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The relationship between CO_2 emissions, renewable energy and economic growth in the US: evidence from symmetric and asymmetric spectral granger causality analysis

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Abstract
This study analyzes the relationship between renewable energy consumption, CO_2 emissions, and economic growth for 1973:M01-2022:M06 in the USA. The study employs Spectral Granger Causality analysis symmetrically and asymmetrically. The symmetric causality test presents a bidirectional causality relationship between CO_2 emissions, renewable energy consumption, and economic growth. Regarding asymmetric causality results, there is bidirectional causality between positive and negative shocks of CO_2 emissions, renewable energy consumption, and economic growth. The results suggest that renewable energy consumption is essential in increasing sustainable economic growth and environmental quality for the USA.

Keywords Renewable energy consumption · CO_2 emission · Economic growth · Symmetric and asymmetric spectral granger causality · USA

Jel Codes C32 · O11 · Q20 · Q50

1 Introduction

Climate change, combating global warming, and sustainable economic growth have gained importance over the years. In this context, concerns about global warming, one of the most significant environmental problems, have led to the literature examining comprehensively global warming. The greenhouse gases resulting from human activities are the main source

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of global warming, and CO_2 emissions account for 76% of greenhouse gases (including fossil fuel and industrial use, forestry, and land use) (EPA, 2022).

Using renewable energy instead of fossil fuels may negatively affect the economic performance of countries and cause lower growth rates. Nevertheless, renewable energy sources are crucial for ensuring sustainable economic growth and reducing the effects of climate change by playing an essential role in minimizing greenhouse gases, especially CO_2 emissions. Moreover, expected from renewable energy consumption to reduce CO_2 emissions (Bento & Moutinho, 2016; Ito, 2017; Dogan & Ozturk, 2017; Toumi & Toumi, 2019; Dimitriadis et al., 2021; Lei et al., 2022) and fight against global warming and climate change (Balsalobre-Lorente et al., 2023a). At the same time, using renewable energy to diminish carbon dioxide emissions is recognized as a crucial element for achieving sustainable economic growth. A common solution is transitioning from fossil fuels to renewable energy sources to ensure environmental quality and economic growth. (Balsalobre-Lorente et al., 2018). Energy security is important in ensuring sustainable economic growth. Promoting renewable energy sources helps to improve environmental quality, combat global warming and climate change, and ensure energy supply security (Abban et al., 2023).

Countries are actively working on significant projects and investments, with an increasing emphasis on the importance of renewable energy on a global level (Zhang et al., 2022). Although countries possess different structural, institutional, and cultural characteristics, these researches produce a common coefficient for all of them. Therefore, it is important to conduct studies on individual country studies (Dogan & Ozturk, 2017), and we aim to contribute to the literature by focusing on the USA. The USA has the highest rate after China, with 4.71 billion tons of CO_2 emissions as of 2020 (Ritchie & Roser, 2020). Therefore, for authorities, the USA is an important factor in solving both economic and global problems on a global scale. Although, there is no American signature on the Kyoto Protocol, which is important in combating global warming and reducing greenhouse gas emissions. (Dogan & Ozturk, 2017). Moreover, renewable energy became the fastest-growing energy source in the USA between 2010 and 2020 (C2ES, 2022). Figure 1 shows the monthly CO_2 emissions, industrial production index, and the development of renewable energy consumption in the USA for the 1973:M01-2022:M06 period.

Figure 1 presents that the CO_2 emissions of the USA increased between 1973 and 2019, and the emissions reduced after the 2000s. Renewable energy consumption in the US grew

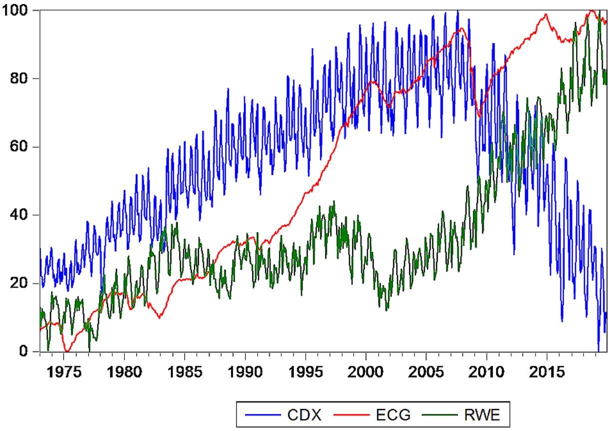

Fig. 1 CO_2 emissions, industrial production index, and renewable energy consumption in the USA (1973-:M01-2022:M06). *Note* ECG is the total industrial production index, CDX is the total CO2 emissions, and RWE is the total renewable energy consumption. *Source* Established by the authors with data from the Energy Information Administration (EIA) (2022) and FRED (2022)

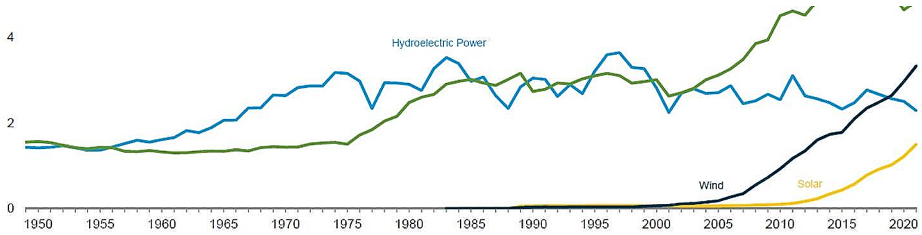

Fig. 2 Types of renewable energy in the USA. *Source* (EIA, 2022)

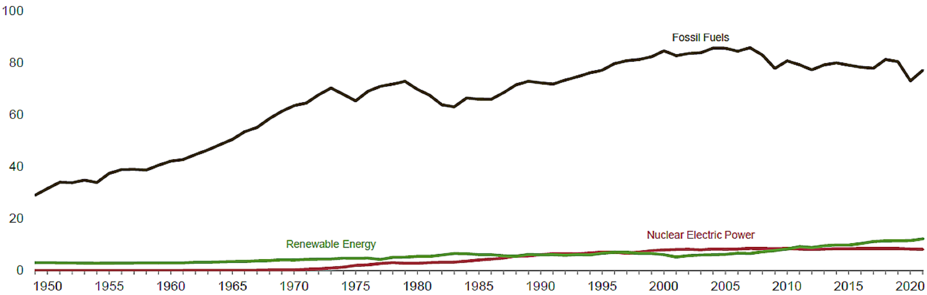

Fig. 3 Other energy sources in the USA. *Source* (EIA, 2022)

rapidly after the 2000s due to its increasing use and importance. Figure 1 also shows a serious break in CO_2 emissions and economic growth (industrial production index) due to the COVID-19 pandemic in 2020:04. The measures implemented under pandemic conditions led to a serious reduction in CO_2 emissions. Analyzing the types of consumption of renewable energy in the USA is important. Figure 2 shows sources of renewable energy consumption in the USA.

In the USA, wind energy ranks first in renewable energy consumption, followed by Hydroelectric power and Biofuels. Geothermal energy brings up the rear. However, wind and solar are the main sources of increase in renewable energy uses. Figure 3 compares renewable energy consumption with other energy sources in the USA.

Fossil fuels are placed at the top among energy production sources in the USA. Renewable energy and Nuclear Electric power rank second and third, respectively. Although the share of renewable energy has increased recently and surpassed Nuclear electric power, it is still way below the share of fossil fuels. It is understood that the share of both safe and environmentally friendly energy sources has increased in the USA.

This study analyzes the relationship between renewable energy consumption, CO_2 emissions, and economic growth for 1973:M01-2022:M06 in the USA. The USA ranks first in the world in CO_2 emissions and renewable energy consumption. In this respect, it is essential to analyze the USA. Moreover, the findings of this paper will provide crucial information for policymakers and other researchers. There are various studies related to the USA, in literature; however, it is vital to retest similar relationships with new methods, analysis techniques, and data sets. Because new empirical methods that provide realistic results between variables are now developed, this study contributes by employing the Spectral

Granger causality analysis, which is quite limited in the literature, by including the asymmetric structure.

This study contributes to the literature in various ways. The literature generally focuses on cross-country comparisons. Papers analyzing countries with different structural, institutional, and cultural characteristics suffer from estimating a common coefficient. Therefore, it is crucial to conduct studies on individual countries (Dogan & Ozturk, 2017). We, first, aim to contribute by employing time series data on the USA.

Second, the relationship between CO_2 emissions, renewable energy consumption, and economic growth is generally analyzed with annual data in the literature. Ignoring detailed fluctuations, such as monthly changes, can create a serious problem in obtaining accurate results. At the same time, variables consist of positive and negative components, which may not always move in the same direction. Therefore, it is important to analyze the movement patterns of the positive and negative components of the variables (Hatemi-J, 2012). This study employs symmetric and asymmetric Spectral Granger causality analyses using monthly data from the USA. Thus, examining the relationship between the variables in depth and controlling whether the relationship is temporary or permanent becomes possible. Another important contribution is revealing the relationship between positive and negative shocks belonging to the neglected variables in the symmetric analysis. In addition, the results and findings of the paper provide the basis for studies of other developed and developing countries. The importance of renewable energy consumption in the struggle against global warming and climate change is emphasized again, specifically in the United States.

The next section reviews the empirical literature. Then, the next chapter introduces the data and methodology and discusses the empirical findings. The final section discusses the findings and makes policy recommendations.

2 Empirical literature review

Many studies in the literature examine the relationship between economic growth, renewable energy, and CO_2 emissions. However, in our study, we generally discussed studies examining CO_2 emissions, renewable energy consumption, and economic growth variables. Much as the studies in this field extend back a long time, they intensified after the 2000s. This is because studies conducted in the 2000s are mostly included. It is observed that these studies obtained different results between these variables. Literature has studies which found bidirectional relationship (Apergis & Payne, 2010; Chang, 2010; Narayan & Narayan, 2010; Menyah & Wolde-Rufael, 2010; Arı & Zeren, 2011; Akpan & Akpan, 2012; Burnett et al., 2013; Alkhathlan & Javid, 2013; Sebri & Ben-Salha, 2014; Akay et al., 2015; Dogan, 2016; Lu, 2017; Rafindadi & Ozturk, 2017; Kahia et al., 2019; Shahbaz et al., 2020); relationship with unidirectional causality (Vidyarthi, 2014; Dogan & Seker, 2016; Alper & Oguz, 2016; Ito, 2017; Dogan & Ozturk, 2017; Demir & Gozgor, 2018; Toumi & Toumi, 2019; Dimitriadis et al., 2021; Çıtak et al., 2021; Lei et al., 2022) and relationship no causality (Soytaş & Sarı, 2009; Payne, 2009; Bowden & Payne, 2010; Bhattacharya et al., 2016; Acheampong et al., 2021; Zuhal (2022). Ewing et al. (2007) examined the effect of energy consumption on industrial output in the USA. For findings, the explanatory power of consumption of various energy sources on industrial production in the USA remains low in the short, medium, and long term. It is stated that coal, one of the energy sources, is higher than other energy sources in the long run and that the sources in the renewable energy class have quite low explanatory pow. Soytaş and Sarı (2009) performed a causality review between carbon emissions, economic growth, and energy consumption in Turkey. There is no causality between economic growth and carbon emissions in Turkey, while a one-way causality from carbon emissions to energy consumption can be identified.

Payne (2009) researched the effect of renewable and non-renewable energy consumption on real GDP in the USA for the period 1949–2006. No causality could be found between GDP and both renewable and non-renewable energy consumption in the USA for the relevant period. The effects of sectoral renewable and non-renewable energy use on economic growth in the USA were analyzed by Bowden and Payne (2010). Again, for the results, there is no causal relationship between renewable energy consumption and economic growth in the commercial and industrial sectors, while a positive one-way causality towards economic growth in the use of households was determined. Moreover, using non-renewable energy in the commercial sector and residences has a positive and bidirectional relationship with economic growth, while there is a negative and one-way causality from industrial use to economic growth.

Apergis and Payne (2010) analyzed the relationship between renewable energy consumption and economic growth for countries in the Eurasian region. Regarding these countries, there is a bidirectional relationship between economic growth and renewable energy consumption for the short and long term.

The relationship between CO_2 emissions, energy consumption, and GDP in China was examined by Chang (2010). It is emphasized in the relevant study that GDP growth increases crude oil, coal consumption, and CO_2 emissions.

Narayan and Narayan (2010) tested the existence of the Environmental Kuznets curve (EKC) in developing countries. Countries were analyzed by classifying regionally; for findings, the Middle East and South Asian countries are compatible with the EKC hypothesis, while the results are incompatible with the EKC hypothesis in Latin America, East Asia, and Africa.

Menyah and Wolde-Rufael (2010) analyzed the relationship between nuclear energy, renewable energy, and economic growth in the USA for the period 1960–2007 with causality analysis. According to the results, there is one-way causality from nuclear energy to CO_2 emissions and from CO_2 emissions to renewable energy. They also found bidirectional causality between GDP and CO_2 emissions in the USA. Moreover, for the authors, renewable energy is not at a level that can reduce emissions in the USA and, therefore, cannot reduce emissions (Menyah & Wolde-Rufael, 2010:2913).

Arı and Zeren (2011) analyzed the relationship between economic growth and CO_2 emissions; their findings suggest deviations from the Kuznets curve and that CO_2 emissions may tend to increase even at high-income levels.

The relationship between CO_2, electricity consumption, and economic growth in Nigeria was reviewed by Akpan and Akpan (2012). The authors expressed that these variables are cointegrated; they move together in the long run. Therefore, based on the causality analysis, it can be said that income and electricity consumption cause CO_2 emissions.

Burnett et al. (2013) worked on the USA; according to the results, an increase in population and welfare puts pressure on CO_2 emissions to increase. However, a decreasing trend was observed in emissions due to the pressure of population, welfare increase, and technological developments. Again, the authors confirm that CO_2 emissions positively affect energy production while there is a U-shaped relationship with income.

Alkhathlan and Javid (2013) researched the relationship between energy consumption, carbon emissions, and economic growth in Saudi Arabia. For their results, there is a positive relationship between economic growth and carbon emissions in the long run in Saudi Arabia, while economic growth increases emissions, and there is no U-shaped relationship between the variables.

Vidyarthi (2013) examined the relationship between India's carbon dioxide emissions, economic growth, and electricity consumption. It was seen as a result of the analysis that all three variables are related to each other in the long run, and there is one-way causality from energy consumption and carbon dioxide emissions to GDP. However, economic growth must be sacrificed to reduce emissions in India in the short term.

Vidyarthi (2014) surveyed South Asian countries and found that energy consumption, CO_2 emissions, and economic growth are cointegrated. There is one-way causality from CO_2 emissions to economic growth in the long run, while there is one-way causality from CO_2 emissions to economic growth.

The relationship between renewable energy consumption and economic growth in BRICS countries was examined by Sebri and Ben-Salha (2014). The study observed bidirectional causality between renewable energy and economic growth in the relevant countries, except for India.

Yang et al. (2015) endeavored to find the direction and shape of the relationship between CO_2 emissions and economic growth in sixty-seven countries. For results, the EKC model is not suitable in all countries, while there may be a U, inverted U, M, and N-shaped or linear relationship between the variables in countries.

Akay et al. (2015) examined the causal relationship between renewable energy, CO_2 emissions, and economic growth in selected Middle East and North African countries. For results, there is a bidirectional causality relationship between economic growth and renewable energy, one-way causality from CO_2 emissions to renewable energy, and one-way causality from growth to CO_2 in the countries.

The relationship between renewable and non-renewable energy production, GDP, and international trade in Italy was analyzed between by Bento and Moutinho (2016). It is stated that Italy's CO2 emissions and economic growth are positively related in the short term, but this relationship turns negative in the long term. Renewable energy generation negatively affects CO_2 emissions in the short and long term. However, non-renewable energy production has a positive effect in both periods, and the degree of impact increases in the long term.

The relationship between economic growth, CO_2 emissions, trade openness, and financial development in OECD countries was reviewed by Dogan and Seker (2016) within the framework of the EKC hypothesis. It was determined that the variables are cointegrated in the long run, while a positive effect was observed on income emissions in low-income countries but negative in high-income countries. Energy consumption increases emissions at the same time.

The effect of renewable and non-renewable energy consumption on economic growth in Turkey was reviewed by Dogan (2016). Analysis results show us a long-term cointegration between the variables. Again, there is a bidirectional causality relationship between economic growth and non-renewable energy consumption in the short run; there is a unidirectional causality relationship from economic growth to renewable energy, while both renewable and the non-renewable energy consumption is the cause of economic growth in the long run.

Bhattacharya et al. (2016) researched the relationship between renewable energy consumption and economic growth in countries where renewable energy is heavily used. It is expressed that renewable and non-renewable energy consumption affects growth positively. However, besides all these, the causality between renewable energy consumption and economic growth could not be seen at the end of the causality analysis.

Alper and Oguz (2016) researched the relationship between renewable energy consumption, capital, labor, and economic growth in new EU member states. No causality could be found in five countries at the end of the analysis, while there is one-way causality from economic growth to renewable energy consumption in Czechia; from renewable energy to economic growth in Bulgaria.

Ito (2017) reviewed the relationship between renewable and non-renewable energy consumption and economic growth in developed countries. In these countries, non-renewable energy consumption and economic growth increase CO_2 emissions, while renewable energy consumption reduces emissions. It is explained that there is a negative relationship between renewable energy consumption and economic growth.

The relationship between CO_2 emissions, renewable energy, and economic growth in twenty-four Asian countries was researched by Lu (2017). All three variables are cointegrated in the long run in Asian countries. Again, for analysis results, considering country-specific coefficients, CO_2 emissions affected renewable energy consumption in six countries negatively and in six countries positively; there also was an insignificant effect in the remaining countries. At the same time, economic growth and renewable energy consumption are positively related in seven countries, negatively in two countries, and insignificantly in other countries. According to the causality result, bidirectional causality is seen between renewable energy and CO_2 emissions and economic growth, while there is one-way causality from economic growth to CO_2 emissions.

Another study was performed by Dogan and Ozturk (2017); the study is about the relationship between real GDP and renewable and non-renewable energy consumption in the USA. They determined a long-run relationship between carbon dioxide emissions, GDP, and the USA's renewable and non-renewable energy consumption. It was emphasized in the study that increases in the use of renewable energy negatively affect emission levels; it also increases non-renewable energy consumption and increases air pollution. Therefore, CO_2 emissions affect GDP positively, and the EKC hypothesis is not valid in the USA.

The relationship between renewable energy consumption and economic growth in Germany was analyzed by Rafindadi and Ozturk (2017); for results, there is a bidirectional causality relationship between the series in the long run.

Demir and Gozgor (2018) used unit root tests to review the effect of renewable energy consumption on CO_2 emissions in fifty-four developing countries. According to the findings, renewable energy sources permanently affect CO_2 emissions in only nine countries.

Kahia et al. (2019) examined the relationship between renewable energy, FDI economic growth, and CO_2 emissions in the Middle East and African countries. Besides other study results, it is highlighted that there is bidirectional causality between CO_2 emissions, renewable energy consumption, and GDP.

Toumi and Toumi (2019) asymmetrically analyzed the relationship between renewable energy, CO_2 emissions, and GDP in Saudi Arabia. They found no causality from economic growth to CO_2 emissions and positive and negative components of renewable energy in the short and long term; however, there is one-way causality from the negative and positive components of CO_2 emissions and renewable energy to economic growth in the long run.

Shahbaz et al. (2020) examined the effect of renewable energy consumption on economic growth. They determined that GDP, renewable energy, non-renewable energy, labor, and capital are related in the long run. Furthermore, renewable and non-renewable energy consumption positively and significantly affect economic growth. They also observed a bidirectional causality between renewable energy consumption and economic growth.

Acheampong et al. (2021) conducted research in Sub-Saharan African countries. They determined that the institutional structure does not affect carbon emissions, renewable energy, and economic growth, while there is bidirectional causality between economic growth and renewable energy. Moreover, there is no causality between carbon emissions and renewable energy, while there is one-way causality from economic growth to carbon emissions.

Dimitriadis et al. (2021) analyzed the relationship between renewable and non-renewable energy, CO_2 emissions, and economic growth in developing countries. They found a positive relationship from economic growth to CO_2 emissions and fossil fuels and a negative relationship from renewable energy to CO_2 emissions in the long term.

Çelik (2021) surveyed to review the relationship between renewable energy production and employment in the USA. There was found no causality relationship between renewable energy production and employment. According to the author, the reason for the lack of a causal relationship between renewable energy production and employment is insufficient renewable energy consumption in the USA (Çelik, 2021:13053).

Çıtak et al. (2021) asymmetrically reviewed the effects of renewable energy and natural gas use on CO_2 emissions in states in the USA. The results varied by country. Nevertheless, long-term positive causality was seen between renewable energy, natural gas consumption, and carbon dioxide emissions.

Lei et al. (2022) examined the relationship between energy efficiency, renewable energy, and CO_2 emissions in China. As a result, energy efficiency and GDP are positive on CO_2 emissions in the short and long term in China; renewable energy consumption and internet use have an insignificant effect on the same issue. However, internet use and renewable energy consumption negatively affect emissions in the short term. The positive component of renewable energy consumption negatively affects CO_2 emissions, while the positive shock of renewable energy consumption positively affects emissions. It is expressed that the negative trend in renewable energy consumption in China increases CO_2 emissions.

Zuhal (2022) analyzed the long-run relationship between CO_2 emissions and economic growth in G-20 countries. According to the country-specific results, the long-term coefficients between the variables were positive but insignificant in the USA.

Balsalobre-Lorente et al. (2023a) examined the effects of economic complexity, globalization, and renewable energy consumption on CO_2 emissions in European countries. The study stated a long-term relationship exists between economic complexity, globalization, renewable energy consumption, and CO_2 emissions. The study emphasized a negative relationship between renewable energy consumption and CO_2 emissions and that renewable energy is a major factor in reducing emissions.

Abban et al. (2023) conducted a spatial analysis of the impact of renewable energy consumption and patents on environmental quality in twenty-nine European countries. The study reports that environmental regulations across European countries are mutually influential. It also reveals a negative correlation between renewable energy consumption and CO_2 emissions. The authors highlight the potential of renewable energy sources in mitigating global warming and climate change.

Balsalobre-Lorente et al. (2023b) examined the impact of economic complexity, foreign direct investment, and renewable energy consumption on CO_2 emissions in BRICS countries. It is stated that economic growth has a CO_2 effect in the short run, but this effect is neutralized in the long run. It is emphasized that foreign direct investments positively affect CO_2 emissions, while renewable energy consumption is negatively related. It is recommended to reduce the use of environmental pollutants and increase the use of renewable energy sources.

Chu et al. (2023) examined the impact of the informal economy, environmental regulations, CO_2 emissions, and oil prices on renewable energy consumption in high and middle-income countries. The study revealed a positive relationship between CO_2 emissions and renewable energy in high-income countries and a negative relationship in middle-income countries. At the same time, no relationship was found between GDP and renewable energy consumption in middle-income countries. Renewable energy consumption is the main argument for reducing carbon emissions and achieving energy efficiency.

In literature, CO_2 emissions, renewable energy, and economic growth have been studied among different country groups. The results indicate varying relationships between the three variables: some studies found no causal relationship (Payne, 2009; Bhattacharya et al., 2016), others found a unidirectional relationship (Vidyarthi, 2014; Dogan & Ozturk, 2017; Demir & Gozgor, 2018), and some found a bidirectional relationship (Apergis & Payne, 2010; Kahia et al., (2019). Possible reasons for variations in findings may include analyzing countries with differing structural, institutional, and cultural characteristics, using different estimation methods, and covering different years. This study aims to reveal the shortcomings of previous research by using time series analysis. By doing so, it eliminates the differences between countries. Additionally, it uses monthly data instead of annual data to capture both monthly fluctuations and breakdowns of changes in periodic components. The study employs the Spectral Causality Analysis method, which tests the causality relationship between periodic components in the short and long term.

Therefore, this study reviewed the relationship between renewable energy consumption, CO_2 emissions, and economic growth with monthly data for the 1973:M01-2022:M06 in the USA. The relationship between CO_2 emissions, economic growth, and income in the literature was also discussed within the framework of the EKC hypothesis. This study did not test the EKC hypothesis, but the relationship between CO_2 emissions, renewable energy consumption, and economic growth was scrutinized. Again, we, thanks to this study, aim to contribute to the literature in different ways. First, since Spectral causality analysis works with monthly data, it provides an opportunity to examine the relationship between the series in detail. It also helps to determine whether the relationship between the series is permanent or temporary. This paper symmetrically and asymmetrically tested this method. The causality relationship between the variables' positive and negative components in detail allows us to examine the relation in detail. Since renewable energy consumption is of special importance in terms of CO_2 emissions and economic growth, in addition to all these, the purpose was to form the basis for studies on other developed and developing countries.

3 Data and methodology

We employ monthly data for the period 1973:M01-2022:M06, the most recent for detailed analysis in the USA. Table 1 shows the data and sources.

In the study, the total industrial production index of the USA was employed to represent economic growth. Following the literature, we used the industrial production index to represent economic growth because GDP data are not measured monthly. CO_2 emissions, among the greenhouse gases that affect global warming, are at the fore and preferred because of their extensive use in literature. The total renewable energy consumption was preferred as another variable. Most studies in the literature test the validity of the EKC hypothesis. Since the EKC hypothesis was not tested in the USA, we only examined the causal relationship between the relevant variables and did not use the square of the industrial production index.

3.1 Empirical methodology

The paper examines the relationship between renewable energy, CO_2 emissions, and economic growth by Spectral Causality Analysis developed by Breitung and Candelon (2006). The variability in a time series into its periodic components is separated by spectral causality analysis, and it also identifies the relatively more important frequencies that affect the fluctuations in these variables. In addition, it helps to give meaning to the causal relationship between the variables as short-term or long-term (Tastan, 2015). The strength/power and direction of causality between variables may be different for the short-term and long-term. Thanks to this method, besides the direction of causality, we can determine whether the existence of causality is frequency dependent and the exact lag length regardless of the causality direction (Fromentin & Tadjeddine, 2020). This test can be easily generalized to analyze cointegration relationships and higher dimensional data (Breitung & Candelon, 2006). If we assume that Breitung and Candelon (2006) $d_{max} > 0$, test regression is expressed as follows (Tastan, 2015):

$$x_t = c_1 + \sum_{j=1}^{p} \alpha_j x_{t-j} + \sum_{j=1}^{p} \beta_j y_{t-j} + \sum_{k=p+1}^{p+d_{\max}} \alpha_k x_{t-k} + \sum_{k=p+1}^{p+d_{\max}} \beta_k y_{t-k} + e_t$$

H_0: $M_{y \to x}(\omega) = 0$ formula is written as "*Y is not the reason for X*".

The asymmetric spectral causality test is another method used in the study. Bahmani-Oskooee et al. (2016) conducted a study and expressed that the basic assumption in the traditional Granger causality test is that the causal effects of positive and negative shocks

Table 1 Data and sources

Variables	Definitions	Sources
Economic Growth (ECG)	USA, Total Industrial Production Index, (seasonally adjusted 2017 = 100)	Federal Reserve Economic Data
CO_2 Emissions (CDX)	Total CO_2 Emissions (Million Metric Tons)	US Energy Information Administration
Renewable energy (RWE)	Total Renewable Energy Consumption (Trillion Btu)	US Energy Information Administration

are symmetrical. However, this assumption is restrictive to their findings because economic agents such as investors or consumers respond differently to negative shocks than positive ones. For example, according to Hatemi-J (2012), people react differently to a positive shock than a negative shock in financial markets. So, analyzing the positive and negative shocks separately within the causal relationship between the variables is important.

$$y_{1t} = y_{1t-1} + \epsilon_{1t} = y_{10} + \sum_{i=1}^{t} \epsilon_{1i}$$

$$y_{2t} = y_{2t-1} + \epsilon_{2t} = y_{20} + \sum_{i=1}^{t} \epsilon_{1i}$$

Positive and negative shocks are defined as follows (Hatemi-J, 2012) $\epsilon_{1i}^{+} = \max(\epsilon_{1i}, 0)$ $\epsilon_{2i}^{+} = \max(\epsilon_{2i}, 0)$ and $\epsilon_{1i}^{-} = \max(\epsilon_{1i}, 0)\epsilon_{2i}^{-} = \max(\epsilon_{2i}, 0)$.

$M_{x_t^+ \to y_t^+}(\omega) = 0$ H_0 hypothesis in the Asymmetric Spectral Causality test is established as ''Y^+ is not the reason for X^+'' (Bahmani-Oskooee et al., 2016). The null hypothesis is also established for negative components.

4 Empirical findings and discussions

First, unit root tests were performed as the control mechanism for the stationarity of the series. In addition to the first-generation ADF and PP unit root tests, ZA structural breaks were applied. Table 2 presents the unit root test results.

According to the ADF test, the constant and trend of ECG and the constant of RWE contain a unit root. However, it is understood as the result of these series's PP and ZA unit root tests that they do not contain a unit root. So, the series was accepted as stationary. There is no unit root in CDX, ADF, PP, and ZA tests. At the end of the analyses, it is understood that the level states of the series are suitable for causality analysis. The series was divided into positive and negative components to perform asymmetric causality in the study. Unit root control was carried out for positive and negative components. The components were not stationary in level in the ADF and PP tests but constant in the ZA test and stationary in the trend. It is decided that the components are stationary at the level because the ZA test considers structural breaks. Therefore, the analysis used the level values of the components.

4.1 Symmetric spectral granger causality test

In the first stage of the study, Spectral causality analysis was applied using the variables' level state. Then, as is emphasized in the study belongs to Tastan (2015), the appropriate lag length for analysis was determined based on AIC (Akaike information criterion), HQIC (Hannan–Quinn information criterion), and SBIC (Schwarz–Bayesian information criterion). Figures 4, 5 and 6 show the Symmetric Spectral Granger causality analysis results.

The opportunity of examining the causality relationship between the variables in the short and long term is provided by spectral causality analysis. The analysis specifies frequency lengths as 0.5 for the long term and 2.5 for the short term. In other words, 0.5 is a

Table 2 Unit root test results

Variables	Lags	ADF		Lags	PP		Lags	ZA	
		Constant	Trend		Constant	Trend		Constant	Trend
ECG	2	-0.659784 [0.8541]	-2.700688 [0.2367]	Constant:8 Trend:11	-3.248774 [0.0178]**	-13.27587 [0.0000]*	11	-4.171102 [0.001250]*	-4.722312 [0.001468]*
CDX	7	-2.900058 [0.0459]**	-3.048432 [0.1200]	Constant: 2 Trend: 4	-8.143326 [0.0000]*	-8.348532 [0.0000]*	14	-3.198904 [0.001504]*	-4.364271 [0.009398]*
RWE	4	-1.951884 [0.3084]	-3.532251 [0.0369]*	Constant:4 Trend:8	-2.622177 [0.0890]***	-3.626945 [0.0284]**	17	-1.703915 [0.081784]***	-4.605589 [0.000177]*

Note * 1%, ** 5%, and *** 10% are significant. Lag lengths are automatically determined according to the AIC. It was automatically determined based on Newey-West Bandwidth in the PP test. [ ] shows p-value permanent causality, while 2.5 is temporary causality. While the long-term refers to periods longer than one year, the short-term refers to periods of approximately three months (Aydin et al., 2022:123). Between CDX and ECG demonstrated in Fig. 4, there is causality at a 10% significance level in the frequency ranges [1.59, 1.94], [2.27, 2.48], and [2.64, 3.14] from CDX to ECG. It is seen when looking at causality from ECG to CDX in Fig. 5 that there is causality at a 10% significance level in the frequency ranges [0.01, 0.97], [1.17, 1.53], and [1.94, 2.19]. We can mention a persistent bidirectional causality between economic growth and CO_2 emissions in the USA. These results are consistent with Menyah and Wolde-Rufael (2010), Akpan and Akpan (2012), Kahia et al. (2019), and Çıtak et al. (2021).

In Fig. 5, there is causality from RWE to ECG at frequency ranges [0.52, 0.84] and [1.85, 2.53], and from ECG to RWE at the frequency ranges [1.02, 1.77] and [2.53, 3.14]. This presents a permanent bidirectional causality between renewable energy consumption and economic growth in the USA. These results are consistent with Apergis and Payne (2010), Sebri and Ben-Salha (2014), Akay et al. (2015), Lu (2017), Rafindadi and Ozturk (2017), Kahia et al. (2019), Shahbaz et al. (2020) and inconsistent with the findings of Chu et al. (2023).

In Fig. 6, there is causality from RWE to CDX in the frequency ranges [0.39, 0.68], [0.88, 1.04], [1.70, 2.09] and [2.49, 3.14], and from CDX to RWE in the frequency ranges [0.10, 0.40], [0.52, 0.73], [0.93, 1.12], [1.26, 2.27] and [2.51, 3.06]. While there is bidirectional causality between CO_2 emissions and renewable energy in the USA, both in the short and long run, permanent causality is observed between the variables in the long run. These results are consistent with Bento and Moutinho (2016), Lu (2017), Kahia et al. (2019), and Balsalobre-Lorente et al. (2023).

4.2 Asymmetric spectral granger causality test

In addition to examining the relationship between the variables symmetrically in the study, Hatemi-J (2012) also examined this relationship asymmetrically. Variables are divided into positive and negative components; classified as follows; CDX (PCDX: Positive CDX, NCDX: Negative CDX), ECG (PECG: Positive ECG, NECG: Negative ECG), and RWE (PRWE: Positive RWE, NRWE: Negative RWE). The unit root test was applied after the series was separated into its components; according to the findings, the series are suitable for causality analysis according to the ZA test. Figures 7, 8 and 9 present Asymmetric Spectral Granger Causality results.

Considering Asymmetric Spectral Granger Causality results, there is causality from PCDX to PECG in [0.01, 0.42] and [1.60, 1.91] frequency ranges; from PECG to PCDX in [1.28, 1.66] and [2.35, 2.76] frequency ranges. Permanent causality is found from PCDX to PECG, whereas transient causality is observed in the opposite case. The positive shock in economic growth in the USA temporarily increased CO_2 emissions. The causality is found from NCDX to NECG [0.03, 0.51] in the frequency ranges and from NECG to NCDX in the frequency ranges [0.07, 0.56], [1.33, 1.43] and [2.43, 2.57]. There is permanent bidirectional causality between CO_2 emissions and negative shocks to economic growth. These results agree with Vidyarthi, 2013), 2014); Dimitriadis et al. (2021); Menyah and Wolde-Rufael (2010); Akpan and Akpan (2012); Kahia et al. (2019); Çıtak et al. (2021); Balsalobre-Lorente et al. (2023b).

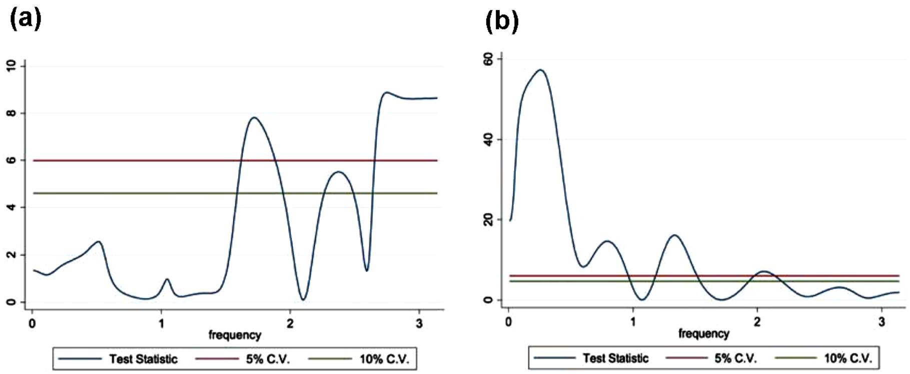

Fig. 4 ECG and CDX symmetric spectral granger causality analysis results **a** from CDX to ECG **b** from ECG to CDX. *Note* Lag length is determined as 15 based on AIC, HQIC, and SBIC

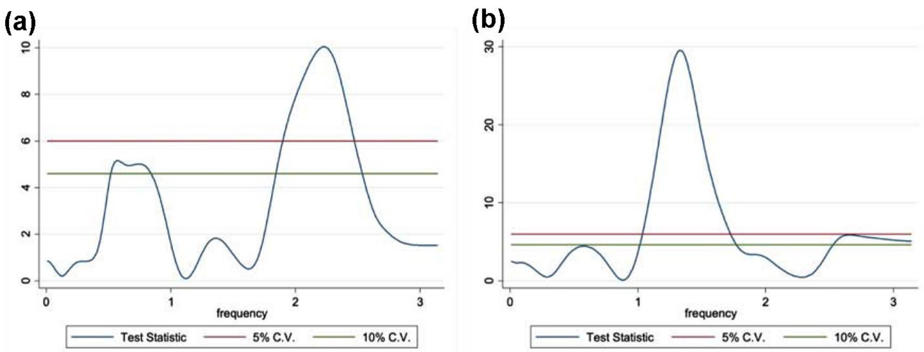

Fig. 5 RWE and ECG symmetric spectral granger test results. **a** from RWE to ECG **b** from ECG to RWE. *Note* Lag length is determined as 13 based on HQIC and SBIC

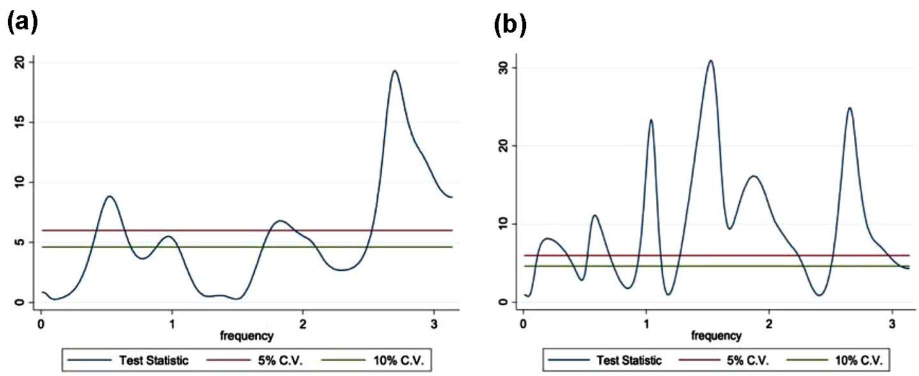

Fig. 6 RWE and CDX symmetric spectral granger test results **a** from RWE to CDX **b** from CDX to RWE. *Note* Lag length is determined as 18 based on AIC and HQIC

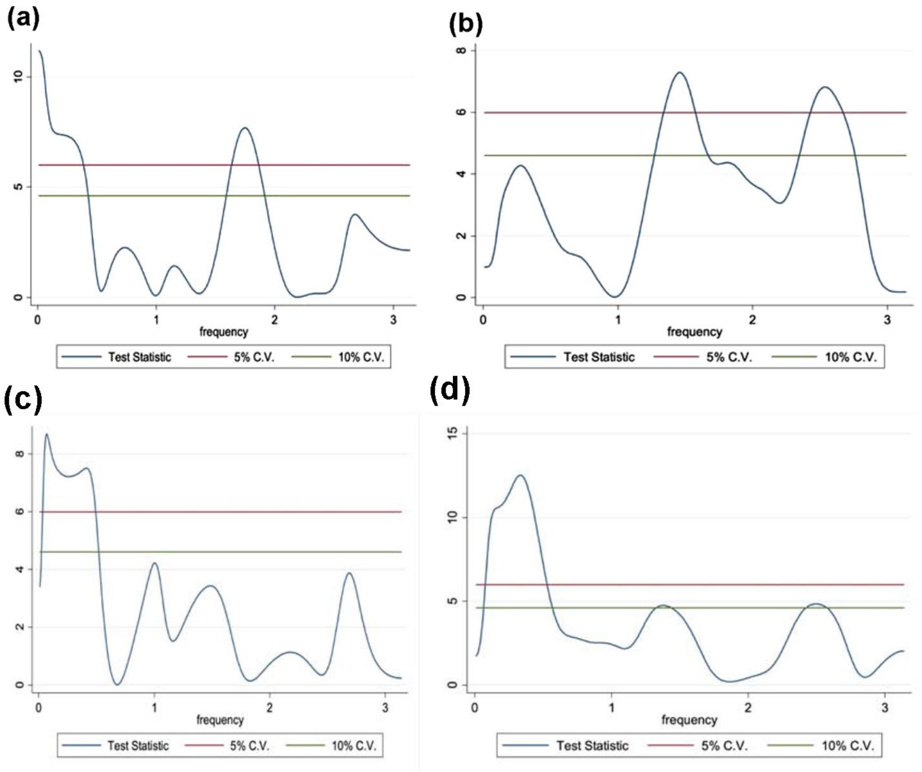

Fig. 7 CDX and ECG asymmetric spectral granger causality results **a** from PCDX to PECG **b** from PECG to PCDX. *Note* Lag length is determined as 14 based on AIC and HQIC (**a**, **b**); **c** from NCDX to NECG **d** from NECG to NCDX. *Note* Lag length is determined as 13 based on HQIC and SBIC (**c**, **d**)

A permanent causality exists from PRWE to PECG in the frequency ranges [0.01, 0.09] and [1.85, 2.48] and [1.96, 2.08], while there is also a permanent causality from PECG to PRWE in [0.01, 1.87] and [2.07, 2.42]. There is a permanent causality from NRWE to NECG in the frequency ranges [0.01, 0.08], [0.46, 0.95], and [1.74, 2.57], while there is a permanent causality from NECG to NRWE in the frequency ranges [0.71, 1.49] and [2.44, 3.14]. The results demonstrate a permanent bidirectional causality between positive and negative shocks of renewable energy consumption and economic growth in the United States. These results agree with Apergis & Payne, 2010, Sebri & Ben-Salha, 2014, Akay et al., 2015, Lu, 2017, Rafindadi & Ozturk, 2017, Kahia et al., 2019, and Shahbaz et al., 2020.

There is permanent bidirectional causality from PRWE to PCDX in the frequency ranges [0.48, 0.92], [1.08, 1.28], [1.57, 1.84], and [2.03, 2.78] while there is also permanent bidirectional causality from PCDX to PRWE in the frequency ranges [0.46, 1.13], [1.34, 1.63] ve [1.83, 3.14]. There is permanent bidirectional causality from NRWE to NCDX in the frequency ranges [0.05, 0.20], [0.51, 0.95] ve [2.33, 3.14], and permanent bidirectional causality from NCDX to NRWE in the frequency ranges [0.09, 0.13], [0.47, 1.20], [1.37, 1.78], and [2.04, 3.14]. For findings, there is a permanent bidirectional causality between the positive and negative shocks of CO_2 emissions and renewable energy consumption in the USA.

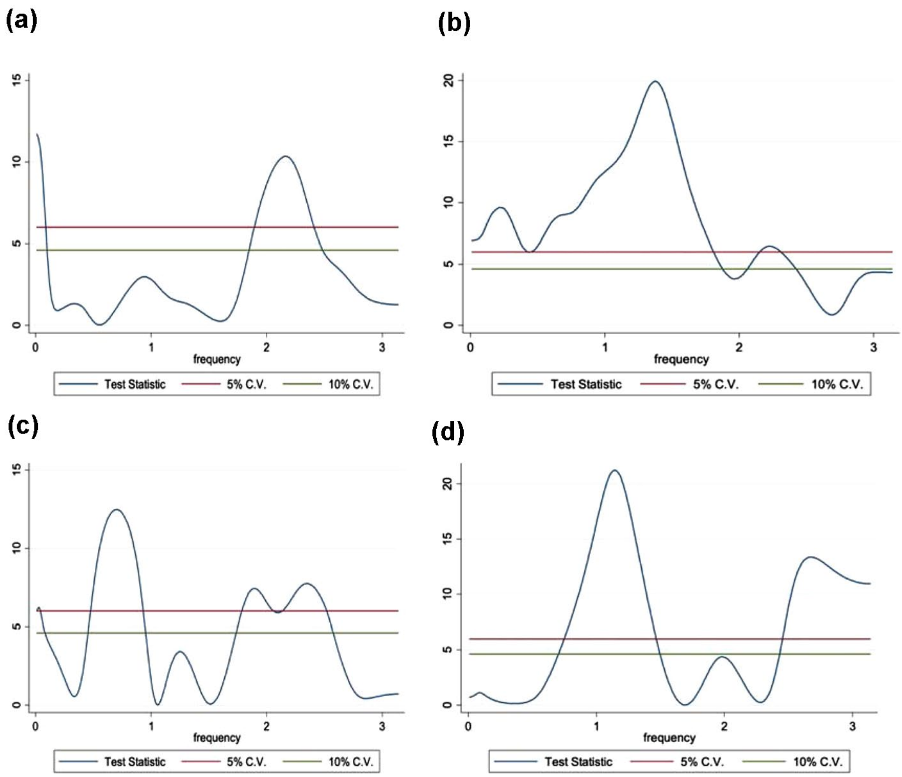

Fig. 8 RWE and ECG asymmetric spectral granger causality results **a** from PRWE to PECG **b** from PECG to PRWE. *Note* Lag length is determined as 13 based on HQIC and SBIC (**a**, **b**); **c** from NRWE to NECG **d** from NECG to NRWE. *Note* Lag length is determined as 13 based on HQIC and SBIC (**c**, **d**)

These findings agree with Bento and Moutinho (2016); Dogan and Ozturk (2017); Rafindadi and Ozturk (2017); Lu (2017) and; compatible with Kahia et al. (2019).

Figure 2 shows significant increases in renewable energy consumption sources, and Fig. 3 shows that renewable energy consumption is at a low level among the total energy consumption in the USA. However, renewable energy affects both economic growth and CO_2 emissions. Menyah and Wolde-Rufael (2010) highlight that renewable energy in the USA is not at a sufficient level to minimize emissions and, therefore, cannot reduce emissions. On the other hand, we have observed recently that renewable energy affects both economic growth and CO_2 emissions due to the increase in renewable energy types and usage areas. According to Çelik (2021), renewable energy consumption in the USA is not satisfying because there is no causal relationship between renewable energy production and employment. However, renewable energy is the cause of economic growth. Therefore, we can evaluate the study belonging to Çelik (2021); renewable energy is the cause of economic growth in the USA, but this growth is growth without employment. However, the relationship between renewable energy consumption, economic growth, and employment needs to be reviewed again. Dogan and Ozturk (2017) emphasize that increases in renewable energy use affect emission levels negatively. After all, it is vital to consider renewable

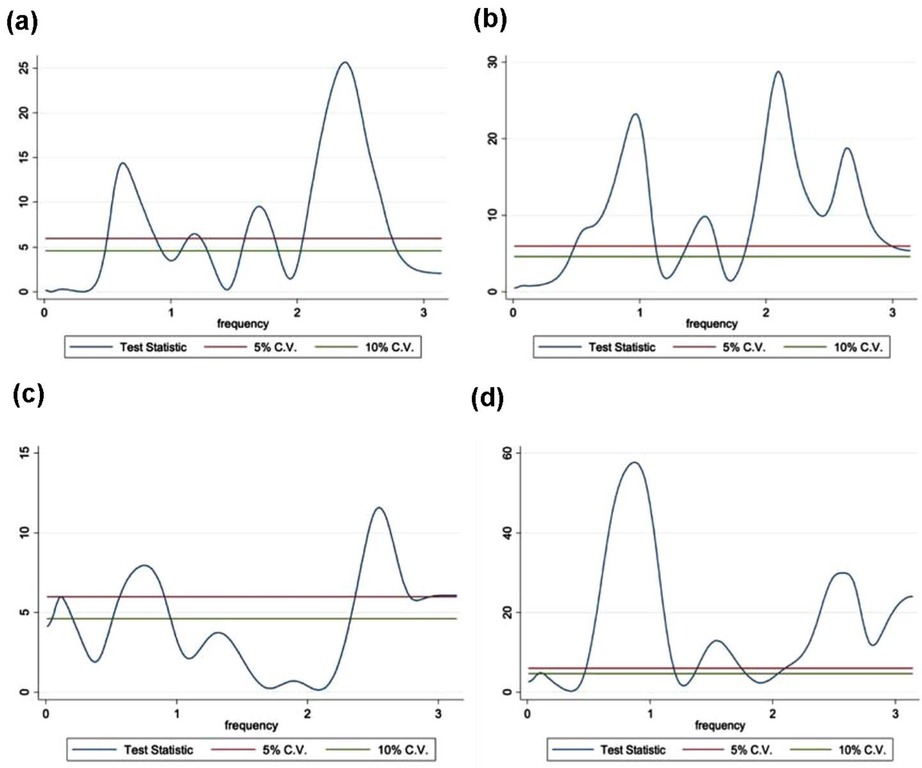

Fig. 9 RWE and CDX asymmetric spectral causality results **a** from PRWE to PCDX **b** from PCDX to PRWE. *Note* Lag length is determined as 15 based on AIC and HQIC (**a**, **b**); **c** from NRWE to NCDX **d** from NCDX to NRWE. *Note* Lag length is determined as 13 based on HQIC and SBIC (**c**, **d**)

energy consumption to minimize the USA's negative environmental pressures. Moreover, the number of green energy types should be increased, and their usage areas should be expanded at the same time.

Findings suggest that renewable energy consumption is essential to provide sustainable economic growth and increase environmental quality in the USA. Therefore, diversifying renewable energy sources with necessary green investments and projects and thus increasing the share of renewable energy in total energy consumption is necessary.

5 Conclusion and policy recommendations

Renewable energy consumption is essential in ensuring sustainable economic growth. At the same time, renewable energy consumption has the potential to reduce CO_2 emissions and contribute to the fight against global warming and climate change (Bento & Moutinho, 2016; Ito, 2017; Dogan & Ozturk, 2017; Toumi & Toumi, 2019; Dimitriadis et al., 2021; Lei et al., 2022). Various studies have been conducted to scrutinize the effects of this type of energy due to the importance of renewable energy. The majority of these studies are about country groups. Studies have emphasized the importance of examining the countries individually due to the heterogeneous structure of the countries (Dogan & Ozturk, 2017). The relationship between renewable energy consumption, CO_2 emissions, and economic growth in the USA in the 1973-January-2022-June period has been examined in light of these suggestions. Spectral Granger Causality analysis was applied symmetrically and asymmetrically in the study. At the end of the symmetric analysis, bidirectional causality was determined between CO_2 emissions, economic growth, and renewable energy consumption. Different results were obtained from the symmetric analysis as a result of the asymmetric analysis.

Regarding asymmetric analysis results, the relationship between positive and negative shocks differs permanently or temporarily. Therefore, this study reveals the importance of modeling negative and positive shocks separately by examining the relationship between variables. In this respect, this study contributes to asymmetric analyzes that are quite limited in the literature. There is a temporary causality between positive shocks of economic growth and CO_2 emissions in the US. At the same time, there is a permanent bidirectional causality between negative shocks of CO_2 emissions and negative shocks of economic growth. These results show that economic growth can be achieved with low CO_2 emissions. Governments should promote low-emission investments and projects while ensuring economic growth. The study recommends that countries increase energy efficiency to reduce CO2 emissions, support R&D efforts to develop more energy-efficient production processes, and increase public awareness of environmental protection. There is permanent bidirectional causality between the positive and negative components of economic growth and renewable energy consumption in the US. These results show the importance of renewable energy consumption. Using renewable energy is important in the struggle against global warming and climate change. At the same time, its causal relationship with economic growth points to an important opportunity. These findings suggest that renewable energy consumption can help address global warming and climate change without compromising economic growth. Economies should promote the necessary policies and projects to increase the share of renewable energy types among energy sources. The study found a permanent bidirectional causality between the positive and negative components of economic growth and renewable energy consumption. This result shows that economic growth and renewable energy consumption are closely related. Renewable energy resources play an essential role in realizing environmentally friendly economic growth. Initiatives to increase the share and diversity of renewable energy sources should be supported to ensure environmental sustainability and green growth in the US. Although these findings and policy recommendations are specific to the United States, they have important implications for other developed and developing countries. In this regard, it is important to evaluate the results obtained in the US for developing countries.

In conclusion, the paper reintroduces the importance of renewable energy consumption in increasing environmental quality and ensuring sustainable economic growth. In all countries, especially the USA, it is necessary to diversify renewable energy sources and increase their usage. The participation of developed countries, especially the USA, in global green initiatives and their support, may facilitate the fight against global warming. It would not be surprising if the successful results in developed countries spread to other countries. So, developed countries need to be role models for a greener world. In addition, renewable energy sources are important in ensuring a sustainable energy supply. Permanent solutions can be developed with green energy types today when a significant part of the world is in an energy supply crisis. It emphasizes the importance of increasing the share of renewable resources among energy sources to achieve economic growth and control environmental degradation.

This study used Symmetrical and Asymmetric Spectral Granger Causality models for the 1973M01-2022M06 in the USA. When new and larger datasets, different series, and current empirical models are obtained, this study can be replicated for both the USA and other developed and developing countries.

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Data availability EIA (2022) https://www.eia.gov/totalenergy/data/monthly/. FRED (2022) https://fred.stlouisfed.org/series/INDPRO.

Declarations

Ethical approval This study does not include research involving humans or other participants.

Informed consent Informed consent was obtained from all participants in the study.

Conflict of interest The authors do not have any conflicts of interest.

References

Abban, O. J., Xing, Y. H., Nuta, A. C., Nuta, F. M., Borah, P. S., Ofori, C., & Jing, Y. J. (2023). Policies for carbon-zero targets: Examining the spillover effects of renewable energy and patent applications on European environmental quality. *Energy Economics*, *126*(106954), 1–22. https://doi.org/10.1016/j.eneco.2023.106954.

Acheampong, A., Dzator, J., & Savage, D. (2021). Science Direct renewable energy, CO_2 emissions and economic growth in sub-saharan Africa: Does institutional quality matter? *Journal of Policy Modeling*, *43*, 1070–1093. https://doi.org/10.1016/j.jpolmod.2021.03.011.

Akay, E., Abdieva, R., & Oskonbaeva, Z. (2015). Yenilenebilir Enerji Tüketimi, İktisadi Büyüme ve Karbondioksit Emisyonu Arasındaki Nedensel İlişki: Orta Doğu ve Kuzey Afrika Ülkeleri Örneği. *International Conference On Eurasıan Economıes 2015*. Accessed November 28, 2022 https://www.avekon.org/proceedings/avekon06.pdf.

Akpan, G., & Akpan, U. (2012). Electricity consumption, carbon emissions and economic growth in Nigeria. *International Journal of Energy Economics and Policy, 2 (4)*:292–306. Accessed November 28, 2022 https://dergipark.org.tr/en/pub/ijeeep/issue/31902/350692?publisher=http-www-cag-edu-tr-ilhan-ozturk.

Alkhathlan, K., & Javid, M. (2013). Energy consumption, carbon emissions and economic growth in Saudi Arabia: An aggregate and disaggregate analysis. *Energy Policy*, *62*, 1525–1532. https://doi.org/10.1016/j.enpol.2013.07.068.

Alper, A., & Oguz, O. (2016). The role of renewable energy consumption in economic growth: Evidence from asymmetric causality. *Renewable and Sustainable Energy Reviews*, *60*, 953–959. https://doi.org/10.1016/j.rser.2016.01.123.

Apergis, N., & Payne, J. (2010). Renewable energy consumption and growth in Eurasia. *Energy Economics*, *32*, 1392–1397. https://doi.org/10.1016/j.eneco.2010.06.001.

Arı, A., & Zeren, F. (2011). CO2 Emisyonu ve Ekonomik Büyüme: Panel Veri Analizi. *Yönetim ve Ekonomi, 18 (2)*:37–47. Accessed November 28, 2022 https://dergipark.org.tr/tr/pub/yonveek/issue/13695/165744.

Aydin, M., Pata, U., & Inal, V. (2022). Economic policy uncertainty and stock prices in BRIC countries: Evidence from asymmetric frequency domain causality approach. *Applied Economic Analysis*, *30*(89), 114–131. https://doi.org/10.1108/AEA-12-2020-0172.

Bahmani-Oskooee, M., Chang, T., & Ranjbar, O. (2016). Asymmetric causality using frequency domain and time-frequency domain (wavelet) approaches. *Economic Modelling*, *56*, 66–78. https://doi.org/10.1016/j.econmod.2016.03.002.

Balsalobre-Lorente, D., Shahbaz, M., Roubaud, D., & Farhani, S. (2018). How economic growth, renewable electricity and natural resources contribute to CO2 emissions? Energy Policy 113, 356–367. https://doi.org/10.1016/j.enpol.2017.10.050.

Balsalobre-Lorente, D., Shahbaz, M., Murshed, M., & Nuta, F. M. (2023a). Environmental impact of globalization: The case of central and eastern European emerging economies. *Journal of Environmental Management*, *341*(118018), 1–13. https://doi.org/10.1016/j.jenvman.2023.118018.

Balsalobre-Lorente, D., Santos Parente, C., Leitao, N. C., & Cantos-Cantos, J. M. (2023b). The influence of economic complexity processes and renewable energy on CO2 emissions of BRICS. What about industry 4.0? *Resources Policy*, *82*(103547), 1–10. https://doi.org/10.1016/j.resourpol.2023.103547.

Bento, J., & Moutinho, V. (2016). C02 emissions, non-renewable and renevvable electricity production, economic growth, and international trade in Italy. *Renewable and Sustainable Energy Reviews*, *55*, 142–155. https://doi.org/10.1016/j.rser.2015.10.151.

Bhattacharya, M., Paramati, S., Ozturk, I., & Bhattacharya, S. (2016). The effect of renewable energy consumption on economic growth: Evidence from top 38 countries. *Applied Energy*, *162*, 733–741. https://doi.org/10.1016/j.apenergy.2015.10.104.

Bowden, N., & Payne, J. (2010). Sectoral analysis of the causal relationship between renewable and non-renewable energy consumption and real output in the US. *Energy Sources Part B: Economics Planning and Policy*, *5*(4), 400–408. https://doi.org/10.1080/15567240802534250.

Breitung, J., & Candelon, B. (2006). Testing for short- and long-run causality: A frequency-domain approach. *Journal of Econometrics*, *132*, 363–378. https://doi.org/10.1016/j.jeconom.2005.02.004.

Burnett, J., Bergstrom, J., & Wetzstein, M. (2013). Carbon dioxide emissions and economic growth in the U.S. *Journal of Policy Modeling*, *35*, 1014–1028. https://doi.org/10.1016/j.jpolmod.2013.08.001.

C2ES. *Renewable Energy*. Retrieved October 4, 2022 from https://www.c2es.org/content/renewable-energy/.

Çelik, O. (2021). Assessment of the relationship between renewable energy and employment of the United States of America: Empirical evidence from spectral Granger causality. *Environmental Science and Pollution Research*, *28*, 13047–13054. https://doi.org/10.1007/s11356-021-12414-x.

Chang, C. C. (2010). A multivariate causality test of carbon dioxide emissions, energy consumption and economic growth in China. *Applied Energy*, *87*, 3533–3537. https://doi.org/10.1016/j.apenergy.2010.05.004.

Chu, L. K., Doğan, B., Ghosh, S., & Shahbaz, M. (2023). The influence of shadow economy, environmental policies and geopolitical risk on renewable energy: A comparison of high- and middle-income countries. *Journal of Environmental Management*, *342*(118122), 1–15. https://doi.org/10.1016/j.jenvman.2023.118122.

Çıtak, F., Uslu, H., Batmaz, O., & Hoş, S. (2021). Do renewable energy and natural gas consumption mitigate CO2 emissions in the USA? New insights from NARDL approach. *Environmental Science and Pollution Research*, *28*, 63739–63750. https://doi.org/10.1007/s11356-020-11094-3.

Demir, E., & Gozgor, G. (2018). Are shocks to renewable energy consumption permanent or temporary? Evidence from 54 developing and developed countries. *Environmental Science and Pollution Research*, *25*, 3785–3792. https://doi.org/10.1007/s11356-017-0801-9.

Dimitriadis, D., Katrakilidis, C., & Karakotsios, A. (2021). Investigating the dynamic linkages among carbon dioxide emissions, economic growth, and renewable and non-renewable energy consumption: Evidence from developing countries. *Environmental Science and Pollution Research*, *28*, 40917–40928. https://doi.org/10.1007/s11356-021-13613-2.

Dogan, E. (2016). Analyzing the linkage between renewable and non-renewable energy consumption and economic growth by considering structural break in time-series data. *Renewable Energy*, *99*, 1126–1136. https://doi.org/10.1016/j.renene.2016.07.078.

Dogan, E., & Ozturk, I. (2017). The influence of renewable and non-renewable energy consumption and real income on CO2 emissions in the USA: Evidence from structural break tests. *Environmental Science and Pollution Research*, *24*, 10846–10854. https://doi.org/10.1007/s11356-017-8786-y.

Dogan, E., & Seker, F. (2016). An investigation on the determinants of carbon emissions for OECD countries: Empirical evidence from panel models robust to heterogeneity and cross-sectional dependence. *Environmental Science and Pollution Research*, *23*, 14646–14655. https://doi.org/10.1007/s11356-016-6632-2.

EIA. (2022). *Renewable Energy*. Accessed October 04, 2022 https://www.eia.gov/totalenergy/data/monthly/pdf/sec10.pdf.

EPA. (2022). *Global Greenhouse Gas Emissions Data*. Greenhouse Gas Emissions. Retrieved July 25, 2022 from https://www.epa.gov/ghgemissions/global-greenhouse-gas-emissions-data.

Ewing, B., Sari, R., & Soytas, U. (2007). Disaggregate energy consumption and industrial output in the United States. *Energy Policy*, *35*, 1274–1281. https://doi.org/10.1016/j.enpol.2006.03.012.

FRED. (2022). *Federal Reserve Economic Data*. Retrieved October 4, 2022 from https://fred.stlouisfed.org/.

Fromentin, V., & Tadjeddine, Y. (2020). Cross-border workers and financial instability: A frequency domain causality analysis applied to the Luxembourg financial centre. *Applied Economics Letters*, *27*(4), 280–285. https://doi.org/10.1080/13504851.2019.1613496.

Hatemi-J, A. (2012). Asymmetric causality tests with an application. *Empir Econ*, *43*, 447–456. https://doi.org/10.1007/s00181-011-0484-x.

Ito, K. (2017). CO2 emissions, renewable and non-renewable energy consumption, and economic growth: Evidence from panel data for developing countries. *International Economics*, *151*, 1–6. https://doi.org/10.1016/j.inteco.2017.02.001.

Kahia, M., Jebli, M., & Belloumi, M. (2019). Analysis of the impact of renewable energy consumption and economic growth on carbon dioxide emissions in 12 MENA countries. *Clean Technologies and Environmental Policy*, *21*, 871–885. https://doi.org/10.1007/s10098-019-01676-2.

Lei, W., Xie, Y., Hafeez, M., & Ullah, S. (2022). Assessing the dynamic linkage between energy efficiency, renewable energy consumption, and CO2 emissions in China. *Environmental Science and Pollution Research*, *29*, 19540–19552. https://doi.org/10.1007/s11356-021-17145-7.

Lu, W. C. (2017). Renewable energy, carbon emissions, and economic growth in 24 Asian countries: Evidence from panel cointegration analysis. *Environmental Science and Pollution Research*, *24*, 26006–26015. https://doi.org/10.1007/s11356-017-0259-9.

Menyah, K., & Wolde-Rufael, Y. (2010). CO2 emissions, nuclear energy, renewable energy and economic growth in the US. *Energy Policy*, *38*, 2911–2915. https://doi.org/10.1016/j.enpol.2010.01.024.

Narayan, P., & Narayan, S. (2010). Carbon dioxide emissions and economic growth: Panel data evidence from developing countries. *Energy Policy*, *38*, 661–666. https://doi.org/10.1016/j.enpol.2009.09.005.

Payne, J. (2009). On the dynamics of energy consumption and output in the US. *Applied Energy*, *86*, 575–577. https://doi.org/10.1016/j.apenergy.2008.07.003.

Rafindadi, A., & Ozturk, I. (2017). Impacts of renewable energy consumption on the German economic growth: Evidence from combined cointegration test. *Renewable and Sustainable Energy Reviews*, *75*, 1130–1141. https://doi.org/10.1016/j.rser.2016.11.093.

Ritchie, H., & Roser, M. (2020). *$CO_2$and Greenhouse Gas Emissions*. OurWorldInData.org. Retrieved October 4, 2022 from https://ourworldindata.org/co2/country/united-states?country=~USA#what-are-the-country-s-annual-co2-emissions.

Sebri, M., & Ben-Salha, O. (2014). On the causal dynamics between economic growth, renewable energy consumption, CO2 emissions and trade openness: Fresh evidence from BRICS countries. *Renewable and Sustainable Energy Reviews*, *39*, 14–23. https://doi.org/10.1016/j.rser.2014.07.033.

Shahbaz, M., Raghutla, C., Chittedi, K., Jiao, Z., & Vo, X. (2020). The effect of renewable energy consumption on economic growth: Evidence from the renewable energy country attractive index. *Energy*, *207*, 118162. https://doi.org/10.1016/j.energy.2020.118162.

Soytaş, U., & Sarı, R. (2009). Energy consumption, economic growth, and carbon emissions: Challenges faced by an EU candidate member. *Ecological Economics 6 (8)*: 1667–1675. https://doi.org/10.1016/j.ecolecon.2007.06.014.

Tastan, H. (2015). Testing for spectral Granger causality. *The Stata Journal*, *15*(4), 1157–1166. https://doi.org/10.1177/1536867X1501500411.

Toumi, S., & Toumi, H. (2019). Asymmetric causality among renewable energy consumption, CO2 emissions, and economic growth in KSA: Evidence from a non-linear ARDL model. *Environmental Science and Pollution Research*, *26*, 16145–16156. https://doi.org/10.1007/s11356-019-04955-z.

U.S. Energy Information Administration. (2022). *Total Energy*: Retrieved October 4, 2022 from https://www.eia.gov/totalenergy/data/monthly/.

Vidyarthi, H. (2013). Energy consumption, carbon emissions and economic growth in India. *World Journal of Science Technology and Sustainable Development*, *10*(4), 278–287. https://doi.org/10.1108/WJSTSD-07-2013-0024.

Vidyarthi, H. (2014). An econometric study of energy consumption, carbon emissions and economic growth in South Asia: 1972–2009. *World Journal of Science Technology and Sustainable Development*, *11*(3), 182–195. https://doi.org/10.1108/WJSTSD-08-2013-0037.

Yang, G., Sun, T., Wang, J., & Li, X. (2015). Modeling the nexus between carbondioxide emissions and economic growth. *Energy Policy*, *86*, 104–117. https://doi.org/10.1016/j.enpol.2015.06.031.

Zhang, W., Hu, J., & Hao, J. (2022). Proportion of renewable energy consumption and economic growth: Theoretical and empirical analysis. *Environmental Science and Pollution Research*, *29*, 28884–28895. https://doi.org/10.1007/s11356-022-18500-y.

Zuhal, M. (2022). The Effects of Green Innovation on Environmental Quality and Economic Growth: An Investigation for G-20 Countries. In: P. Hayaloğlu, & S. Artan, Current Debates On Sustainable Development (pp. 53-72). UK: IJOPEC Publication. Retrieved from http://www.ijopec.co.uk/wp-content/uploads/2022/04/2022_02_ISBN_978-1-913809-23-2.pdf.