 | 5.640 $^{b}$ |
| 8 | Gas = $CO_2$ | 0.583 | 0.357 | 0.039 | 0.649 | 0.167 | 0.512 | 0.411 |
| 9 | $CO_2$ = $Gas^{+}$ | 10.018 $^{a}$ | 8.369 $^{a}$ | 10.508 $^{b}$ | 0.967 | 0.325 | 4.902 $^{b}$ | 14.576 $^{a}$ |
| 10 | $Gas^{+}$ = $CO_2$ | 4.015 $^{c}$ | 2.198 | 10.274 $^{b}$ | 1.561 | 0.280 | 0.889 | 0.084 |
| 11 | $CO_2$ = $Gas^{-}$ | 0.377 | 13.066 $^{a}$ | 6.546 $^{c}$ | 0.065 | 0.010 | 5.313 | 0.034 |
| 12 | $Gas^{-}$ = $CO_2$ | 2.486 | 1.597 | 5.016 $^{c}$ | 0.285 | 1.600 | 18.320 $^{b}$ | 1.672 |
| 13 | $CO_2$ = Coal | 0.362 | 5.461 | 1.559 | 2.557 | 4.471 $^{b}$ | 1.097 | 3.348 |
| 14 | Coal = $CO_2$ | 0.907 | 0.858 | 16.705 | 4.540 | 0.676 | 0.732 | 3.188 |
| 15 | $CO_2$ = $Coal^{+}$ | 3.602 | 11.697 $^{b}$ | 30.403 $^{a}$ | 22.240 $^{a}$ | 0.127 | 33.606 $^{a}$ | 15.503 $^{a}$ |
| 16 | $Coal^{+}$ = $CO_2$ | 5.456 | 1.591 | 27.689 $^{a}$ | 3.649 | 1.591 | 0.013 | 1.267 |
| 17 | $CO_2$ = $Coal^{-}$ | 1.245 | 2.764 $^{c}$ | 109.613 | 4.943 $^{b}$ | 4.098 $^{c}$ | 20.045 $^{a}$ | 0.335 |
| 18 | $Coal^{-}$ = $CO_2$ | 0.078 | 0.099 | 0.609 | 1.099 | 1.567 | 0.008 | 1.782 |

Superscript lowercase letters a, b, and c signify 1%, 5%, and 10% significance levels, respectively, and the estimated values are Hatemi-J (2012)'s Wald test value methodologies to examine different countries. The study also needs to be conducted to measure the efficiency level of different energy sources on environmental stability.

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**Author contribution** Muhammad Nasrullah: conceptualization, formal analysis, investigation, and writing the original draft. Muhammad Rizwanullah: data collection, software, methodology, and formal analysis. Yu Xiu Yuan: writing review, investigation, software, and methodology. Liang Li Zhi: supervision, investigation, data correction, formal analysis, methodology, and editing

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**Data availability** The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

## Declarations

**Ethics approval and consent to participate** This is an observational study. We confirmed that no ethical approval is required. Consent to participate is not applicable.

**Consent for publication** Not applicable.

**Competing interests** The authors declare no competing interests.

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