The role of green energy deployment and economic growth in carbon dioxide emissions: evidence from the Chinese economy

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Abstract
After reform and opening-up, rapid industrialization and urbanization led to environmental degradation in China, including excessive energy consumption, soil contamination, and water pollution. Toward sustainable development, the Chinese government has promoted the introduction of clean energy sources such as geothermal and hydroelectric power generation, which have reduced the environmental burden. However, the impact of this energy shift on environmental improvement and economic growth is unclear. This study empirically analyzes the impact of green energy deployment and economic growth on CO2 emissions in China. The analysis of time series data from 1980 to 2020 shows that in the long run, a 1% increase in renewable energy significantly reduces CO2 emissions by 0.87%, and a 1% increase in GDP significantly increases CO2 emissions by 0.26%. In contrast, in the short run, the negative effect of renewable energy on CO2 emissions and the positive effect of GDP on it are not significant. This result was confirmed after the robustness checks. Based on the results obtained, several policy recommendations are made.

Keywords Sustainable development · Green energy deployment · Economic growth · China

JEL Classification Q01 · Q51 · Q55

Introduction
After opening up in the mid-1980s, China has witnessed tremendous transformation in improving economic indicators, industrialization, and rapid urbanization. To do so, China had to use many natural resources; consume much energy; pollute the soil, air, and water; and do other things to degrade the environment. Nonetheless, since the late 1990s, the Chinese government has taken necessary steps in the interest of the environment and sustainable development, launching several proactive environmental policies and legislative projects that demonstrate a growing awareness of the ecological and energy crisis. In this regard, the Chinese government is trying hard to shift toward green energy sources. Moreover, policymakers are trying to develop innovative concepts or introduce new technology to reduce environmental loss while sustainable ecological measures. The intensive use of green energy sources such as solar and wind will help increase the involvement of renewable energy, lessen pollution, and improve the air quality in urban areas, thus making a substantial contribution to building sustainable anticipations of energy systems in China. In
this process, the lifespan of oil and gas resources should be longer while retaining China’s status as a major consumer of petroleum and renewable energy in the future. However, does this shift toward renewable energy impact protecting the environment? In this long journey, does trading off with economic growth be significant?

Environmental innovation is also a proposed way of maintaining economic growth, conserving the environment, and encouraging sustainable development. Studies found a consistent long-term correlation exists between CO₂ emissions, commerce, income, environmental innovation, and the use of renewable energy (Khan et al. 2020). Thus, the question addressed here has the recent implementation of environmental innovation measures and exploitation of several green energy sources contributed to reduced greenhouse gasses in China? In this context, this investigation aims to discuss and explore the role of efficient energy source deployment in China’s carbon dioxide (CO₂) emissions while maintaining its economic growth. There has been extensive research in energy policy regarding the causal relationship between CO₂ emissions and energy use or non-renewable energies. Recently, researchers have been looking at the causal relationship between the use of green energy and CO₂ emissions. The studies have taken into consideration various geographical areas, complex econometric instruments, and various describing variables. For example, Khan et al. (2020) have tried to identify the role of environmental innovation and renewable energy for developed countries regarding consumption-based carbon emissions and international trade. Another study by Ma et al. (2021) examined the effects of emission levies, energy sector investments, R&D spending, technical advancement, and tertiary sector development on the Chinese province’s carbon dioxide emission data between 1995 and 2019. Huang and Li (2018) have sorted how resource alignment moderates the relationship between green innovation performance and environmental innovation strategy. Li et al. (2020) have tested new determinants of renewable energy consumption concerning eco-innovation and energy productivity. Belaïd et al. (2021) conducted empirical research on key drivers of renewable energy in the MENA region. Usman et al. (2021) looked into the environmental quality generated by renewable energy and recorded innovative research investment in renewables under the environmental Kuznets curve (EKC) model for G-7 nations. Their results supported the validity of the EKC hypothesis for the G-7 nations. However, analyzing related articles, we have noticed that the environmental effects of environmental innovation should be studied. The environmental effects of environmental innovation have gained very little research attention. Some individual studies on China’s economic growth are focused on environmental protection. But as far as we are concerned, there are few existing investigations that have examined the connection between green energy use and CO₂ emissions in the Chinese economy. Maintaining economic growth and protecting the environment are crucial and challenging for China at this current stage. Thus, one hypothesis testing in our proposal is a comparatively new research and will create a new scope for future research in a similar arena. These two indicators should give us a clear idea of maintaining the trend.

Additionally, after analyzing the dataset and testing the hypothesis, we will suggest realistic and suitable solutions based on the obtained findings to the concerned authorities. This paper will examine this causal association for China based on research objectives and key scientific problems as follows: first, display the debate between green energy use and the CO₂ emissions issues in China, mainly after economic reform; second, explore the role of green energy deployment in improving and protecting the environment in China; third, suggest realistic and suitable solutions based on the obtained findings for the concerned authorities. The paper theme is demonstrated in Fig. 1.

This paper’s rest is organized as follows: “Literature review” presents the literature review. “Econometric methodology” displays the econometric methodology. “Result and interpretation” provides results and interpretations. “Sensitivity analysis” discusses the sensitivity analysis. In the end, “Conclusion and future research” concluded and suggested some future research.

**Literature review**

One of the earliest studies was made by Sadorsky (2009), citing the literature on causality between green energy use and CO₂ emission in developing economies. The authors found proof of a long-term conservation hypothesis and a short-term neutrality hypothesis in emerging economies. Subsequent studies are still extending his primary findings. For example, Zeb et al. (2014) find bidirectional Granger causality between energy production and poverty in Pakistan, as well as Granger causality from energy

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**Fig. 1** Demonstration of the theme

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**Economic reform (1990-)**

- Green Energy ↑
- CO₂ emission ↓
- Environmental protection ↑
- Economic Growth ↑ ??
production to poverty in Bangladesh and India, and from poverty to energy production in Sri Lanka, when looking at the relationship between energy production and poverty in selected SAARC countries.

Moreover, GDP and poverty positively influence energy production. Sadorsky’s (2009) results, which cover the period 1994–2003, are valid for more extended periods. Paramati et al. (2017) intend to investigate renewable energy consumption’s role in output and CO2 emissions in the next fastest developing economies of the world from the period 1990 to 2012. Empirical results indicate that the variables have a significant long-term association. The findings also show that green energy use contributes positively to economic growth and harms CO2 emissions. Studies so far have shown that poverty increases energy consumption and production. Renewable energy, a form of green energy, reduces CO2 emissions and promotes sustainable development (Usman et al. 2022) and energy intensity, while it enhances aggregate national savings (Salahuddin et al. 2020). The authors have found that economic growth still seems expensive for the region as it stimulates CO2 emissions for 34 sub-Saharan African nations.

Generally, poorer households are more dependent on fossil fuels as a source of energy. In other words, deprivation leads to global warming through energy. However, education, which is important for economic development, is also effective in reducing poverty. Consequently, education may reduce greenhouse gas emissions by reducing poverty and reducing energy consumption with greenhouse gas emissions. Zafar et al. (2020) examined the effects of renewable energy on CO2 emissions and other relevant factors in 28 OECD nations from 1990 to 2012. The empirical findings suggest that green energy positively impacts environmental quality. This is due to the fact that renewable energy use boosts economic growth, while education reduces CO2 emissions. They also discovered a bidirectional causal association between CO2 emissions, education, and renewable energy consumption. This means that these factors have a feedback effect. As a result, countries should encourage investment in green energy and education to create a more sustainable society.

The empirical findings obtained separately for emerging and industrialized countries imply a structural shift from energy- and carbon-intensive to service-oriented economies. According to Sarkodie and Adams (2018), (i) a 1% increase in fossil fuel consumption increases CO2 emissions, (ii) a 1% increase in renewable energy consumption reduces CO2 emissions, (iii) pollution is exacerbated by energy consumption and economic growth, and (iv) improvements in political and institutional quality minimize pollution. Significantly, the research from 1971 to 2017 suggests that the environmental Kuznets curve (EKC) theory may be valid in South Africa. They reveal the importance of the quality of political institutions in adapting to climate change. Responding to climate change requires governments to implement environmental policies. However, their policies impose a financial burden on pollutive firms in the energy- and carbon-intensive economy. When political institutions are immature, firms may try to escape the responsibility of environmental policies by paying bribes (Hamaguchi 2020). The study reveals that fossil fuel-rich countries need energy portfolio diversification, which promotes environmental sustainability and, at the same time, reduces price volatility vulnerabilities of their economies.

The government must encourage R&D in renewable energy for a sustainable society to realize this aim. Ike et al. (2020) examined renewables use and electricity costs, and trade carbon effects. They also confirm the EKC hypothesis at the panel and country-specific levels in G7 countries. The findings suggest that, while the scale of exchange exerts a strong positive impact on CO2, clean energies and oil costs exert negative pressure on CO2 emissions. Previous studies have clarified the relationship between renewable energy, the environment, and growth, while expanding the period and region of interest. As a result, the EKC hypothesis has also been discovered. Under this hypothesis, the relationship above will change depending on where the turning point is located.

Environmental innovations should significantly impact the relationship between renewable energy, the environment, and growth through the turning point because they affect energy efficiency and economic growth. Besides, it will also play a decisive role in oil prices and other factors, which Ike et al. (2020) point out. However, there has not been sufficient analysis of the relevance and effect of this important variable on the relationship between renewable energy and the environment in China. This study will help fill this gap.

As an empirical investigation examining the relationship between environmental protection and innovation, Carrión-Flores and Innes (2010) assessed the nexus between toxic air pollution rate and environmental innovation using the simultaneous panel data model from 1989 to 2004. They found that environmental innovation is a significant catalyst for reducing harmful emissions in the USA and that tighter emission standards cause environmental improvements leading to greater reductions in emissions. Besides, Chiu et al. (2011) displayed that innovation in the environmental field considerably increases the environmental efficiency of “greening” suppliers in Taiwan. They found that environmental process and goods innovation can be more successful than environmental managerial innovation in enhancing environmental efficiency. Recently, Wang et al. (2020) found that technological innovation has a damaging effect on carbon emissions for N-11 economies. However, the impact of environmental innovation on economic growth and pollution emissions is unclear. Zhang et al. (2017) show that environmental innovation in China’s case is essential and
impactful and considers energy efficiency and R&D as the critical elements in reducing CO₂ emissions from 2000 to 2013. The conclusions of the latter study are validated by the consistent outcomes of Long et al. (2017), while further additional findings show that environmental control and attitudes are positive for environmental innovation. This finding is important because theoretical analysis using an endogenous growth model reveals how environmental policy leads to sustainable development. For example, increasing environmental taxes reduce pollution emissions, expand economic growth, and improve welfare via innovation (Nakada 2004; Grimaud and Tournemaine 2007; Chu and Lai 2014). Moreover, decreasing permits leads to sustainable development (Hamaguchi 2019, Hamaguchi 2021a). By contrast, Grimaud (1999) and Hamaguchi (2020) indicate that stricter environmental policy expands pollution emissions and reduces economic growth. Hence, the theoretical analysis results continue to debate the impact of environmental policy on pollution emissions and economic development through innovation. Our analysis will make specific contributions to these contexts.

Dogan and Ozturk (2017) used the environmental Kuznets curve (EKC) model to examine the effects of real income (GDP), renewable energy use, and non-renewable energy use on carbon dioxide (CO₂) emissions for the United States of America (USA) during the years 1980 through 2014. They found that escalating non-renewable energy use increases CO₂ emissions, whereas growing renewable energy consumption mitigates environmental damage. Chien et al. (2022) looked at how urbanization, economic development, and clean energy from renewable sources affected the amount of greenhouse gas emissions in ten Asian countries from 1995 to 2018. The study’s findings demonstrated that GDP and renewable energy contributed positively to lowering GHG emissions in the environment or specific economies. Thus, a new form of green energy invention, environmental innovation, may foster economic growth by lessening environmental pollution expenditure. However, the summary of the covered literature is listed in Table 1.

From the above discussion, we formulate the following hypothesis for our proposed research project: CO₂ emissions are adversely related to green energy use. Regarding

| Authors                    | Method/Model       | Content                                                                 | Result                              |
|----------------------------|--------------------|-------------------------------------------------------------------------|-------------------------------------|
| Carrión-Flores and Innes   | Bi-directional     | Env. innovation and air pollution                                        | Env. innovations reduce toxic emission; tighten pollution targets induce Env. innovation |
| Chiou et al. (2011)        | Structural equation modeling | Green supply chain, Green Inno., Env. Performance, competitive advantage | Green supply + green inn benefits Env. performance and competitive advantage |
| Zhang et al. (2017)        | SGMM               | Env. Inno. → CO₂ emission, CO₂ emission effect on CET                  | Env. Inno. reduce CO₂ emission      |
| Wang et al. (2020)         | Pesaran unit root test (2007) | Fin. Dev., human capital, RE, GDP → CO₂ emission                       | CO₂ emission & Fin Dev. and GDP has (+) relation |
| Long et al. (2017)         | Structural equation model | Env. innovation and TPB                                                 | Env. norm Env. behavior (+) affect Env. innovation |
| Dogan and Ozturk (2017)    | EKC                | GDP, RE, N-RE, and CO₂ nexus                                           | RE reduce Env. pollution, N-RE increase CO₂ |
| Chien et al. (2022)        | CS-ARDL            | Urbanization, ED, RE, and CO₂ nexus                                     | GDP growth and RE lower CO₂         |
| Sadorsky (2009)            | Panel cointegration | Per capita income and RE nexus                                         | Increases in per capita promotes RE/ per capita use |
| Zeb et al. (2014)          | FMOLS              | RE, CO₂, NRD, GDP, and Poverty                                         | GDP and poverty has pos.; CO₂ has negative impact. Energy production |
| Zafar et al. (2020)        | Second generation methodologies | RE and CO₂ nexus with Edu., → FDI, ED                                  | RE promotes Env. quality Edu. reduce CO₂, FDI detoriate Env. quality |
| Sarkodie and Adams (2018)  | CUSUM, OLS         | Energy, ED, Urban., Poli. Ins                                          | Poli. Ins. plays a huge role in climate change |
| Hamaguchi (2020)           | R&D based growth model | Env. Pol → pollution, corruption, welfare, Growth rate                 | Env. tax decrease growth rate       |
| Ike et al. (2020)          | EKC                | RE → energy, Trd in emission                                           | RE and energy price exert neg. pressure on CO₂ |
the hypothesis, we can get an idea of whether there is a correlation between green energy use and CO₂ emission level. It will also allow us to show some evidence of whether the economic growth has suffered due to environmentally friendly actions taken recently.

**Econometric methodology**

In this study, we used monthly time series data of China for the period from 1980 to 2020. Data for the dependent variable CO₂ emission and all independent variables for model one are as follows: green energy (proxied by renewable energy use in the percentage of total energy), GDP per capita US$ (2010), and labor force (proxied as a number of persons engaged in millions). The data for all of these time series variables have been taken from World Development Indicators (WDI). The designations of the variables are listed in Table 2 below:

According to the time series data, if cointegration exists among the time series variables, there is a long-run relationship among and between the time series variables. An essential requirement for analyzing the cointegration between the time series variables is that the variables must be cointegrated in the same order. Furthermore, researchers generally used Dicky-Fuller and augmented Dicky-Fuller tests to see the integration order. Therefore, we must perform the unit root test and decide which technique is applicable. Because of the time series variables are integrated at the order I(0) or stationary at level, we will use the ordinary least square (OLS) methodology. But if variables are integrated at the order I(1) or stationary at the first difference, we will use Johansen’s cointegration methodology to estimate the long-run relationship among the time series variables (Dickey and Fuller 1979). Furthermore, according to Pesaran et al. (2001), if time series variables are showing mixed order of integration I(0) and I(1) but stationary at the order I(2), then we will use (ARDL) autoregressive distributed lag approach methodology. The whole study process is pictured in Fig. 2.

**Unit root test**

In this study, we use an augmented Dickey-Fuller (ADF) unit root test to test which time series variable is integrated at order I(0) or I(1), or I(2). Therefore, as an example, we consider the AR (1) model for the unit root test via the following:

\[ Y_t = \theta Y_{t-1} + \epsilon_t, \]  

(1)

where if the error term \( \epsilon_t \) is distributed normally, three possible potential circumstances will happen: If \( |\theta| < 1 \), then we conclude that the time series variable is stationary. If \( |\theta| > 1 \), then we conclude that the time series variable is non-stationary. If \( |\theta| = 1 \), then we conclude that the time series variable has a unit root problem and this series may show trend and non-stationary.

To answer the issue of unit root when \( |\theta| = 1 \), then we subtract from both aspects of an equation (A):

\[ Y_t - Y_{t-1} - \theta Y_{t-1} + \epsilon_t, \]

Here, we can say that series is normally distributed and integrated at order I(1), which means that it is stationary at the first difference. Conversely, if the series is stationary without any difference, we may say it is integrated at order I(0) or stationary at level.

**Augmented Dickey-Fuller unit root test**

Augmented Dickey-Fuller (ADF) unit root test is added to the Dickey-Fuller (DF) test. This is because the ADF test includes an extra lagged period of the dependent variable to resolve the issue of autocorrelation between the disturbance terms. We use AIC, Akaike information criteria, and SBC means Schwartz Bayesian criteria (Dickey and Fuller 1979).

| Variables       | Designation                                      |
|-----------------|--------------------------------------------------|
| Labor force (L) | Proxied as the number of persons engaged in millions |
| Green energy (GE) | Proxied by renewable energy use in the percentage of total energy use |
| Economic growth (GDP) | Proxied per capita US$ (2010) |

![Flowchart of the study plan](image)

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Based on succeeding equations, the ADF test is Dickey and Fuller (1979):
\[ \Delta Y_t = \theta Y_{t-1} + \sum_{i=1}^{\rho} \beta_i \Delta Y_{t-i} + \epsilon_t, \]
where \( \Delta t, \rho, \) and \( \epsilon \) indicate the first difference, time sub-
script, lag length, and the disturbance term, respectively. Generally, there are three possible types of ADF tests (Dickey and Fuller 1979):

1) With intercept but no trend
\[ \Delta Y_t = \alpha_o + \theta Y_{t-1} + \sum_{i=1}^{\rho} \beta_i \Delta Y_{t-i} + \epsilon_t, \]
where \( \alpha \) is the intercept.

2) With trend and intercept
\[ \Delta Y_t = \alpha_o + \theta Y_{t-1} + \beta t + \sum_{i=1}^{\rho} \beta_i \Delta Y_{t-i} + \epsilon_t, \]
where \( \beta \) is the time trend.

3) No intercept and no trend
\[ \Delta Y_t = \theta Y_{t-1} + \sum_{i=1}^{\rho} \beta_i \Delta Y_{t-i} + \epsilon_t, \]
where \( \epsilon_t \) is the error term. We will also repeat the analysis for this model for the error correc-
tion model (Frank 2009). However, we obtain the following re-

eresult and interpretation

Augmented Dickey Fuller unit root test

In this study, we used the unit root test to estimate the sta-
tionarity level of the time series variables. All of the time series variables are converted into a log form. However, observing Table 3 for the variables, carbon dioxide emissions, renewable energy use, and GDP are stationary at the first difference, or we can say they are integrated at the order \( I(1) \). In contrast, a variable of the labor force is station-
ary at the level. However, according to the unit root test, if variables show mixed order of integration, we will use the ARDL methodology to see the short-run and the short-run relationship between the dependent and independent time series variables (Cheema and Atta 2014).

VAR lag order selection criteria

Before applying the ARDL methodology, we must first see the lag order selection criteria in Table 4. Therefore, after using the var test, the SBIC criteria indicate that the optimal lag order should be one and the HQIC, AIC, and FPE criteria suggest that the optimal lag order should be four.

| Variables    | Level | First difference | Integrated order |
|--------------|-------|------------------|-----------------|
| Ln_CO2       | 0.036 | 3.466***         | I(1)            |
| Ln_Renewenergy | -0.672 | 2.791*          | I(1)            |
| Ln_GDP       | -0.793 | 3.245**         | I(1)            |
| Ln_LaborForce | -6.83*** | -            | I(0)            |

* is \( p < 0.05 \), ** is \( p < 0.01 \), and *** is \( p < 0.001 \)
data, and thus, we are applying the autoregressive distributed lags (ARDL) model approach. Table 5 indicates that a coefficient of Ln_CO$_2$ at first lagged indicates a positive and significant effect at the 5% level on the current period of Ln_CO$_2$. The coefficient of Ln_Renewenergy indicates a negative and significant effect at a 1% level on Ln_CO$_2$. It shows that a 1% increase in the use of renewable energy will decrease 0.74% carbon dioxide emissions. Coefficient Ln_LaborForce at the current period shows a statistically significant positive impact on Ln_CO$_2$ and negatively affects at first lagged. It was significant at the 1% level. This implies that a 1% increase in Ln_LaborForce will increase 7.5% Ln_CO$_2$. In contrast, a 1% increase in Ln_LaborForce at lagged will decrease 7.9% Ln_CO$_2$. However, the variable Ln_GDP shows an insignificant impact on the dependent variable Ln_CO$_2$. The $R^2$ shows the goodness or fitness of the model, and it also explains how many explanatory variables are explained about the dependent variable. So, according to the results, the independent variables explain 99% variation in carbon dioxide emissions. Although many researchers say that a high $R^2$ shows a good model, in the opposite, many researchers say that our main concern is the relationship between independent and dependent variables. $F$-statistics (1737.40) show that the overall model is significant at a 1% level.

### ARDL long-run and short-run model results

Table 6 indicates that the long-run coefficient of Ln_Renewenergy indicates a negative and significant effect at 1% level on Ln_CO$_2$. It shows that a 1% increase in the use of renewable energy will decrease 0.87% carbon dioxide emissions. The number of studies also highlights the importance of

| Lag | LL | LR | df | p   | FPE | AIC | HQIC | SBIC |
|-----|----|----|----|-----|-----|-----|------|------|
| 0   | 134.604 | -  | -  | -  | 4.3e-09 | -7.91537 | -7.85433 | -7.73397 |
| 1   | 379.994 | 490.78 | 16 | 0.000 | 4.0e-15 | -21.8178 | -21.5126 | -20.9108* |
| 2   | 402.308 | 44.629 | 16 | 0.000 | 2.8e-15 | -21.2005 | -21.6512 | -20.5679 |
| 3   | 416.918 | 29.22 | 16 | 0.000 | 3.5e-15 | -21.1162 | -21.3228 | -19.7581 |
| 4   | 449.212 | 64.588* | 16 | 0.000 | 1.7e-15* | -23.1038* | -22.0662* | -20.02 |

Endogenous: ln$_c2$, lnrenewenergyn, lngdp, lnlaboreforcenn. Exogenous: _cons

Selection order criteria

Sample 1984–2016; number of obs = 33
renewable energy. They found that renewable energy reduces carbon dioxide emissions (Bilgili et al. 2016; Qi et al. 2014; Silva et al. 2012). Notably, Qi et al. (2014) stated that if the cost of renewable energy reduces because of policy efficiency, GDP will also consistently increase yearly. Therefore, the cost-efficient policy can reduce carbon dioxide emissions and achieve China’s economic growth target. Coefficient Ln_GDP shows a statistically significant positive impact on Ln_CO2, significant at 5% level. A 1% increase in Ln_GDP will increase by 0.26% Ln_CO2. However, in the long run, variable Ln_laborforce shows an insignificant negative impact on dependent variable Ln_CO2.

**Sensitivity analysis**

**Error correction model**

We estimate the error correction results to see whether our long-run relationship among time series variables is true or not. The error correction methodology is used to see the short-run results. The first pioneer who used the error correction term (ECT) was Sargan (1964) to identify short-run cointegration (Cheema and Atta 2014). This technique explains how adjusting time series variables from the short-run to long-run equilibrium position occurs (Engle and Granger 1987). Lagged value of the coefficient of ECT (−1) indicates the speed of adjustment from the short-run to long-run equilibrium only if it has a negative sign. If it has a positive sign, then it means that variables will move away from the long-run equilibrium position (Lal et al. 2010). Using these empirical techniques, our results in Table 4 demonstrate that the error correction term (−1) shows a significant negative sign at the 1% level. So, the value of the error correction term (−0.644) explains that the time series variables will move toward a long-run equilibrium position at a speed of 64% after a short-run shock. The short-run coefficient Ln_laborforce shows a statistically significant positive impact on Ln_CO2 in the current period. It was significant at 1% level. This implies that a 1% increase in Ln_laborforce will increase 7.90% Ln_CO2 in the short run. However, variable Ln_Renewenergy showed an insignificant negative and inconsistent Ln_GDP showing an insignificant positive impact on dependent variable Ln_CO2 in the short run.

**ARDL bound test results**

The null hypothesis is that no cointegration exists. Table 7 shows that the F-statistics value is 5.40 greater than the upper bound value of −3.78 at 5% level. Therefore, we reject the null hypothesis and can say that there is cointegration that exists among the time series variables.

The diagnostic and stability tests are used to determine the ARDL model’s goodness of fit. The model’s serial correlation, functional form, normalcy, and heteroscedasticity are all examined in the diagnostic test. CUSUM (cumulative sum of recursive residuals) and CUSUM (cumulative sum of squares of recursive residuals) are used in the stability test (CUSUMsq). Another method of determining the ARDL model’s reliability is to look at the model’s prediction error. The model can be regarded as the best fitting if the error or discrepancy between the actual observation and the forecast is minuscule. The recursive CUSUM test is shown in (Fig. 3).

In this study, we used Durbin Watson (DW) (Durbin and Watson 1950) test to see whether the problem of autocorrelation exists in the model or not. The DW test value of 2.11 explains that there is no autocorrelation problem in the ARDL model via the following:

| Table 6 | Long- and short-run results (ARDL) |
|---------|----------------------------------|
|         | D.lnc2  | Coef | Std.Err | t     | P > t | [95%Conf Interval] |
| ECT (−1)| −0.644  | 0.146 | −4.420  | 0.000 | −0.942 | −0.345 |
| Long-run| Ln_renewenergyn          | −0.876  | 0.115  | −7.630 | 0.000 | −1.111 | −0.641 |
|         | Ln_gdp          | 0.267  | 0.120  | 2.220  | 0.034 | 0.021 | 0.514 |
|         | Ln_laborforce   | −0.478  | 0.595  | −0.800 | 0.428 | −1.696 | 0.740 |
| Short-run| Ln_renewenergyn | −0.185  | 0.204  | −0.910 | 0.372 | −0.483 | 0.233 |
|         | D1 Ln_gdp | 0.180  | 0.231  | 0.780  | 0.443 | −0.294 | 0.653 |
|         | D1 Ln_laborforce | 7.907  | 2.592  | 3.050  | 0.002 | 2.598 | 13.216 |
|         | _cons          | 7.474  | 7.109  | 1.050  | 0.302 | −7.089 | 22.036 |
Furthermore, we also use the Breusch-Godfrey LM test for the autocorrelation test to see whether the problem of serial correlation exists in the model or not. In Table 8, the p-value of 0.121 of the Breusch-Godfrey LM test for autocorrelation explains that we will accept the null hypotheses.

### Table 8  Results in LM test

| Breusch-Godfrey LM test for autocorrelation | df | Prob > chi² |
|-------------------------------------------|----|-------------|
| 5.822                                     | 3  | 0.121       |

Note that H0 indicates no serial correlation.
and say that no serial correlation problem exists in the ARDL model.

In the same context, we use the heteroskedasticity test to see whether the problem of hetero exists in the model or not. In Table 9, according to the $p$-value 0.33, we will accept the null hypotheses and say that no hetero problem exists in the ARDL model.

CUSUM square test is used to see the stability of parameters in the model. Figure 4 states that the predicted line is within the region. This means that our parameters are stable and reliable.

### Conclusion and future research

This study empirically analyzes how China’s green energy deployment and economic growth affect CO$_2$ emissions. Aiming for economic development, the Chinese government implemented reform and an open-door policy in the mid-1980s, which led to rapid industrialization and urbanization. However, in addition to excessive energy consumption, environmental degradation such as soil and water pollution becomes a social problem. In the 1990s, the Chinese government actively introduced environmental policies to achieve a sustainable society. As a result, the introduction of clean energy sources such as geothermal and hydroelectric power generation has progressed, and the environmental burden has been reduced by reducing greenhouse gases. However, it is unclear whether a series of initiatives by the Chinese government has brought about these results. This study investigates this relationship by developing the following hypotheses. Under hypothesis, carbon dioxide emissions are inversely related to green energy use. In the long run, a 1% increase in renewable energy significantly reduces carbon dioxide emissions by 0.87%, while a 1% increase in GDP significantly increases carbon dioxide emissions by 0.26%. In contrast, in the short run, the negative effect of renewable energy on carbon dioxide emissions and the positive effect of GDP on it is not significant. This result was confirmed after the robustness checks. Given the analysis results, we can say that the diffusion of green energy in China is effective in eventually reducing carbon dioxide emissions. Hence, the diffusion of renewable energy through environmental innovation has enhanced China’s sustainability. However, certain reservations must be placed on this result.

Theoretical analysis reveals that environmental policies reduce pollution and economic growth through innovation (e.g. Nakada 2004; Grimaud and Tournemaine 2007; Chu and Lai 2014; Hamaguchi 2019, Hamaguchi 2021b). Empirical studies also captured this relationship (e.g., Carrión-Flores and Innes 2010; Chiou et al. 2011; Long et al. 2017; Zhang et al. 2017; Wang et al. 2020). These previous studies commonly regarded environmental innovation as an essential variable. In particular, theoretical analyzes believe that environmental policies stimulate innovation. Our analysis argues that the Chinese government’s environmental policy played a significant role in the energy shift through environmental innovation. However, this environmental innovation is not considered an explanatory variable. For our argument to be more convincing, we should show that our results are not overturned in an empirical analysis that considers this variable. Additionally, in our analysis, the error term of the labor force is high in both the short and long run. This suggests that we may be missing some important explanatory variables. It is worth noting here that education and awareness may significantly negatively impacts the carbon emission. Zafar et al. (2020) found that poverty alleviation through education contributes to reducing fossil energy consumption as a share of household expenditures another theoretical analysis shows that households substitute leisure time for education through environmental policies to achieve economic growth and pollution reduction through human capital accumulation (e.g., Hettich 1998; Pautrel 2012; Hamaguchi 2021b).
Given these various results, the effect of improving labor productivity through education on reducing carbon emissions may have been overlooked. This effect may be newly discovered if education is considered an explanatory variable.

Thus, we would like to suggest that even though China is facing some economic difficulties (due to COVID-19, lockdowns, inbound tourism, unemployment, and domestic force), the country should continue to promote using of green energy, green growth, environmental innovation subsidies, ETS (energy trading system), electronic vehicles, MREs (marine renewable energy), public awareness, and so on. Few policies like enhancing public perception, increasing government support, feed-in tariffs (FiT), and green certificates systems (GCS) could be implemented to promote green growth at a larger scale.

Some other variables (like rapid urbanization, fossil fuel consumption, unplanned industrialization) can influence CO₂ emission. In addition, due to data limitations, we have used the 1980–2020 data for this study. These limitations of our analysis remain a topic for future research.

Author contribution MAB: original draft, BK: proofreading, YH: drafting, conceptualizing, QZ: supervising.

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Data availability Will be provided if needed.

Declarations

Ethical approval All co-authors give consent that there is no unethical experiment conducted in this research.

Consent to participate All co-authors give consent to participate in this manuscript.

Consent for publication All co-authors consent to publish this article upon acceptance.

Competition interests The authors declare no competing interests.

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