The relationship between renewable energy consumption, carbon emissions, output, and export in industrial and agricultural sectors: evidence from China

Yuanyuan Hao

Abstract
This paper examines the long-term and short-term relationships between renewable energy consumption, output and export, and CO₂ emissions in China over the period 1990–2020 from the perspective of industry and agriculture using econometric methods. The results of the study found that there is a long-run relationship and there is a causality between these variables, indicating that renewable energy consumption, output, and export are related to CO₂ emissions. Specifically, from a long-term perspective, the results of co-integration and causality reveal that there is a two-way causal relationship between renewable energy consumption, output, export, and CO₂ emissions, supporting the feedback hypothesis; that is, output and export have an adverse impact on the environment, while renewable energy consumption has a favorable impact on the environment. In the short term, there is a direct or indirect one-way causal relationship between export, CO₂ emissions, and renewable energy consumption, which supports the growth hypothesis. The impulse response analysis has further verified the causality test results and supported this hypothesis. However, there is a strong negative correlation between industrial and agricultural export and renewable energy consumption, which will cause the use of renewable energy to fail to meet the peak demand for industrial and agricultural export in the short term. Conversely, large amounts of fossil fuels will be consumed to meet output and export demand. Therefore, on the road to social, economic, and environmental sustainability, it is necessary to consider the impact of economic growth and energy consumption (renewable and non-renewable energy) of related industries on CO₂ emissions, which also provides a strong basis for the development and reduction of China’s renewable energy and the long-term implementation of the emission control policy.

Keywords Renewable energy consumption · Output and export · CO₂ emissions · Cointegration test · Causality test · Impulse response

Introduction
Energy is the basic support for the development of modern society and the foundation for human survival. With the development of the global economy and population growth, the demand for energy in human society has also increased substantially (Xu et al. 2019). In addition, due to its non-renewability, fossil energy, which is the main source of energy for human society, is gradually facing the danger of exhaustion with the consumption of human life and social development, and it will cause serious environmental problems because of long-term dependence and use of traditional fossil energy (Apergis and Payne 2012; Belaïd and Zrelli 2019). For example, the waste generated by the burning of fossil energy will cause the increase of harmful substances such as sulfides, nitrides, and soot in the air, causing air pollution; at the same time, the increase in greenhouse gas emissions (carbon dioxide (CO₂), nitrous oxide (N₂O), freon, methane (CH₄), etc.) will lead to faster global warming, melting of glaciers, rising sea levels, and frequent occurrence of extreme weathers, seriously threatening human production and life (Aydin, 2019). However, in order to obtain sufficient energy resources, over-exploitation of mining areas has caused issues such as geological disasters, soil erosion, and groundwater pollution. In fact, relying on fossil
energy has not only caused human beings to face the danger of energy shortages, but also brought about increasing threats caused by environmental problems to human daily life and health for life, while renewable energy is regarded as an important alternative energy source by countries all over the world, trying to use renewable energy will realize the sustainable development of human society to ensure complementarity between economic and environmental development (Chen et al. 2020; Murshed et al. 2021b). Although, non-renewable energy sources (fossil fuels) play an important role in facilitating economic growth of most countries, especially developing countries (Murshed et al. 2021d). However, the excessive consumption of non-renewable energy has gradually reduced the carrying capacity of the ecological environment on which mankind depends, which has seriously hindered the sustainable development of the economies of all countries in the world (Zafar et al. 2019; Adedoyin et al. 2020). As countries around the world vigorously promote energy-saving and emission-reduction measures, the renewable energy industry, which is clean and pollution-free, has attracted more and more attention from governments, enterprises, and scholars (Chen et al. 2019; Zhang et al. 2021). In addition to improving the environment, the renewable energy industry involves a wide range of fields, which can vigorously drive the development of related industries, can significantly increase the number of new jobs, and is also an important measure to achieve poverty alleviation, a positive impact on macroeconomic development, and an essential driving force to achieve the transformation of economic development.

China surpassed Japan to become the world’s second largest economy in 2010. However, China’s carbon emissions and energy consumption have surged, and the conflict between energy consumption, carbon emissions, and economic growth has become increasingly prominent. On the one hand, the current high per capita carbon emissions put China under enormous domestic and international pressure; on the other hand, China’s coal-based consumption structure has resulted in low levels of consumption of major renewable energy sources such as nuclear and wind power. Therefore, driven by the background of green development, it is imperative to vigorously develop renewable energy. According to the statistics of China’s National Energy Administration (NEA), the renewable energy industry investment will reach US$800 billion from 2016 to 2030 in China. At the same time, it is expected that, by 2030, renewable energy will account for at least 20% of total energy consumption. According to a report released by the World Greenpeace Organization (Greenpeace), China plans to increase the share of solar and wind energy as primary energy consumption. Total renewable energy consumption in 2020 is 186 million tons of oil equivalent, accounting for 5.36% of total energy consumption, an increase of 15.41% from 2019. By the end of 2030, renewable energy will account for at least 20% of total energy consumption, which is higher than the 12% in 2015. In addition, around 2030, China’s CO2 emissions are expected to reach peak. If wind and solar energy goals can be achieved by 2030, China can reduce fossil fuel consumption by nearly 300 million tons of standard coal each year, which is equivalent to France’s total primary energy consumption in 2015. On the basis of the Analysis Report on Development Trends and Prospects of China’s Renewable Energy Industry from 2021 to 2027, in terms of electricity, by the end of 2020, China’s cumulative installed capacity of non-aqueous renewable energy power generation has reached 25.6%, of which the installed capacity of wind power is 280 million kilowatts, accounting for 38% of the newly added power generation installed capacity; the newly installed photovoltaic power generation capacity is 48.2 million kilowatts, accounting for 25% of the newly added power generation installed capacity. In this context, the Chinese government is expected to complete the goal of energy conservation and emission reduction and to a certain extent promotes the sustainable development of the economy and the environment.

The Chinese economy is currently in a period of transition, facing the challenge of stabilizing economic development and achieving a soft landing of economic development rate, but also facing the pressure of international public opinion about the high level of carbon emissions in China. Therefore, the Chinese government needs to balance economic development and carbon emission reduction, and under the condition of stable economic development, countries around the world have turned to the development of renewable energy as a measure to solve the problem of carbon emission reduction. Under this background, this study aims to assess the impact of renewable energy consumption and economic growth on environmental pollution in China’s industrial and agricultural sectors during 1990–2020, and thus tries to suggest relevant energy and emission reduction policies for government departments, which is of immense practical importance.

In this frame, the rest of the paper is arranged as follows: “Literature review” introduces literature on the relationship between renewable energy consumption and economic growth. “Methodology and data” describes econometric methodology and data. “Results and discussion” provides the results and discussion, and “Conclusion and policy implication” concludes and provides some policy implication.
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China’s renewable energy consumption, economic growth

Therefore, this article examines the relationship between correlation research is mainly based on the following three from the perspective of industry and agriculture, and the consumption on economic growth and respectively effects model to analyze their respective effects on economic growth and CO\textsubscript{2} emissions. However, regarding the impact of renewable energy consumption on economic growth and CO\textsubscript{2} emissions, there seems that no consensus has been reached in the previous literature (Menegaki, 2011; Apergis and Payne, 2012; Wang, 2012; Farhani and Shahbaz, 2014; Bhattacharya et al. 2016; Destek and Aslan, 2017; Riti et al. 2017; Sankaran et al. 2019; Chen et al. 2020; Zhang et al. 2021). Therefore, this article examines the relationship between China’s renewable energy consumption, economic growth (output and export), and CO\textsubscript{2} emissions from 1990 to 2020 from the perspective of industry and agriculture, and the correlation research is mainly based on the following three aspects.

Literature review

With the vigorous development of the global renewable energy industry and the much attention paid to the energy transition by countries around the world, the academic community has begun to attach importance to the role of renewable energy in economic growth. They divide energy consumption into two independent factors of production, namely, renewable energy consumption and non-renewable energy consumption, and apply them to the production function (Menegaki, 2011; Apergis and Payne, 2012; Koçak and Şarkgüneşi, 2017; Aydin, 2019; Rahman and Velayutham, 2020), so as to analyze their respective effects on economic growth and CO\textsubscript{2} emissions. However, Bhattacharya et al. (2016) have studied the annual economic growth of 57% selected countries. However, Marques and Fuinhas (2012) have examined the panel data of 24 European countries from 1990 to 2007 and concluded that the use of renewable energy has a negative impact on economic growth; that is, increasing the cost of electricity will lead to a slowdown in economic activities. This finding is similar to existing energy literature such as Ocal and Aslan (2013) for the case of Turkey and Maji (2015) and Ibrahim et al. (2017) for the case of Nigeria. However, Bhattacharya et al. (2016) have studied the annual data of the 38 largest renewable energy consumers in the world from 1991 to 2012 and concluded that renewable energy consumption has a significantly positive impact on the economic growth of 57% selected countries. However, the increase in renewable energy consumption in countries such as India, Ukraine, the USA, and Israel has inhibited economic growth. This finding is similar to existing energy literature such as Apergis and Payne (2010) for the case of Eurasia and Apergis and Payne (2011) for the case of Central America.

Finally, some researchers have shown that renewable energy consumption does not have a significant impact on economic growth. Menegaki (2011) has used a random effects model to analyze the causal relationship between economic growth?}

In recent years, with the rapid economic development and the intensification of CO\textsubscript{2} emissions, people have become more and more interested in renewable energy. The relationship between renewable energy consumption and economic growth has been frequently discussed in the literature. However, the impact of the rapid development of renewable energy on economic growth has triggered a heated discussion. Surprisingly, many researchers seem to have not reached a consensus so far. Firstly, some literatures have found that the increase in renewable energy consumption will promote economic growth. For example, Apergis and Payne (2012) have studied the panel data of 80 major renewable energy consuming countries in the world from 1990 to 2007 and concluded that there is a two-way causal relationship between long-term and short-term renewable energy consumption and economic growth, supporting the feedback hypothesis. This finding is similar to existing energy literature such as Farhani and Shahbaz (2014) for the case of MENA region, Shahbaz et al. (2015) for the case of Pakistan, Aydin (2019) for the case of OECD countries, Belaïd and Zrelli (2019) for the case of Mediterranean countries, Zafar et al. (2019) for the case of Asia–Pacific Economic Cooperation countries, and Adedoyin et al. (2020) for the case of EU. On the contrary, Rahman and Velayutham (2020) have analyzed the relationship between renewable energy consumption and economic growth in five South Asian countries from 1990 to 2014 and believed that renewable energy consumption has a positive impact on economic growth, supporting the growth hypothesis (Ito, 2017; Murshed, 2021a). Destek and Aslan (2017) have investigated the impact of renewable energy consumption on the economic growth in 17 emerging economies from 1980 to 2012 and concluded that in terms of renewable energy consumption, the growth hypothesis is only true in Peru; the conservation hypothesis is true in Colombia and Thailand; the feedback hypothesis applies to Greece and South Korea, and the neutral hypothesis applies to other 12 emerging economies (Koçak and Şarkgüneşi, 2017). On the basis of this study, Sankaran et al. (2019) have used the ARDL bounds test method to analyze the causal relationship between electricity consumption and industrial output in 10 late-industrialized countries from 1980 to 2016. The results of the study found that the relationship between renewable energy (electricity consumption) and economic growth is found to be complex and varies considerably across countries, and the results support the growth, conservation, feedback, and neutral hypotheses in different countries.

Secondly, other researchers have hinted that increased consumption of renewable energy will sacrifice economic growth.

Does renewable energy consumption promote economic growth?
economic growth and renewable energy consumption in 27 European countries from 1997 to 2007 and believed that there is no causal relationship between renewable energy consumption and GDP, and meanwhile, it is a result of the unbalanced and insufficient development and utilization of renewable energy throughout Europe (Apergis and Payne, 2010). Liu (2016) has investigated the panel data of 31 provinces in China from 2000 to 2010 and found that the deployment of renewable energy in rural areas has a significant positive impact on the income increase of rural households, but it has no significant impact on the economic growth of developed cities. Ozcan and Ozturk (2019) have analyzed the panel data of 17 emerging countries from 1990 to 2016 and found that there is no significant causal relationship between renewable energy consumption and economic growth; on the contrary, the implementation of energy-saving policies seems to slow down economic activities. Based on this research, Chen et al. (2020) have used a threshold model to analyze the causal relationship between renewable energy consumption and economic growth. Nevertheless, the unbalanced and insufficient development and utilization of renewable energy consumption and economic growth has always been a hot discussion topic by many researchers. For example, Wang (2012) has investigated the panel data of 98 countries around the world from 1971 to 2007 and found that under a slow economic growth system, economic activities are the main reasons for the increase in greenhouse gas emissions (Chontanawat, 2020a,b; Murshed et al. 2021c). Riti et al. (2017) have used different estimation methods, such as ARDL (autoregressive distributed hysteresis) model, FMOLS, DOLS, and impulse response and variance decomposition to examine the relationship between CO2 emissions, economic growth, and energy consumption in China. The study has found that China’s extensive economic development and rapid growth in energy consumption are the main reasons for the increase in greenhouse gas emissions (Chontanawat, 2020a,b; Murshed et al. 2021c). However, this result is contrary to the findings of Murshed (2021b), who concluded that in most cases, energy consumption has a favorable impact on the environment in South Asia. On the basis of this study, some researchers have found that renewable energy is direct evidence of reducing pollution shocks (Murshed et al. 2021c). Apergis et al. (2018) have examined the relationship between renewable energy consumption and CO2 emissions in sub-Saharan Africa countries from 1995 to 2011 and found that there is a short-run two-way causal relationship between renewable energy consumption and CO2 emissions (supporting the feedback hypothesis), while long-run elasticities suggest that renewable energy consumption helps reduce CO2 emissions. This finding is similar to existing energy literature such as Chen et al. (2019) and Zhang et al. (2021) for the case of China and Brini (2021) for the case of African countries. In response to this view, Hu et al. (2021) found a unidirectional causal relationship between renewable energy consumption and CO2 emissions by examining the effects of disaggregated energy consumption, technological innovation, and capital on economic output and CO2 emissions in India over the period from 1990 to 2018, although renewable energy consumption can significantly reduce CO2 emissions in India. Nevertheless, Farhani and Shahbaz (2014) have investigated the panel data of 10 Middle East and North Africa (MENA) countries from 1980 to 2009 and found that renewable energy consumption has all contributed to the increase of CO2 emissions, and there seems to be a two-way causality relationship between renewable energy consumption and CO2 emissions (supporting feedback hypothesis). On the basis of this study, Nguyen and Kakinaka (2019) have surveyed the panel data of 107 countries from 1990 to 2013 and found that the correlation between renewable energy consumption and CO2 emissions has a direct relationship with the country’s income and believed that there is a positive correlation between renewable energy consumption and CO2 emissions in low-income countries, while the correlation between renewable energy consumption and CO2 emissions in high-income countries is negative. In addition, other researchers believe that renewable energy consumption can increase energy self-sufficiency, stimulate sustainable economic growth, and reduce CO2 emissions to a certain extent (Noorpoor and Kudah, 2015; Gill et al. 2018; Lin and Raza, 2019).

Does renewable energy improve the environment?

In recent years, energy consumption relying on burning fossil fuels has led to a rapid increase in global greenhouse gas emissions, causing climate change and environmental degradation (Ahmad et al. 2018; Hu et al. 2021; Zhang et al. 2021). Riti et al. (2017) have used different estimation methods, such as ARDL (autoregressive distributed hysteresis) model, FMOLS, DOLS, and impulse response and variance decomposition to examine the relationship between CO2 emissions, economic growth, and energy consumption in China. The study has found that China’s extensive economic development and rapid growth in energy consumption are the main reasons for the increase in greenhouse gas emissions (Chontanawat, 2020a,b; Murshed et al. 2021c). However, this result is contrary to the findings of Murshed (2021b), who concluded that in most cases, energy consumption has a favorable impact on the environment in South Asia. On the basis of this study, some researchers have found that renewable energy is direct evidence of reducing pollution shocks (Murshed et al. 2021c). Apergis et al. (2018) have examined the relationship between renewable energy consumption and CO2 emissions in sub-Saharan Africa countries from 1995 to 2011 and found that there is a short-run two-way causal relationship between renewable energy consumption and CO2 emissions (supporting the feedback hypothesis), while long-run elasticities suggest that renewable energy consumption helps reduce CO2 emissions. This finding is similar to existing energy literature such as Chen et al. (2019) and Zhang et al. (2021) for the case of China and Brini (2021) for the case of African countries. In response to this view, Hu et al. (2021) found a unidirectional causal relationship between renewable energy consumption and CO2 emissions by examining the effects of disaggregated energy consumption, technological innovation, and capital on economic output and CO2 emissions in India over the period from 1990 to 2018, although renewable energy consumption can significantly reduce CO2 emissions in India. Nevertheless, Farhani and Shahbaz (2014) have investigated the panel data of 10 Middle East and North Africa (MENA) countries from 1980 to 2009 and found that renewable energy consumption has all contributed to the increase of CO2 emissions, and there seems to be a two-way causality relationship between renewable energy consumption and CO2 emissions (supporting feedback hypothesis). On the basis of this study, Nguyen and Kakinaka (2019) have surveyed the panel data of 107 countries from 1990 to 2013 and found that the correlation between renewable energy consumption and CO2 emissions has a direct relationship with the country’s income and believed that there is a positive correlation between renewable energy consumption and CO2 emissions in low-income countries, while the correlation between renewable energy consumption and CO2 emissions in high-income countries is negative. In addition, other researchers believe that renewable energy consumption can increase energy self-sufficiency, stimulate sustainable economic growth, and reduce CO2 emissions to a certain extent (Noorpoor and Kudah, 2015; Gill et al. 2018; Lin and Raza, 2019).

Can carbon reduction and economic growth be balanced?

In the stage of rapid economic development, economic growth will inevitably bring about CO2 emission problems of varying degrees, such as greenhouse gas emissions of carbon dioxide, methane, and nitrous oxide (Luo et al. 2020). Whether CO2 reduction and economic growth can be balanced has always been a hot discussion topic by many researchers. For example, Wang (2012) has investigated the panel data of 98 countries around the world from 1971 to 2007 and found that under a slow economic growth system, economic growth has a negative impact on CO2 emissions;
under a modest economic growth system, economic growth has a positive impact on CO\(_2\) emissions growth; and under a rapid economic growth, the impact on economic growth is minimal (Charfeddine and Kahia, 2019). This result is consistent with the study of Murshed et al. (2021a), who concluded that economic growth promotes increased carbon emissions in the long run, but trade between neighboring countries has a positive role in reducing carbon emissions. On this basis, Khan et al. found that economic growth in RCEP countries has a dampening effect on CO\(_2\) emissions and supports the environmental Kuznets curve (EKC) hypothesis by studying the role of export diversification and compound country risk in carbon emission reduction. In response to this view, Bento and Moutinho (2016) have used the ARDL boundary check method to investigate the relationship between CO\(_2\) emissions, economic growth, and renewable energy consumption in Italy from 1960 to 2011. The study has found that both long-term and short-term renewable electricity production can effectively reduce CO\(_2\) emissions while also promoting economic growth. The results of this study are consistent with those of Zhang et al. (2021). Their survey with China’s provincial panel data from 2000 to 2017 concludes that when the proportion of low-emission electricity in total power generation increases by 1%, per capita GDP will increase by 0.16%, and CO\(_2\) emissions will also be reduced by 0.848%. Moreover, some researchers also believe that renewable energy consumption can reduce CO\(_2\) emissions to a certain extent, but in most cases, CO\(_2\) emission reduction is not conducive to human development and economic growth (Cosmas et al. 2019; Maalej and Cabagnols, 2020; Adekoya et al. 2021; Hao and Cho 2021).

Overall, relevant researchers have mostly paid attention to the impact of energy structure on economic growth and the environment, and emphasized the importance of the development and utilization of renewable energy. However, there are still some shortcomings in previous research, which can be divided into the following three aspects: (1) Most studies are conducted from the perspective of countries to analyze the relationship between renewable energy consumption and economic growth and the environment. Few studies have been conducted from the overall perspective to the partial perspective. (2) In the rare studies, more attention is paid to the total amount, and the research on the consumption structure is very few. (3) Most studies mainly analyze the impact of renewable energy consumption on economic growth and the environment from the national level, and most of them study the direct effect of renewable energy consumption on economic growth and the environment. However, few have conducted in-depth exploration of the indirect impact of renewable energy consumption on economic growth and the environment from a local or industry perspective. Furthermore, the results of past studies are inconclusive. Therefore, this article explores the impact of renewable energy consumption on output and export, and environmental quality from the perspective of industry and agriculture in China is being conducted to fill up this gap in the literature and makes relevant recommendations for the development of renewable energy in China.

**Methodology and data**

**Data source and pre-analysis**

At present, China’s energy consumption structure is represented by a multi-energy complementary mode of relying on traditional fossil fuel energy and co-developing with other energy sources, such as renewable energy and biomass energy. According to the National Bureau of Statistics of China, from 2000 to 2020, China’s energy consumption mainly includes coal, oil, natural gas, and renewable energy (hydroelectricity, nuclear power, and wind power), of which energy consumption is mainly coal consumption, leading to the rapid rise of China’s CO\(_2\) emissions and making China quickly become a major CO\(_2\) emitter (see Fig. 1). Of the total energy consumption in the industrial and agricultural sectors, coal consumption in 2020 accounts for 67.79%, oil consumption accounts for 20%, and natural gas and renewable energy consumption accounts for 6.8% and 11%, respectively. This shows that in the energy consumption structure of China’s industrial and agricultural sectors, coal and oil consumption account for a large proportion, and traditional fossil energy still occupies an important position in China’s energy consumption structure. In addition, according to data from the National Energy Administration of China, from 2000 to 2020, China’s total renewable energy consumption and the average annual growth rate of electricity consumption in the whole society have reached 6.29% and 8.97%, respectively. At the same time, the role of renewable energy as a substitute for non-renewable energy has been gradually intensified. The specific manifestation is that the ratio of renewable energy consumption to total energy consumption has continued to increase, from 7.3% in 2000 to 15.9% in 2020.

Theoretically, the increase of renewable energy consumption leads to a larger share of renewable energy in primary energy. The past coal-based energy mix is optimized by the replacement of renewable energy sources, and the growth of renewable energy consumption will promote the growth of renewable energy investments, the reduction of energy use costs, and technological innovation, thus improving energy use efficiency and reducing the emission of environmental pollutants. Currently, in this study, we used observations from different sources of data for the years 1990–2020 (see Table 1). In addition, time frames and ranges were used
based on data availability constraints, and all variables in the specified models were converted to natural logarithmic form for examining the relationship between renewable energy consumption, output, export, and environmental pollution (CO2 emissions).

As mentioned earlier, the main purpose of this article is to examine the relationship between China’s renewable energy consumption, output, export, and CO2 emissions from the perspective of the industrial and agricultural sectors. To eliminate possible heteroscedasticity, all variable indicators are converted to the natural logarithmic form. Table 2 shows the result of descriptive test of the variables under consideration. The results show that the average values for renewable energy consumption, CO2 emissions, output, and export are all positive. Specifically, output shows the more variability than export while CO2 emissions have the highest variability among the selected variables, which was consistent with the findings of Riti et al. (2017). In addition, the Jarque–Bera test results suggest that the variables are normally distributed since the probability values of the variables are greater than the 5% significance level (0.144, 0.162, 0.349, and 0.135 > 0.05) for renewable energy consumption, CO2 emissions, output, and export respectively.

![Fig. 1 China’s energy consumption structure](image)

**Table 1** Variable description

| Variables | Description | Data source | Measure |
|-----------|-------------|-------------|---------|
| RE        | Renewable energy consumption | Energy Statistical Yearbook of China, and IEA | % of primary energy |
| CE        | Carbon emissions | World Bank | Tons per capita |
| OTP       | Total output of industrial and agricultural sectors | World Bank | % of GDP |
| EXP       | Total value of export of and agricultural sectors | National Bureau of Statistics of China | % of GDP |

**Table 2** Descriptive statistics of variables used

| Variables | Mean | Min  | Max  | Std. dev | Kurtosis | Skewness | Jarque–Bera |
|-----------|------|------|------|----------|----------|----------|-------------|
| RE        | 1.871| 1.417| 2.767| 0.373    | 2.535    | 0.834    | 3.870 (0.144) |
| CE        | 1.404| 0.649| 1.968| 0.488    | 1.344    | −0.133   | 3.634 (0.162) |
| OTP       | 3.949| 3.682| 4.147| 0.139    | 2.148    | −0.475   | 2.102 (0.349) |
| EXP       | 3.091| 2.845| 3.561| 0.216    | 2.624    | 0.859    | 3.994 (0.135) |

*p*-values are given in parentheses
Conceptual framework

Through the preliminary analysis, we found the same convergence trend between renewable energy consumption, output, export, and environmental pollution (CO$_2$ emission) in China’s industrial and agricultural sectors, which indicates that with the rapid development of China’s industrial and agricultural sectors, energy consumption has increased dramatically, leading to increased environmental pollution, thus seriously threatening human daily life and health. In the context of global green economy development, renewable energy, as a clean and non-polluting energy industry, has gained more and more attention from governments, enterprises, and research scholars. Therefore, in the context of China’s current efforts to upgrade its industrial structure, it is important to re-examine the relationship between renewable energy consumption, output, export, and CO$_2$ emissions in the industrial and agricultural sectors, and to formulate relevant environmental regulations from theoretical and empirical perspectives to promote the upgrading and sustainable development of China’s industrial and agricultural industrial structure. To achieve this goal, an estimation procedure will be designed to explore the relationship between renewable energy consumption, output, exports, and CO$_2$ emissions in China’s industrial and agricultural sectors (see Fig. 2).

In this study, unit root tests, namely, ADF, DF-GLS, and PP tests, will be used to test whether the variables are stable time series at the level or at the first-order difference. If all variables are stable at the first-order difference, the long-run equilibrium and short-run dynamics among the variables will be analyzed using the co-integration test and the causality model of VECM. In addition, to further understand and determine the impact of the degree of fluctuations in China’s renewable energy consumption, output and exports, and environmental pollution (CO$_2$ emission) on the current and future values of other variables in the industrial and agricultural sector perspectives, we also use impulse response analysis based on the VAR model to further portray the dynamics of the variables.

Econometric methodology

Since the main goal of this article is to explore the relationship between renewable energy consumption, output

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**Fig. 2** Analysis framework of estimation procedure of renewable energy consumption, output and export, and environmental pollution
and export, and CO₂ emissions in agricultural and industrial sectors, an econometric model will be designed. Before conducting series tests, the natural logarithm of the variables should be used to eliminate the effects of heteroscedasticity in the time series data (Zhao and Wang, 2015). The econometric model is specified as follows:

\[ CE_t = \alpha + \beta RE_t + \gamma OTP_t + \delta EXP_t + \varepsilon_t \]  

(1)

where \( RE \) denotes renewable energy consumption in agricultural and industrial sectors, \( CE \) represents CO₂ emissions, \( OTP \) represents output in agricultural and industrial sectors, \( EXP \) represents export in agricultural and industrial sectors, \( t \) represents time, \( \alpha \) is the slope coefficient, and \( \varepsilon \) is the residual errors.

**Unit root test**

The first step in the unit root test process is the execution of an integrated analysis of the model, which aims to test the smoothness of the data of the serial variables in the constructed model. According to the autoregressive sequence estimator distribution, the unit root of the sequence data is studied. It is not difficult to find that non-stationary time series variables can also be stationary through free linear combinations. If there is such a time series variable that makes the series stable through linear free combination, then it can be thought that there is such a co-integration relationship between the variables in the time series model. However, this requires that all variables in the sequence model need to have the same integration sequence (Chontanawat, 2020b). Therefore, we will introduce three types of unit root tests, namely, ADF, DF-GLS, and the PP test to examine the stationary of renewable energy consumption, output and export, and CO₂ emissions in agricultural and industrial sectors (Zhao and Wang, 2015; Hao and Cho 2021).

\[ \Delta X_t = \alpha_1 + \alpha_2 T + \delta X_{t-1} + \sum_{i=1}^{n} \lambda_i \Delta X_{t-i} + \varepsilon_t \]  

(2)

where \( X_t \) represents any variable (\( EC_t, OTP_t, EXP_t, \) and \( EC_t \)) that changes with time in the time series model, \( T \) represents the time trend, and \( \Delta \) is a different operator. However, the unit root test is mainly to study the coefficient \( \delta \), so if the null hypothesis \( X_t \) is non-stationary or \( \delta = 0 \), it means that there may be a unit root problem of \( \delta < 0 \) in this sequence.

**Co-integration test**

Before performing the co-integration test, we first need to use the Akaike information criterion (AIC), Schwarz information criterion (SIC), and Hannan-Quinn information criterion (HQIC) to determine the optimal lag length of the VAR model. Then, if the variable is a stationary series at the first difference, the time series is a first-order integral or so-called I (1). Therefore, the long-term relationship between variables is tested according to the co-integration test method based on the unrestricted vector autoregressive (VAR) model proposed by Johansen and Juselius, where the variable vector (\( X \times 1 \)) of time \( t \) is related to the vector of past variables (Johansen and Juselius, 2009; Seyoum, 2021). According to the Granger representation theorem, the vector \( X_t \) has a vector autoregressive error correction representation in the following specification:

\[ \Delta X_t = \alpha_1 + \alpha_2 T + \prod_{i=1}^{p} X_{t-i} + \sum_{i=1}^{n} \Gamma_i \Delta X_{t-i} + \Delta W_t + \varepsilon_t \]  

(3)

where \( \Pi = \sum_{i=1}^{n} \beta_i - I \) and \( \Gamma_i = - \sum_{j=i+1}^{n} \beta_j \), \( y_i \) is the dimensional vector of \( (y \times 1) \); all corresponding variables are I (1), \( \Pi, \Gamma_i \); and \( A \) is the matrix of estimated parameters; \( w_t \) is a vector with deterministic elements (constant and trend), and \( \varepsilon \) is a random error matrix. If the matrix \( \Pi = 1 \), there is a single co-integration vector or a fixed linear combination, so that the co-integration rank matrix \( \Pi \) can be decomposed into \( \Pi = \alpha \beta^t \), in which \( \alpha \) is the speed adjustment vector, and \( \beta \) is a long-term equilibrium vector. In this case, \( X_t \) is I (1), and \( \beta^t X_t \) is I (0). The method of Johansen’s test is to carry out an unrestricted estimation matrix \( \Pi \), and to test whether the model has constraints that can reject the implicit reduction of rank reduction \( \Pi \). Therefore, the test methods for rank reduction, the trace test, and the maximum eigenvalue test are as follows:

\[ \lambda_{\text{trace}} = -T \sum_{i=r+1}^{k} \ln(1 - \lambda_i^2) \]

\[ \lambda_{\text{max}}(r, r+1) = -T \ln(1 - \lambda_{r+1}) \]

where \( \lambda_i \) is the estimated ordered eigenvalue obtained, and \( T \) is the number of lag-adjusted observations. In practical applications, the time series with the critical value \( k = 10 \) of the Johansen cointegration tests are all valid, and the critical value depends on the trend hypothesis, but it is not suitable to be applied to models containing other deterministic regression variables. During the analysis, the results of the trace statistics and the maximum eigenvalue statistics may conflict.

**Causality test**

According to Chontanawat (2020a, b), if each sequence variable in the sequence model is a stationary sequence, and each variable has a long-term equilibrium co-integration relationship after free combination, there must be an error correction term (ECM) in the model. Therefore, for constructing the vector error correction model (VECM), we need to consider the long-term equilibrium and short-term dynamic relationship between variables; that is, the causality model is as follows:
\[ \Delta RE_t = c_1 + \sum_{i=1}^{p} \delta_i \Delta RE_{t-i} + \sum_{i=1}^{q} \beta_i \Delta OTP_{t-i} + \sum_{i=1}^{r} \gamma_i \Delta EXP_{t-i} + \epsilon_t \]  
(4)

\[ \Delta OTP_t = c_2 + \sum_{i=1}^{p} \sigma_i \Delta RE_{t-i} + \sum_{i=1}^{q} \beta_i \Delta OTP_{t-i} + \sum_{i=1}^{r} \gamma_i \Delta EXP_{t-i} + \epsilon_t \]  
(5)

\[ \Delta EXP_t = c_3 + \sum_{i=1}^{p} \alpha_i \Delta RE_{t-i} + \sum_{i=1}^{q} \beta_i \Delta OTP_{t-i} + \sum_{i=1}^{r} \gamma_i \Delta EXP_{t-i} + \epsilon_t \]  
(6)

\[ \Delta CE_t = c_4 + \sum_{i=1}^{p} \delta_i \Delta RE_{t-i} + \sum_{i=1}^{q} \beta_i \Delta OTP_{t-i} + \sum_{i=1}^{r} \gamma_i \Delta EXP_{t-i} + \epsilon_t \]  
(7)

where \( ECM_{t-1} \) is the normalize cointegration equation. There are two sources of causation, i.e., through the ECM, if \( \Phi_1 \neq 0 \), or through the lagged dynamic terms. The ECM term represents the long-run equilibrium, relationship whereas the coefficients on lagged difference term show the short-run dynamics. The coefficient of ECM term indicates the speed of adjustment or an error mechanism that drives the variables back to long-run equilibrium. Regarding two sources of causation, there are three different causality tests, short-run Granger non-causality test, long-run non causality test, and joint non-causality test. The interpretation is as follows (Chontanawat, 2020a). For example, in Eq. (4), \( OTP \), Granger causes \( EC \), in the short run if the null hypothesis \( H_0 \) : (all \( \beta_{1i} = 0 \)) is statistically rejected. For the long-run causality, \( EXP \) Granger causes \( EC \), if the null \( H_0 : (\Phi_1 = 0) \) is statistically rejected. For the strong causality result, \( OTP \), Granger caused \( EC \), if the null Hypothesis \( H_0 : (\Phi_1 = 0) \) is statistically rejected. Similarly, \( EXP \), Granger causes \( EC \), in the short run if the null hypothesis \( H_0 \) : (all \( \gamma_{1i} = 0 \)) is statistically rejected. For the long-run causality, \( EXP \) Granger causes \( EC \), if the null \( H_0 : (\Phi_1 = 0) \) is statistically rejected. For the strong causality result, \( EXP \), Granger caused \( EC \), if the null \( H_0 : (\Phi_1 = 0) \) is statistically rejected. The interpretation of Eqs. (5) and (6), and (7) can be done following the same notion.

## Results and discussion

### Unit root test

Before executing the time series model, the nature of the variable series must be checked. If the variable series is a non-stationary time series, it will lead to pseudo-regression, and the statistical test will be meaningless. Therefore, we use three methods of the augmented Dickey-Fuller (ADF), Dickey-Fuller GLS, and Phillips-Perron to test the stationary conditions of all variables. According to Table 3, the unit root test results show that the renewable energy consumption, output, and export of the industrial and agricultural sectors, as well as CO2 emissions, include the unit root at the level, and only after the first difference, they are stable at the significant levels of 1%, 5%, and 10%. Therefore, all the variables are integrated of order one I(1) (Bhattacharya et al. 2016; Hao and Cho 2021). Since all variables are stable at the first difference, it is particularly important to study whether there is a co-integration relationship between them. Therefore, we need to determine the maximum lag order of the model using the Akaike information criterion (AIC), Schwarz information criterion (SIC), and Hannan-Quinn information criterion (HQIC) before conducting the cointegration test and causality test (Hao, 2021). In Table 4, we refer to these three standards and choose the maximum lag order as \( p = 1 \).

| Variable | Augmented Dickey-Fuller | Dickey-Fuller GLS | Phillips-Perron |
|----------|-------------------------|-----------------|-----------------|
|          | Level | 1st difference | Level | 1st difference | Level | 1st difference |
| RE       | −3.679 | −5.912*** | −2.647 | −5.638*** | −3.679 | −5.935*** |
| CE       | −1.610 | −1.866* | −1.953 | −2.559** | −1.610 | −1.813* |
| OTP      | −1.610 | −1.752* | −1.610 | −1.749* | −1.610 | −1.786* |
| EXP      | −3.679 | −4.083*** | −2.647 | −3.866*** | −3.679 | −4.144*** |

\( RE \) stands for renewable energy consumption, \( CE \) stands for CO2 emissions, OTP and EXP stand for output and export

*Significant at 10% level; **significant at 5% level; ***significant at 1% level
Co-integration test

Co-integration test is a method to test the co-integration relationship of the regression coefficients of two or more time series variables based on the VAR model. Its purpose is to analyze whether there is a long-term relationship equation and an estimated co-integration vector between each sequence variable index in the model. Just like the previous analysis, the variables we selected all have the same integral property I (1), so the long-term co-integration relationship between variables can be used to test the linear deterministic trend (there is no trend in the intercept). The results of trace test and maximum eigenvalue tests in Table 5 consistently show that there is at most one co-integration relationship between the selected variables at the 5% significance level. This finding is consistent with the findings of Bento and Moutinho (2016), Dogan et al. (2016), Ibrahim et al. (2017), Chen et al. (2019), Chukwuma and King (2020), and Zhang et al. (2021) which revealed the existence of a long-run relationship between renewable energy consumption, output, and export, and CO₂ emissions in agricultural and industrial sectors. Table 6 shows the co-integration vector, the deviation from the long-term equilibrium coefficient and the ECM equation. Obviously, in the long run, there is a co-integration relationship between renewable energy consumption, output, export, and CO₂ emissions, but there is a negative correlation between renewable energy consumption and CO₂ emissions. Among them, the long-term elasticity of CE, relative to RE, EXP, and OTP, is 0.174, 0.370, and 0.214, respectively. In addition, the load factor (\(\Phi\)), which measures the speed of adjustment back to the long-term equilibrium level, has the correct sign (negative), which indicates that the CO₂ emissions are adjusted to its long-term level at an adjustment speed of approximately 5.7% in the first year.

Causality test

Once the cointegration relationship is established between the sequence variables, then the direction of causation both in the short-run and long-run can be detected via the multivariate error correcting process (Ibrahim et al. 2017). The causal relationship results in Table 7 prove to a certain extent that there is a causal relationship between renewable energy consumption, output, export, and CO₂ emissions, especially a long-term relationship. In the short term, there is a one-way or unidirectional causal relationship between export and CO₂ emissions and renewable energy consumption, and the results support the growth hypothesis. This means that the increase in industrial and agricultural export in the short term promotes the increase in CO₂ emissions, while the increase in renewable energy consumption also promotes the increase in export, and vice versa (in the long run). In addition, the results also show that there is a one-way or unidirectional causal relationship between renewable energy consumption and CO₂ emissions, which means that renewable energy consumption may lead to the increase in CO₂ emissions. However, surprisingly, there is no evidence to directly prove that there is a causal relationship between renewable energy consumption (or CO₂ emissions) and output, and the results support the conservation hypothesis. Chiu and Chang (2009) suggest that this result may be due to the fact that China’s industrial and agricultural output has not yet reached the threshold at which renewable energy
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Table 7 Causality test results based on the VECM model

| Dependent variables | Short-term F-statistics | Long-term t-statistics | Short-term and long-term F-statistics |
|---------------------|-------------------------|------------------------|--------------------------------------|
|                     | \( \sum \Delta CE_{t+1} \) | \( \sum \Delta RE_{t+1} \) | \( \sum \Delta OTP_{t+1} \) | \( \sum \Delta EXP_{t+1} \) | \( \text{ECM}_{t+1} \) | \( \sum \Delta CE_{t+1} \) and \( \text{ECM}_{t+1} \) | \( \sum \Delta RE_{t+1} \) and \( \text{ECM}_{t+1} \) | \( \sum \Delta OTP_{t+1} \) and \( \text{ECM}_{t+1} \) | \( \sum \Delta EXP_{t+1} \) and \( \text{ECM}_{t+1} \) |
| \( \Delta CE_t \)   | –                       | 0.720                  | 0.594                                | 2.589*                              | \( \sum \Delta CE_{t+1} \) and \( \text{ECM}_{t+1} \) | \( \sum \Delta RE_{t+1} \) and \( \text{ECM}_{t+1} \) | \( \sum \Delta OTP_{t+1} \) and \( \text{ECM}_{t+1} \) | \( \sum \Delta EXP_{t+1} \) and \( \text{ECM}_{t+1} \) |
| \( \Delta RE_t \)   | 1.266                   | –                      | 0.900                                | 0.937                               | \( \sum \Delta CE_{t+1} \) and \( \text{ECM}_{t+1} \) | \( \sum \Delta RE_{t+1} \) and \( \text{ECM}_{t+1} \) | \( \sum \Delta OTP_{t+1} \) and \( \text{ECM}_{t+1} \) | \( \sum \Delta EXP_{t+1} \) and \( \text{ECM}_{t+1} \) |
| \( \Delta OTP_t \)  | 0.317                   | 0.302                  | –                                    | 0.200                               | \( \sum \Delta CE_{t+1} \) and \( \text{ECM}_{t+1} \) | \( \sum \Delta RE_{t+1} \) and \( \text{ECM}_{t+1} \) | \( \sum \Delta OTP_{t+1} \) and \( \text{ECM}_{t+1} \) | \( \sum \Delta EXP_{t+1} \) and \( \text{ECM}_{t+1} \) |
| \( \Delta EXP_t \)  | 2.080                   | 5.09***                | 1.144                                | –                                   | \( \sum \Delta CE_{t+1} \) and \( \text{ECM}_{t+1} \) | \( \sum \Delta RE_{t+1} \) and \( \text{ECM}_{t+1} \) | \( \sum \Delta OTP_{t+1} \) and \( \text{ECM}_{t+1} \) | \( \sum \Delta EXP_{t+1} \) and \( \text{ECM}_{t+1} \) |

*Values are given in parentheses. \( RE \) stands for renewable energy consumption, \( CE \) stands for \( \text{CO}_2 \) emissions, \( OTP \) and \( EXP \) stand for output and export.

Ozcan and Ozturk (2019), Rahman and Velayutham (2020), and Seyoum (2021) may be the use of different causality tests. According to the existing literature, the direction of the causal relationship between economic growth (output and export), renewable energy consumption, and \( \text{CO}_2 \) emissions depends on both method and time. Therefore, our empirical results have important implications for the formulation of policies related to energy conservation and emission reduction; that is, on the road to social, economic, and environmental sustainability, the impact of economic growth and energy consumption (renewable and non-renewable energy) of related industries on \( \text{CO}_2 \) emissions must be considered.

Impulse response analysis

The impulse response functions (IRFs) are widely used to describe the shock response of any dynamic system to some external changes. In other words, impulse response analysis describes the change of a standard deviation shock from a random disturbance item to an endogenous variable shock trajectory. To further understand and judge the impact of China’s renewable energy consumption, output, export, and \( \text{CO}_2 \) emissions, and fluctuations on the current and future values of other variables from the perspective of the industrial and agricultural sectors, this paper analyzes them based on VAR models using impulse response functions (see Fig. 3). This article uses 10 cycles as the lag interval of the impulse response. It can be seen from the response curve that each variable shows a gradual convergence trend in the later period, which shows that the VAR model constructed in this study is robust.

Firstly, for \( \text{CO}_2 \) emissions, in the causality model, \( \text{CO}_2 \) emissions cannot determine renewable energy consumption, output, and export. Therefore, we need to carefully consider the explanation of the impulse response function imposing a standard deviation impact on \( \text{CO}_2 \) emissions.
If CO₂ emissions (CE) are significant with the same sign for renewable energy consumption (RE), output (OTP), and export (EXP), it will help to understand the expected impact on the results (Charfeddine and Kahia, 2019). The impulse response results show that when a standard deviation shock is applied to CE, CO₂ emissions have a negative impact on renewable energy consumption and a positive impact on output and export, verifying the validity of the EKC hypothesis (Bilgili et al. 2016). This shows that CO₂ emissions promote the development of China’s industry and agriculture, but also hinder the development of renewable energy. Our findings do not support the papers of Khan et al. (2021a), who put forward that the increase in carbon emission brings climate change and results in the decline of product export but agrees with Khan et al. (2019).

Secondly, when a standard deviation shock is imposed on renewable energy consumption (RE), renewable energy consumption has a negative impact on CO₂ emissions and export, and a positive impact on output. This shows that renewable energy consumption can help reduce CO₂ emissions and improve environmental quality in the long term, so renewable energy can be the most effective means to reduce CO₂ emissions. This result is consistent with previous empirical results, and it further confirms the fundamental role of renewable energy in reducing CO₂ emissions. This result was supported by studies undertaken in relation to China by Chen et al. (2019) and Zhang et al. (2021) and in emerging economies by Hu et al. (2021). However, we find that renewable energy has promoted industrial and agricultural output to a certain extent, but inhibited export (Bhattacharya et al. 2016; Dogan et al. 2016; Ito, 2017). At present, China’s renewable energy accounts for a relatively low proportion of primary energy, and it is still in the initial stage of development. It is unrealistic for industrial and agricultural export to rely solely on renewable energy to meet peak demand (Apergis and Payne, 2010). Therefore, under the premise of meeting the peak demand of industrial and agricultural export, the proportion of renewable energy consumption in primary energy can be appropriately increased, which is also an effective way to reduce CO₂ emissions. Obviously, this result is consistent with the fact that China’s use of renewable energy has been increasing in recent years, which was consistent with the findings of Apergis and Payne (2010) and Charfeddine and Kahia (2019).

Thirdly, when a standard deviation shock is applied to output (OTP), output has a negative impact on CO₂ emissions and renewable energy consumption, which shows that China’s industrial and agricultural output does not promote renewable energy consumption. On the contrary, it will sacrifice the development of renewable energy, which may be the result of the inability of renewable energy to meet the needs of industrial and agricultural production, which in turn leads to aggravation of CO₂ emissions (Cosmas et al. 2019; Maalej and Cabagnols, 2020; Adekoya et al. 2021). However, we notice that the impact of output on CO₂ emissions is minimal. In addition, we also find that output has a positive to negative impact on export, but the overall impact is not very high, and it declines rapidly in the first 2 years, and the impact of the shock disappears completely after 7 years. This shows that the output of industry and agriculture will not promote the increase of export volume in the short term, but in the long term, this situation has been alleviated to a certain extent, but it will still bring negative effects. Since joining the World Trade Organization (WTO) in 2001, China’s
low-cost comparative advantage in low-end factors of production has led to a “steep” rise in the volume of agricultural and industrial export trade. However, as China’s population ages and the price of labor factors rises, the competitiveness of China’s exports declines, leading to a weaker pull effect of global exports on output. On the other hand, in the face of the global financial crisis and COVID-19, which led to a decline in global economic growth and weak demand from developed countries, China’s economy has gradually transformed and upgraded to implement a comprehensive strategy to expand domestic demand, gradually moving away from relying on exports of low-end products to drive output growth. This strategy of expanding domestic demand also leads to a decrease in the dependence of output on exports, which in turn makes the pull effect of exports on output weaker. Our findings do not support the papers of Hacker and Hatemi-J (2003), who put forward the positive association between output and export.

Finally, when a standard deviation shock is applied to the export (EXP), the export has a positive impact on CO2 emissions and a negative impact on the consumption of renewable energy. The impact on CO2 emissions is greatest in the 2nd year (0.007), and then it slowly decreases and disappears completely after 9 years. As expected, CO2 emissions will fluctuate strongly in the short term due to the impact of export, but this effect will gradually weaken in the long term. This indicates that the increase in industrial and agricultural export in the short term greatly consumes traditional energy sources (fossil fuels) and promotes an increase in CO2 emissions. This may be the result of current renewable energy sources that cannot meet the short-term peak industrial and agricultural production demand. This was consistent with the findings of Hakimi and Hamdi (2016), Kaya et al. (2017), and Charfeddine and Kahia (2019). However, we note that the impact of export shocks on output is negligible, which may be the result of the uncertainty of supply and demand in the export trade market (Chen et al. 2019). In fact, the spread of international trade conflicts has led to increased instability in the trade market, which in turn has increased the asymmetry of industrial and agricultural export. These results were supported by studies undertaken in relation to India and South Asia by Kumar (2020) and in emerging and developed countries by Jafarzadeh and Shuquan (2021).

Overall, as China’s status in the world economy continues to improve, China has now become a major industrial and agricultural country. At the same time, with the rapid development of China’s industry and agriculture, it will consume a lot of energy (renewable and non-renewable energy). Therefore, the output and export of the industrial and agricultural sectors are the direct reasons for the rapid increase in China’s CO2 emissions (Riti et al. 2017). In addition, according to the existing literature, from the perspective of sustainable economic and environmental development, renewable energy consumption can not only promote the development of industry and agriculture to a certain extent, but also has a suppressive effect on CO2 emissions. This also provides a strong basis for the development and reduction of renewable energy in China and the long-term implementation of the emission control policy. These results were supported by studies undertaken in relation to African countries by Brini (2021), in China by Chen et al. (2019) and Zhang et al. (2021), and globally by Hu et al. (2021).

Conclusion and policy implication

Conclusion

This article uses econometric analysis methods, such as co-integration test, causality test, and impulse response analysis, and the long-term and short-term relationships between renewable energy consumption, output and export, and CO2 emissions in China over the period 1990–2020 are examined from the perspective of industry and agriculture. Firstly, the unit root test shows that the selected variable indicators are non-stationary at the 1%, 5%, and 10% significance levels. However, the variable is stationary at the first difference, rejecting the null hypothesis (Apergis et al. 2018; Brini, 2021). Secondly, the results of the co-integration test show that there is a long-term relationship between these variables. At the same time, this also implies that renewable energy consumption and economic activities (output and export) in the industrial and agricultural sectors are related to CO2 emissions (Chontanawat, 2020a, b). However, long-term estimates indicate that renewable energy consumption has a significantly negative impact on CO2 emissions, which means that renewable energy consumption is beneficial because it helps reduce climate change. Thirdly, the causality test results show that there is a one-way or unidirectional causality between export, CO2 emissions, and renewable energy consumption in the short term, supporting the growth hypothesis. Nevertheless, surprisingly, we find no evidence to directly prove that there is a causal relationship between renewable energy consumption, CO2 emissions, and output, and this result supports the protection hypothesis. In contrast, from a long-term perspective, there is a significant two-way causal relationship between renewable energy consumption, output, export, and CO2 emissions, supporting the feedback hypothesis (Dogan et al. 2016; Ito, 2017; Chen et al. 2020). Finally, impulse response analysis intuitively describes the unstable changes of variables in response to some external shocks. Impulse response analysis further verifies the causality test results. As expected, there is a strong negative
correlation between CO₂ emissions and renewable energy consumption (Bilgili et al. 2016), which confirms the fundamental role of renewable energy in reducing CO₂ emissions. This finding is similar to existing energy literature such as Apergis et al. (2018) and Brini (2021) for the case of Africa countries and Chen et al. (2019), Hu et al. (2021), and Zhang et al. (2021) for the case of China. In addition, CO₂ emissions also play a positive role in promoting industrial and agricultural output and export, but renewable energy has a negative impact on export. This indicates that the use of renewable energy cannot meet the peak of trade export demand in the short term, and a large amount of energy is needed. In non-renewable energy sources, fossil fuels are usually used. Therefore, the output and export of the industrial and agricultural sectors are directly responsible for the rapid increase in China’s CO₂ emissions (Riti et al. 2017), which indirectly indicates that China’s current renewable energy consumption is still a relatively low proportion of primary energy, and that renewable energy consumption alone will not contribute to environmental quality improvement and economic growth in the short term.

Based on the above conclusions, the Chinese government should pay more attention to renewable and non-renewable energy consumption in order to realize the continuous growth trend of renewable energy consumption. As we all know, greenhouse gas emissions from non-renewable energy consumption have an adverse effect on ecosystem activities. However, the economic benefits of non-renewable energy consumption in life and production are more obvious, and the electricity consumption from non-renewable energy sources is also more common. But considering clean energy, carbon emission reduction, and energy security, increasing renewable energy consumption is inevitable. At the same time, in order to achieve the ultimate goal of energy conservation, emission reduction, and ecological environment construction, we still face a large uncertainty in dealing with climate change. For this reason, the Chinese government should provide financial, legal, and policy support, from the perspective of government policy and investment incentives to increase the proportion of renewable energy in energy consumption, so as to reduce the consumption of non-renewable energy.

This study has certain limitations. Firstly, based on the literature, this article only selects renewable energy consumption, output, and export as the determinants of CO₂ emissions from the perspective of industry and agriculture. This will inevitably lead to omissions or missing. Secondly, this article ignores the heterogeneity between China’s regions, which discusses the relationship between renewable energy consumption, output, export, and CO₂ emissions from a national perspective and uses the meteorological analysis method such as co-integration tests, causality tests, and impulse response analysis etc. In addition, the expansion of other variables of this study should include population indicators and other economic indicators that affect environmental degradation as much as possible. Further research considering these issues is of great significance to the study of CO₂ emissions in China.

**Policy implication**

From the above analysis, it is clear that for China, the output and export of the industrial and agricultural sectors are the main reasons for the sharp increase in CO₂ emissions. But in the long term, renewable energy has a positive effect on reducing CO₂ emissions. Therefore, the development of renewable energy is an inevitable trend to cope with the global warming problem. In addition, this paper puts forward the following suggestions from the perspectives of increasing market demand, improving technology, reducing development and utilization costs, and improving relevant policies and regulations.

**Accelerate the adjustment of energy structure and increase the supply of clean energy**

The impact of renewable energy on carbon emissions and economic growth fluctuates sharply in the short term, but the impact effect is low in the long term, so there is a need to establish a long-term mechanism for renewable energy consumption and adhere to long-term policies. In terms of energy structure, the government should actively develop high-quality clean energy; increase subsidies; gradually reduce the energy consumption structure dominated by coal consumption; increase the replacement ratio of wind power, hydropower, and nuclear power; develop and utilize new energy represented by ocean energy, modern biomass, and geothermal energy; and support the photovoltaic industry. In terms of energy utilization, the key to improve energy utilization lies in the development, innovation, and promotion of energy technologies, for example, the application of clean coal technology, circulating fluidized bed technology; and coal liquefaction technology will reduce the amount of coal loss and consumption, reduce the amount of coal consumption per unit, and gradually improve the traditional energy consumption system.

**Increase the investment in technology research and development to improve the level of scientific and technological development**

The development of renewable energy in China is still in the initial stage. In addition, the current economic downward trend has led to an increase in the risk of renewable energy
investment itself. As the result, many enterprises reduced the investment in research and development of related technologies. Therefore, energy management departments should formulate relevant policies to promote enterprises to increase investment in research and development of renewable energy technologies, set market access conditions for investment in relevant renewable energy projects, and strengthen the supervision of renewable energy production to reduce the impact of the production process on local residents and the environment. At the same time, it is also necessary to develop a reasonable scientific research planning, promote the search for new technologies closely related to the development and utilization of renewable energy such as solar energy and biomass energy, and integrate the existing scientific research resources. They should also advocate the cooperation of enterprises, research institutes, and laboratories of universities with leading scientific research capabilities to jointly complete the technical research tasks and strengthen the exchange of talents with various countries to fully realize the advantages of mutual assistance.

Further improve the relevant industrial policies and institutional system

Government departments should further improve the management and decision-making mechanism for the development of the renewable energy industry and promote efficient cooperation and scientific decision-making among relevant departments. Governments at all levels need to improve the financial support system for renewable energy from the perspective of promoting the development of the whole renewable energy industry and promote the prosperous development of the renewable energy consumption market. At the same time, it is also necessary to improve the standard system of renewable energy equipment and products, the testing and certification system, and the strict punishment system for violation, so as to further improve the access system and monitoring system of China’s renewable energy trading market and promote the market to be rationalized continuously.

Strengthen the influence of policies on renewable energy consumption

The government should pay attention to the role of the promotion of policies in the development of renewable energy. It is necessary to compulsorily promote the development of renewable energy from the perspective of industry planning, to make policies have obvious influence on the market through direct legislation and relevant market management system, and to compulsorily promote the proportion of renewable energy in the energy market by policy regulations, so as to achieve the purpose of energy conservation and emission reduction.

Enhance and improve the industry chain

China has not formed a perfect market access system for renewable energy industry; the market entry threshold is low with disorderly competition and severe repeated construction, which are not conducive to the development of renewable energy. With wind power as an example, international and domestic large wind turbine manufacturers have established a relatively good industrial belt in Bohai Bay, but not formed a complete industrial chain. Therefore, China needs to grasp the opportunity of possible major adjustment of the global industry chain of manufacturing industry after COVID-19, develop renewable energy equipment manufacturing industry, form a good industry chain, and build a world advanced renewable energy manufacturing base.

Abbreviations

CO2: Carbon dioxide; IRFs: Impulse response functions; VECM: Vector error correction model; ECM: Error correction term; AIC: Akaike information criterion; SIC: Schwarz information criterion; HQIC: Hannan-Quinn information criterion

Author contribution Not applicable.

Data Availability The datasets used in this study are available from the corresponding author upon request.

Declarations

Ethics approval and consent to participate Not applicable.

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