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RESEARCH ARTICLE

How does income and green technology innovation influence the emissions reduction effect of renewable energy: evidence from Chinese provincial data

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Abstract
The development of renewable energy is a key measure to achieving carbon neutrality in China. Considering the significant regional differences in income levels and green technology innovation, it is essential to discuss the impact of renewable energy development on carbon emissions from the Chinese provincial level. Based on the panel data of 30 provinces in China from 1999 to 2019, this study first explores the impact of renewable energy on carbon emissions and regional heterogeneity. Moreover, the moderating effects of income levels on the nexus between renewable energy and carbon emissions, and the impact mechanism of green technology innovation are further examined. Results show that, first, renewable energy development can significantly reduce carbon emissions in China, and there exist obvious regional differences. Second, income levels present a non-linear moderating effect on the relationship between renewable energy and carbon emissions. The increase in income levels can effectively enhance the emission reduction effect of renewable energy only in high-income regions. Third, renewable energy development is an important mediating mechanism for green technology innovation to achieve emission reduction. Finally, policy implications are proposed to help China in advancing the development of renewable energy and achieve carbon neutrality.

Keywords Renewable energy · Income · Green technology innovation, Emissions reduction, China

Introduction

Addressing climate change is a common and severe challenge facing the world. The sixth assessment report of the Intergovernmental Panel on Climate Change (IPCC) shows that it is necessary to achieve net zero carbon emissions by the middle of the twenty-first century to meet the goal of 2-degree temperature control (IPCC 2022). China has actively undertaken the responsibility of emission reduction and proposed that carbon emissions should peak before 2030 and achieve carbon neutrality by 2060. Moreover, given that fossil fuels like coal, oil, and natural gas are the main source of carbon emissions, the crucial path to attaining carbon neutrality lies in the rapid replacement of fossil fuels with renewable energy. What people need for production and life is the energy services provided by fossil energy (Oswald et al. 2020), renewable energy can also provide these energy services. Therefore, from a source perspective, accelerating the high proportion replacement of renewable energy for fossil energy is the key to achieving carbon neutrality.

Existing studies have analyzed the relationship between carbon emissions and renewable energy. Most studies demonstrate that renewable energy development can significantly lower carbon emissions (Adedoyin et al. 2021, Dogan and Seker 2016a, Shahnazi and Shabani 2021). For instance, Shahnazi and Shabani (2021) analyzed the impact of renewable energy on carbon emissions for EU countries. Their findings show that renewable energy has a negative impact on carbon emissions, and there are spatial spillover benefits of carbon emissions. Zheng et al. (2021a) investigate the effect of renewable energy generation on carbon

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emissions in China. They discovered that for every 1% increase in renewable energy, carbon intensity decreased by 0.028–0.043%. However, some other studies have pointed out that the impact of renewable energy on carbon emissions is statistically insignificant. For example, Dong et al. (2020) examined the relationship between carbon emissions, renewable energy, and economic growth based on the full sample of 120 countries and four different income levels. Their results show that renewable energy consumption had no significant negative impact on carbon emissions at the global level. While for the sub-panel data, renewable energy shows a significant negative impact on carbon emissions only in high-income countries.

Developing renewable energy is a crucial strategy for China to tackle climate change and achieve carbon neutrality. China has promised that by 2030, the total installed capacity of wind and solar power would reach more than 1.2 billion KW. As of the end of July 2022, the total installed capacity of power generation in China was about 2.46 billion KW, and the installed capacity of wind and solar power both are 0.34 billion kilowatts (National Energy Administration 2022). With the rapid development of renewable energy, it is essential to conduct an in-depth analysis on the emission reduction effect and influencing factors of renewable energy. First, although the existing studies have analyzed the relationship between renewable energy and carbon emissions in China (Chen et al. 2019a, Dong et al. 2018, Zheng et al. 2021a), the majority of these studies concentrate on the analysis of China's national level, and they are still insufficient on China's province level.

Second, China is a multi-regional nation with substantial variances in economic development and income levels between provinces, thus the impact of renewable energy on emission reduction in various regions is expected to differ. The existing studies focuses on the direct link between renewable energy and carbon emissions in China, and there is insufficient analysis of how renewable energy affects carbon emissions at various income levels, let alone taking into account how income levels moderates the effect of renewable energy on reducing emissions. For instance, Chen et al. (2019b) used Chinese provincial panel data to examine the effect of economic growth and renewable energy on carbon emissions. Their research revealed that the use of renewable energy reduced carbon emissions in the eastern and western regions, but only marginally and statistically insignificantly in the middle region. Therefore, to provide theoretical support for identifying the impact of income levels on the development of renewable energy in various regions, this study explores the moderating effect of income levels on the nexus between renewable energy and carbon emissions.

Third, reaching carbon neutrality depends greatly on pinpointing the driving forces behind the quick expansion of renewable energy. Green technology innovation is one of them and is crucial in advancing the growth of renewable energy (Khan et al. 2022, Zheng et al. 2021b). The effects of green technology innovation on renewable energy have been examined in previous research (Du et al. 2019, Shan et al. 2021, Suki et al. 2022). For example, Xu et al. (2021) use panel data from 218 Chinese prefecture-level cities to examine the effect of heterogeneous green innovation on carbon emissions. They discovered that heterogeneous green innovation has a favorable effect on China's carbon emissions performance. Based on panel data from 264 Chinese prefecture-level cities, Lin and Ma (2022) investigated the relationship between green technology innovation and carbon emissions. According to their findings, green technology innovations can dramatically lower carbon emissions in western cities but only slightly reduce them in eastern and central cities. Suki et al. (2022) analyzed the impact of green technology innovation and renewable energy on carbon emissions in Malaysia. They conclude that green technology innovation and renewable energy could reduce carbon emissions in both the long and short run. Therefore, from the above analysis, it can be found that most of the existing studies focus on the direct relationship between technology innovation, renewable energy, and carbon emissions. Few studies have explored the impact mechanism of green technology innovation on carbon emissions. Specifically, what role does green technology innovation play in the relationship between renewable energy and carbon emissions? Identifying this relationship plays an important role in revealing how to promote the rapid development of renewable energy.

Therefore, the objective of this study is threefold. First, based on the panel data of 30 provinces in China from 1999 to 2019, we examine the impact of renewable energy on carbon emissions. Second, considering the differences in income levels in China's different provinces, the moderating effect of income levels on the emission reduction effect of renewable energy is analyzed. Third, as green technology innovation is a key driving factor for renewable energy, we further investigate the effects mechanism of green technology innovation on renewable energy development and carbon emission reduction. The analysis of this study could help us to better understand the relationship between renewable energy and carbon emissions, and the influence mechanism of income levels and green technology innovation on the nexus between renewable energy and carbon emissions.

The rest of this study is organized as follows. The "Literature review" section reviews the literature about renewable energy, carbon emissions, and green technology innovations and points out the significance of this study. The "Method and data" section describes the method and data sources. The "Empirical results" section presents the results and discussion. The "Conclusions and policy implications" section concludes with policy implications.

Literature review

The nexus between renewable energy on carbon emissions

The relationship between renewable energy and carbon emissions is analyzed thoroughly in the existing studies. Whether at the global level or in individual countries, most studies show that renewable energy development is conducive to reducing carbon emissions (Adedoyin et al. 2023, Hao 2022, Sarpong et al. 2023). For example, Shahbaz et al. (2022) investigated the impact of renewable energy on production-based and consumption-based carbon emissions. They discovered that renewable energy use has a significant negative impact on carbon emissions in the forty developing economies, and is stronger on the consumption-based carbon emissions. Gyamfi et al. (2022) also found that renewable energy has a strong negative impact on carbon emissions in the BRICS countries. For China, Chen et al. (2019a) explored the relationship between per capita carbon emissions and renewable energy. Their findings demonstrate that renewable energy has a long-term impact on lowering carbon emissions.

However, some studies have shown uncertainty and heterogeneity in the relationship between renewable energy and carbon emissions (Chen et al. 2019b, Long et al. 2015, Saidi and Omri 2020). For example, Saidi and Omri (2020) demonstrated that a bidirectional causal relationship between renewable energy and carbon emissions in the short run, but no causal relationship in the long run for the 15 major renewable energy-consuming countries. Akram et al. (2020) discovered that renewable energy has a significant negative impact on carbon emissions at the 10th quantile based on the panel quantile regression. Yu et al. (2020) investigated whether renewable energy in China has a major effect on carbon reduction. They found that while the development of renewable energy helps reduce emissions, its impact is uneven and limited.

The impact of income levels on the nexus between renewable energy and carbon emissions

With different levels of income, the emission reduction effect of renewable energy maybe varies. Therefore, some studies try to reveal the heterogeneous effect of renewable energy on carbon emissions under different income levels (Ben Jebli et al. 2020, Dogan and Ozturk 2017, Namahoro et al. 2021). For instance, Nguyen and Kakinaka (2019) revealed that for low-income countries, renewable energy consumption is positively correlated with carbon emissions, while for high-income countries, the relationship is negative. Namahoro et al. (2021) examined the impact of renewable energy on carbon emissions across different income levels for 50 African countries. They found that renewable energy significantly contributes to reducing emissions except for the upper-middle group.

Moreover, some scholars try to capture the interaction effect between income levels and renewable energy, and identify the moderating effect of income levels on the emission reduction impact of renewable energy. For example, Fatima et al. (2021) indicate that renewable energy can help to reduce emissions, and the increase in income levels could improve the beneficial effects of renewable energy on the environment. Ehigiamusoe and Dogan (2022) investigated the impact of renewable energy, real income, and their interaction on carbon emissions for the 26 low-income countries. They found that the use of renewable energy lowers carbon emissions, but the interaction effect is positive. This showed that the emissions reduction effects of renewable energy were undermined by an increase in real income.

For China, there exist great differences in income levels among the various regions. Moreover, the current power generation cost of renewable energy is still higher than that of fossil energy. The large-scale development of renewable energy needs a high level of income. This requires us to further consider the moderating effect of income levels on the emission reduction impact of renewable energy. Therefore, based on the panel data of 30 provinces in China, this study introduces the interaction term of income levels and renewable energy to identify the heterogeneity effect of renewable energy on carbon emission.

The impact of green technology innovation on the nexus between renewable energy and carbon emissions

Green technology innovation is considered to be an important driver to promote renewable energy and reducing carbon emissions. However, due to various constraints on the implementation and diffusion of green technology innovation, the relationship between green technology innovation, renewable energy and carbon emissions needs to be further examined. The existing studies that have conducted in-depth analysis try to capture the robust linkage between them (Danish and Ulucak 2021, Du et al. 2019, Su et al. 2022). Specifically, Danish and Ulucak (2021) compared the relationship between technological innovation, renewable energy and carbon emissions in the USA and China. Their results showed that green technology innovation could reduce carbon emissions in the USA, but had no statistically significant effect in China. Su et al. (2022) found that renewable energy significantly lowers emissions, while the effect of technology innovation on emissions reductions was less than that of renewable energy. For China, Lin and Zhu

(2019) observed a threshold effect in the development of renewable energy technology innovation, indicating that as more renewable energy was generated, the effect on reducing emissions grew.

Among the existing literature, it can be found that most studies focus on the direct impact between green technology innovation, renewable energy, and carbon emissions, and few studies focus on the impact mechanism of green technology innovation on the emissions reduction effect of renewable energy. Exploring the impact of green technology innovation on renewable energy plays an important role in how to guide the development of a high proportion of renewable energy. Therefore, this study further analyzes the impact mechanism of green technology innovation on promoting renewable energy to achieve carbon emission reduction.

Method and data

Econometric model

Given the endogenous problem of the reverse causality of renewable energy and carbon emissions, the ordinary least squares or fixed effects models might lead to estimation bias. First, there are so many factors affecting carbon emissions that it is difficult to control for all the important factors. Second, carbon emission is a continuous process, and the current carbon emission is affected by the past period. Therefore, in line with previous literature (Ben Jebli et al. 2020, Fatima et al. 2021), this study adopts the method of system generalized method of moments (GMM) developed by Arellano and Bond (1991). The explained variable, i.e., the lag period of carbon emissions per capita, are used as an instrumental variable to control the endogeneity problem. The econometric model (1) is constructed as follows.

$$CO2_{i,t} = \alpha_0 + \alpha_1 RENEW_{i,t} + \alpha_2 CO2_{i,t-1} + \gamma \sum C_{i,t} + \varepsilon_{i,t} \tag{1}$$

Where the explained variable is the carbon emissions per capita ($CO2_{i,t}$) measured in tones per person. The main explanatory variable is renewable energy generation ($RENEW_{i,t}$).

First, considering that renewable energy in China is mainly used in the form of electricity, and is affected by geographical and climatic factors in various regions, renewable energy generation is more suitable to represent the development level of renewable energy than the installed capacity (Yu et al. 2020, Zheng et al. 2021a). Therefore, this study selects renewable energy generation as the key independent variable, which includes the total amount of hydro, wind, and solar power generation in each region, measured in 100 million kWh. The larger the power generation capacity of renewable energy, the higher the development level of renewable energy. Moreover, $C_{i,t}$ represents a series of control variables. $\varepsilon_{i,t}$ is the error term. Besides, i is province and t represents the year. α and γ are the estimated parameters. Among them, the most interested parameter is the α_1, which are expected to be $\alpha_1 < 0$. It represents that renewable energy development would reduce carbon emissions. Moreover, it is expected that $\alpha_2 > 0$, indicating that current period carbon emissions are influenced by past periods.

Second, the selection of control variables is critical to the validity of the estimation results. Referring to existing literature related to carbon emissions (Dogan and Seker 2016b, Ehigiamusoe and Dogan 2022, Wan et al. 2022), the control variables used in this study include GDP per capita (*GDPCAPITA*), industry structure (*INDS*), foreign trade (*TRADE*), energy consumption structure (*ENESTRU*), and investment in environmental regulation (*ENVREGU*). Moreover, the unit of GDP per capita is RMB per person, which is deflated by the price index based on 1995 and processed into real value. Furthermore, the existing studies (Dinda 2004, Grunewald et al. 2017, Zoundi 2017) show that there is an inverted U-shaped relationship between economic development and carbon emissions at the national level, namely the Environmental Kuznets Curve (EKC). Therefore, this study introduces the square term of GDP per capita in the model to test whether there is a significant inverted U-shaped relationship at the provincial level in China.

Third, in order to further investigate how income levels moderating the relationship between renewable energy and carbon emissions. The interaction term ($RENEW_{i,t}{}^{*}GDPCAPITA_{i,t}$) between renewable energy and income levels is introduced in the model (2). Just as the level of economic development has an inverted U-shaped effect on carbon emissions, the emission reduction effect of renewable energy under different income levels may also be different. Therefore, this study sets a series of indicators to reflect the income levels, including GDP per capita, as well as three dummy variables based on 25%, 50% and 75% quantiles of GDP per capita. β represents the estimated parameters.

$$\begin{aligned} CO2_{i,t} = {} & \beta_0 + \beta_1 RENEW_{i,t} + \beta_2 \left(RENEW_{i,t}{}^{*}GDPCAPITA_{i,t}\right) \\ & + \beta_3 CO2_{i,t-1} + \gamma \sum C_{i,t} + \varepsilon_{i,t} \end{aligned} \tag{2}$$

Finally, this study is interested in the key drivers of carbon reduction achieved by renewable energy. Therefore, a mediating effect model is further constructed for mechanism analysis. Many studies have demonstrated that green technology innovation is a key driver for the sustained improvements of renewable energy generation efficiency (Assi et al. 2021, Sharma et al. 2021). Moreover, from the perspective of causality, technological innovation is the cause of promoting the development of renewable energy, rather than the

Table 1 Variable descriptive statistics

Variable	Definition	N	Mean	Std. Dev.
CO2	Carbon emissions per capita - logarithmic	629	2.041	0.589
RENEW	Renewable energy generation - logarithmic	629	4.302	1.940
GDPCAPITA	GDP per capita - logarithmic	629	9.614	0.782
INDS	Secondary sector as a share of GDP	629	0.454	0.081
TRADE	Proportion of total imports and exports in GDP	629	0.042	0.051
ENESTRU	Proportion of coal in energy consumption	594	0.957	0.474
ENVREGU	Proportion of investment in environmental regulation in GDP	540	0.002	0.001
GREENPAT1	Number of green invention applications - logarithmic	629	5.865	2.002
GREENPAT2	Number of green utility model applications - logarithmic	629	6.050	1.850

result of the development of renewable energy. Therefore, this study uses renewable energy as a mediating variable to examine how green technology innovation can achieve emission reduction by promoting renewable energy. Eq. (3) investigates the impact of green technology innovation on carbon emissions. Eq. (4) discusses the impact of green technology innovation on renewable energy. Eq. (5) examines the effects of renewable energy and green technology innovation on carbon emissions, and then discusses the specific emission reduction mechanism. Moreover, green technology innovation is usually measured by green patent indicator ($GREENPAT_{i,t}$), which is mainly divided into two categories, including the number of green invention patent applications (*GREENPAT1*) and the number of green utility model applications (*GREENPAT2*). Besides, σ, δ and θ are estimated parameters.

$$CO2_{i,t} = \sigma_0 + \sigma_1 GREENPAT_{i,t} + \sigma_2 CO2_{i,t-1} + \gamma \sum C_{i,t} + \varepsilon_{i,t} \quad (3)$$

$$RENEW_{i,t} = \delta_0 + \delta_1 GREENPAT_{i,t} + \delta_2 RENEW_{i,t-1} + \gamma \sum C_{i,t} + \varepsilon_{i,t} \quad (4)$$

$$\begin{aligned} CO2_{i,t} = & \theta_0 + \theta_1 RENEW_{i,t} + \theta_2 GREENPAT_{i,t} \\ & + \theta_3 CO2_{i,t-1} + \gamma \sum C_{i,t} + \varepsilon_{i,t} \end{aligned} \quad (5)$$

Data sources

In this study, 30 provinces in mainland China from 1999 to 2019 are used as research samples. Moreover, Tibet, Hong Kong, Macao, and Taiwan are not included due to the unavailability of data. Besides, for renewable energy generation, considering data availability, this study includes hydropower, wind power, and solar power, which are obtained from the China Energy Statistics Yearbook. Data on carbon emissions and other control variables are obtained from the China Stock Market & Accounting Research Database. The green patent application data are obtained from the Chinese Research Data Services Database. For non-proportional indicators, this study conducts logarithmic processing to reduce the degree of dispersion of the indicators and obtain robust estimation results. The descriptive statistics of the main variables are shown in Table 1.

Empirical results

Benchmark regression

First, this study investigates the impact of renewable energy on carbon emissions. The results based on the system GMM model are shown in Table 2. The Sargan test and autocorrelation test show that the results cannot reject the null hypothesis, which means that the overidentifying restrictions are valid and there is no serial correlation problem. The estimated coefficient of carbon emissions in the one lag period is significantly positive at the 1% significance level. Overall, the model is reasonably set and suitable for fitting the emission reduction effect of renewable energy at the regional level.

The results in columns (1) to (5) of Table 2 show that renewable energy has a significant negative impact on carbon emissions when different control variables are considered, indicating that renewable energy development can effectively reduce carbon emissions. With the increase in renewable energy, fossil energy is gradually replaced, and thus carbon emissions decrease. Specifically, in column (5) of Table 2, for every 1% increase in renewable energy generation, carbon emissions per capita are reduced by 0.013%. These results are consistent with Yu et al. (2020) for 30 Chinese provinces and Gyamfi et al. (2022) for the 5 BRICS countries, which also present that renewable energy development is conducive to reduce carbon emissions. However, it should be noted that the emission reduction effect of renewable energy is at a relatively low level in this study[1]. The possible reason is that the development of renewable energy in China over the past two decades is still at an early stage, with renewable energy being relatively expensive, and the

[1] Considering the rapid development of renewable energy in recent years and the turning point of the 2008 financial crisis, grouping regression was performed in this study for robustness check. Regres-

Table 2 Results for benchmark regressions

	(1) CO2	(2) CO2	(3) CO2	(4) CO2	(5) CO2
RENEW	−0.010***	−0.009***	−0.012***	−0.010***	−0.013***
	(−5.39)	(−4.21)	(−5.65)	(−5.56)	(−5.27)
GDPCAPITA	0.086***	0.126***	0.192***	2.050***	2.229***
	(6.14)	(14.99)	(14.61)	(8.21)	(6.93)
GDPCAPITASQ				−0.099***	−0.103***
				(−7.79)	(−6.49)
INDS		0.321***	0.230***	−0.018	−0.056
		(5.64)	(2.92)	(−0.35)	(−0.89)
TRADE		−0.940***	−0.736***	−1.026***	−0.724***
		(−3.74)	(−2.60)	(−6.98)	(−4.18)
ENESTRU			0.369***		0.425***
			(12.50)		(9.66)
ENVREGU			−3.752**		−1.693
			(−2.08)		(−0.94)
L.CO2	0.735***	0.689***	0.560***	0.655***	0.430***
	(41.99)	(59.08)	(19.99)	(53.60)	(8.64)
Constant	−0.193*	−0.585***	−1.257***	−9.631***	−11.002***
	(−1.93)	(−9.07)	(−12.45)	(−8.06)	(−6.98)
No. of observation	510	510	510	510	510
Sargan Test-*P* value	1.0000	1.0000	1.0000	1.0000	1.0000
AR(1)-*P* value	0.1580	0.1486	0.0217	0.1676	0.1559
AR(2)-*P* value	0.2929	0.3082	0.2576	0.2968	0.3679

The results of Sargan Test, AR(1) test and AR(2) test report the *P* value. z statistics in parentheses, * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

lack of scale effect. Compared to fossil energy, which dominates the energy consumption structure, renewable energy is not yet able to replace fossil energy sources in terms of price and quantity. However, with China proposing the carbon neutrality target and a clear plan for the development of wind and solar power, the pace and scale of renewable energy development will grow significantly in the future, and the role of renewable energy in promoting emission reduction will become more prominent.

Furthermore, the effect of GDP per capita on carbon emissions is significantly positive, indicating that with the improvement of economic development level, the demand for the fossil energy would also increase, leading to an increase in carbon emissions. Besides, column (5) of Table 2 further considers the squared term of GDP per capita, and the estimated coefficient is significantly negative, indicating that economic development and carbon emissions show an inverted U-shaped relationship, in line with the EKC hypothesis proposed by the previous studies (Chen et al. 2019a, Dogan and Seker 2016a, Le et al. 2020). When economic development is at a low level, the increase in GDP per capita would increase carbon emissions. While economic development is at a high level, the increase in GDP per capita is beneficial to reducing carbon emissions. Moreover, Lægreid and Povitkina (2018) pointed out that in examining the EKC relationship between per capita GDP and carbon emissions, energy-related variables should not be controlled, as this may affect the mechanism of the EKC hypothesis. Therefore, we further consider the regression results that do not include energy-related variables, as shown in Column (4) of Table 2. The results show that the EKC hypothesis still holds even without controlling the energy-related variables, which further verifies the robustness of the results.

The results for the control variables are as follows. First, the estimated coefficient of industrial structure is significantly positive, which means that the larger the proportion of the secondary industry, the higher is the carbon emission. This is because the carbon intensity of the secondary industry is higher than that of the other industries. Second, foreign trade has a significant negative effect on carbon emissions,

Footnote 1 (continued)

sion analysis was conducted for samples before and after 2009. The results showed that there was little difference between the regression results after 2009 and the overall sample, which further confirms the robustness of the research results.

implying that closer trade relations are conducive to reducing carbon emissions. Third, the estimated coefficient of the energy consumption structure is significantly positive, which indicates that the higher the proportion of coal in energy consumption, the higher is the level of carbon emission[2].

Heterogeneity analysis

This study further considers the carbon reduction effects of renewable energy at different regional levels in China. There are huge differences in natural resource endowments and economic development levels between different regions in China, the carbon reduction effects of renewable energy would be varied greatly. Therefore, it is necessary to conduct in-depth analysis for different regions. Since the system GMM method cannot directly obtain the specific estimation coefficients of each region, this study further uses the fully modified least square method (FMOLS) to obtain the specific estimation results of each region. Heterogeneity is one of the reasons for estimating the cointegration panel model, because differences in average values within the cross-section and variations in the section can lead to mismatches in the cointegration equilibrium (Pedroni 2004). The FMOLS estimation can solve the heterogeneity issues, because it can obtain effective results by including the specific individuals' interceptions (Khan et al. 2021). Specifically, the FMOLS estimation method obtains a consistent estimator of the cointegration parameter estimator by eliminating the correlation between the explanatory variable and the random interference term. Moreover, the prerequisite for using FMOLS regression is that there is a cointegration relationship between the variables (Liddle 2012). In this regard, we use the panel cointegration test method proposed by Pedroni (2004), and the results indicate that the null hypothesis of no cointegration relationship is rejected at the 1% significance level. Therefore, the econometric model in this study is suitable for using FMOLS estimation. The results are shown in Table 3.

In general, renewable energy shows a significant negative impact on carbon emissions in nineteen regions. Specifically, the carbon emissions reduction effect is stronger in Yunnan (−0.38), Hainan (−0.23), and Guangxi (−0.19), respectively. The above three regions belong to the western and central regions of China and are also the regions with the rapid development of renewable energy-related industries. For example, the renewable energy power generation of Yunnan in 2019 reached 314.9 billion kWh, accounting for 16.3% of the total renewable energy power generation in China. Therefore, these areas can replace fossil energy significantly and effectively reduce carbon emissions. However, renewable energy has a significant positive effect on carbon emissions in eight regions, including Shanxi, Liaoning, Anhui, Hubei, Chongqing, Sichuan, Ningxia, and Xinjiang, which are all in the central and western regions. The possible explanations are as follows. First, for some regions in the process of industrialization and with large energy demand, such as Anhui, Liaoning, and Hubei, renewable energy supply has promoted economic development, and further increased fossil energy consumption and carbon emissions. Second, due to major engineering factors such as the west-to-east power transmission project, the renewable energy generating provinces such as Sichuan, Xinjiang, and Ningxia, use local clean energy to compensate for the energy use of other external regions through power dispatch, which makes it difficult for local renewable energy development to effectively reduce their carbon emissions. Finally, because the underlying green technology is relatively immature, the production of renewable energy requires large infrastructure investment in the early stage, such as in Shanxi, which will lead to large energy consumption and further increase the level of carbon emissions to a certain extent.

The moderating effect of income levels

There may be significant differences in emissions reduction impact of renewable energy at different income levels. Therefore, this study further examines the moderating effect of different income levels on the nexus between renewable energy and carbon emissions. To this end, we construct four indicators reflecting income levels and establish interaction terms with renewable energy. The results are shown in Table 4.

First, the interaction term between GDP per capita and renewable energy is added to the estimation equation, and the results are shown in column (1) of Table 4. The results show that the interaction term is significantly positive, indicating that the increase in income levels weakens the emission reduction effect of renewable energy. To further test the specific moderating effects, we constructed a series of indicators reflecting different income levels. Specifically, the GDP per capita of different regions in each year is sorted from low to high, and 25%, 50%, and 75% quartiles, then three dummy variables GDPCDUM25, GDPCDUM50, and GDPCDUM75 are constructed. For example, when the GDP per capita of a region exceeds 25% of the country, GDPCDUM25 is marked as 1, otherwise, it is 0. Similarly, GDPCDUM50 and GDPCDUM75 are set according to the 50% and 75% quantiles,

[2] There may be a potential multicollinearity problem between renewable energy and energy structure variables. Therefore, this study further conducted ordinary least squares estimation and variance inflation factor (VIF) test to identify collinearity problems. The results show that the VIF estimation results for each variable are less than 10, indicating that there is no multi-collinearity problem.

Table 3 Results for FMOLS estimation

	RENEW	GDPCAPITA	GDPCAPITASQ	INDS	TRADE	ENESTRU	ENVREGU
Beijing	−0.08***	−2.54***	0.14***	0.58***	−0.5***	1.16***	46.11***
Tianjin	−0.02***	14.89***	−0.67***	−1.68***	3.46***	1.14***	−13.91***
Hebei	−0.01***	10.74***	−0.52***	−0.39***	−2.5***	0.27***	12.74***
Shanxi	0.02***	0.04	0.02	−0.12***	2.65***	0.27***	6.65***
InnerMongolia	0	0.49	0.02	−0.8***	48.14***	0.13***	−43.92***
Liaoning	0.06***	5.42***	−0.26***	−0.03	7.99***	−2.3***	29.29***
Jilin	−0.01***	5.61***	−0.27***	0.18***	20.62***	0.66***	−53.12***
Heilongjiang	−0.01**	10.62***	−0.53***	−0.44***	7.13***	−0.17***	−35.55***
Shanghai	−0.02***	5.85***	−0.26***	1.89***	−1.25***	−0.53***	−14.66***
Jiangsu	0	2.76***	−0.1***	0.54***	0.24**	0.66***	27.97***
Zhejiang	−0.03***	3.31***	−0.14***	0.25***	−0.31***	0.59***	2.94***
Anhui	0.01***	3.13***	−0.14***	0.19***	2.33***	0.27***	3.23**
Fujian	−0.06***	6.39***	−0.28***	−0.19	1.93**	0.05***	10.04**
Jiangxi	−0.03***	6.77***	−0.32***	−2.74***	−0.65	2.02***	−14.21***
Shandong	−0.03***	5.26***	−0.23***	−1.91***	−4.73***	0.8***	12.41***
Henan	−0.02***	5.05***	−0.25***	1.1***	2.7***	0.28***	7.4***
Hubei	0.13***	2.84***	−0.13***	−0.71***	4.79***	1.2***	23.6***
Hunan	−0.01	8.87***	−0.44***	−0.44***	12.02***	1.28***	58.71***
Guangdong	−0.05***	0.29***	0.01***	0.96***	0.24***	0.25***	−41.1***
Guangxi	−0.19***	2.56***	−0.1***	0.32***	11.26***	0.68***	−4.28***
Hainan	−0.23***	10.57***	−0.49***	4.82***	−12.47***	1.63***	−47.56***
Chongqing	0.12***	−0.18	0.02*	1.38***	2.56***	−4.25***	−3.43
Sichuan	0.13***	2.44***	−0.14***	0.85***	9.32***	−0.2***	−69.98***
Guizhou	−0.09***	4.01***	−0.2***	1.28***	−0.41	−0.06***	−0.08
Yunnan	−0.38***	3.49***	−0.14***	2.12***	0.15	−0.18***	25.17***
Shaanxi	−0.16***	−0.53***	0.06***	0.67***	−9.42***	−0.52***	28.83***
Gansu	−0.06***	−2.53***	0.17***	0.46***	5.89***	−0.04***	−8.47***
Qinghai	-0.10***	−0.08	0.05***	0.24***	−0.32	0.84***	−2.66*
Ningxia	0.08***	−4.07***	0.24***	0.92***	−2.2***	0.51***	−9***
Xinjiang	0.05***	4.23***	−0.18***	−0.11*	−4.22***	0.14***	37.81***

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

respectively. The results of the interaction terms are shown in columns (2), (3), and (4) of Table 4. It can be found that RENEW*GDPCDUM25 is positive but insignificant, RENEW*GDPCDUM50 is significantly positive, while the estimated coefficient of RENEW*GDPCDUM75 is significantly negative. The results show that income levels have a nonlinear moderating effect on the emission reduction effect of renewable energy. Among them, the results of the full sample show that the improvement of income levels reduces the carbon emission reduction effect of renewable energy.

For the subsample of different income levels, first, when the income level is relatively low, the moderating effect of income level on the emission reduction effect of renewable energy is positive. Specifically, the increase in income level promotes carbon emissions. This may be because, when the income level is at a low stage, the increase of the income level increases the demand for energy consumption. Under the fact that fossil energy dominates, the increase of the income level increases the demand for fossil energy, reduces the contribution of renewable energy in the energy structure, and thus carbon emissions increase. This result is consistent with the existing studies (Ehigiamusoe and Dogan 2022, Fatima et al. 2021). Specifically, Ehigiamusoe and Dogan (2022) show that in low income countries, the interaction of renewable energy and GDP increases carbon emissions. Fatima et al. (2021) indicate that the use of fossil fuels increases with the increase of income, which increases the share of non-renewable energy in the energy mix, minimizes the contribution of renewable energy in the energy mix, and causes environmental deterioration.

Table 4 Moderating effect of income levels on the nexus between renewable energy and carbon emissions

	(1) CO2	(2) CO2	(3) CO2	(4) CO2
RENEW*GDPCAPITA	0.020**			
	(2.01)			
RENEW*GDPCDUM25		0.001		
		(0.95)		
RENEW*GDPCDUM50			0.007***	
			(3.13)	
RENEW*GDPCDUM75				−0.014***
				(−5.77)
RENEW	−0.213**	−0.014***	−0.014***	−0.011***
	(−2.14)	(−4.41)	(−4.19)	(−4.08)
GDPCAPITA	2.290***	2.304***	2.151***	2.093***
	(5.74)	(6.47)	(5.82)	(7.04)
GDPCAPITASQ	−0.110***	−0.107***	−0.100***	−0.096***
	(−5.28)	(−6.21)	(−5.54)	(−6.73)
INDS	−0.052	−0.075	−0.067	−0.013
	(−0.66)	(−1.06)	(−0.72)	(−0.13)
TRADE	−0.438*	−0.744***	−0.802***	−0.883***
	(−1.82)	(−2.90)	(−3.35)	(−2.92)
ENESTRU	0.428***	0.418***	0.410***	0.419***
	(11.62)	(8.44)	(9.78)	(7.10)
ENVREGU	−3.200*	−1.778	−2.629	−1.054
	(−1.94)	(−0.68)	(−1.29)	(−0.39)
L.CO2	0.449***	0.456***	0.485***	0.449***
	(7.86)	(9.04)	(10.51)	(8.91)
Constant	−10.898***	−11.344***	−10.552***	−10.355***
	(−5.85)	(−6.52)	(−5.89)	(−7.20)
No. of observation	510	510	510	510
Sargan Test-*P* value	1.0000	1.0000	1.0000	1.0000
AR(1) -*P* value	0.1562	0.1326	0.1192	0.1090
AR(2) -*P* value	0.3649	0.3467	0.3085	0.3492

The results of Sargan Test, AR(1) test and AR(2) test report the *P* value. z statistics in parentheses. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Second, column (4) of Table 4 shows that when the income levels of a region exceed 75% of China, the moderating effect of income levels on emission reduction of renewable energy is significantly negative. This indicates that when the income level is at a high stage, the increase in income level can effectively enhance the emission reduction effect of renewable energy. The potential economic implication is that since renewable energy generation is still immature and the market scale is relatively low, a large amount of silent cost needs to be invested in the early stage to build infrastructure before realize the large-scale utilization of renewable energy. Therefore, only when the income level is high, people can afford renewable energy to achieve the substitution of fossil energy, which makes the emission reduction effect of renewable energy prominent (Ehigiamusoe and Dogan 2022). Furthermore, Dong et al. (2020) also found that only in high-income countries of global 120 countries that the renewable energy would show a significant inhibitory effect on carbon emissions, and it was not significant in other sub-samples.

Therefore, in a country like China where there are significant differences in regional development, renewable energy will not effectively replace fossil energy in the early stage of rising income levels. Only when the economy is sufficiently developed, people's income levels rise significantly, the regional economy will be able to pay for large-scale renewable energy, and achieve a substantial replacement of fossil energy and reduce carbon emissions. Based on this, when deploying the development strategy of renewable energy, the policymakers should consider the income levels and reasonably lay out the development path of renewable energy to avoid carbon emissions increasing instead of decreasing.

Table 5 Impact mechanism of green technology innovation on renewable energy

	(1) CO2	(2) RENEW	(3) CO2	(4) CO2	(5) RENEW	(6) CO2
RENEW			−0.008***			−0.006**
			(−2.78)			(−2.31)
GREENPAT1	−0.028***	0.128***	−0.022***			
	(-4.16)	(5.48)	(−3.05)			
GREENPAT2				−0.022***	0.044	−0.026***
				(−3.78)	(1.29)	(−4.30)
GDPCAPITA	2.197***	−2.200***	1.868***	2.021***	−2.001**	2.048***
	(6.17)	(−3.14)	(6.56)	(5.71)	(−2.19)	(5.84)
GDPCAPITASQ	−0.099***	0.109***	−0.082***	−0.091***	0.109**	−0.093***
	(−5.69)	(3.24)	(−5.92)	(−5.29)	(2.50)	(−5.44)
INDS	−0.106	−0.188	−0.088	−0.088	−0.622	−0.160*
	(−1.05)	(−0.71)	(−0.94)	(−1.23)	(−0.84)	(−1.79)
TRADE	−0.623***	−1.024	−0.673***	−0.555**	−1.132	−0.751***
	(−2.86)	(−0.46)	(−2.72)	(−2.29)	(−0.55)	(−4.25)
ENESTRU	0.412***	0.281	0.415***	0.410***	0.291	0.408***
	(10.19)	(1.42)	(7.74)	(11.58)	(1.11)	(8.67)
ENVREGU	−3.183*	16.945	−2.130	−5.710***	10.276	−6.064***
	(−1.75)	(0.90)	(−0.95)	(−2.91)	(0.48)	(−3.26)
L.RENEW		0.828***			0.827***	
		(17.97)			(11.04)	
L.CO2	0.453***		0.458***	0.486***		0.499***
	(8.95)		(9.25)	(10.44)		(11.81)
Constant	−10.969***	11.020***	−9.361***	−10.074***	9.747**	−10.097***
	(−6.31)	(3.25)	(−6.63)	(−5.82)	(2.32)	(−5.85)
No. of observation	510	510	510	510	510	510
Sargan Test-*P* value	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
AR(1) -*P* value	0.1439	0.0023	0.1214	0.1509	0.0029	0.1417
AR(2) -*P* value	0.3003	0.8035	0.2878	0.3093	0.8843	0.2956

The results of Sargan Test, AR(1) test and AR(2) test report the *P* value. z statistics in parentheses. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

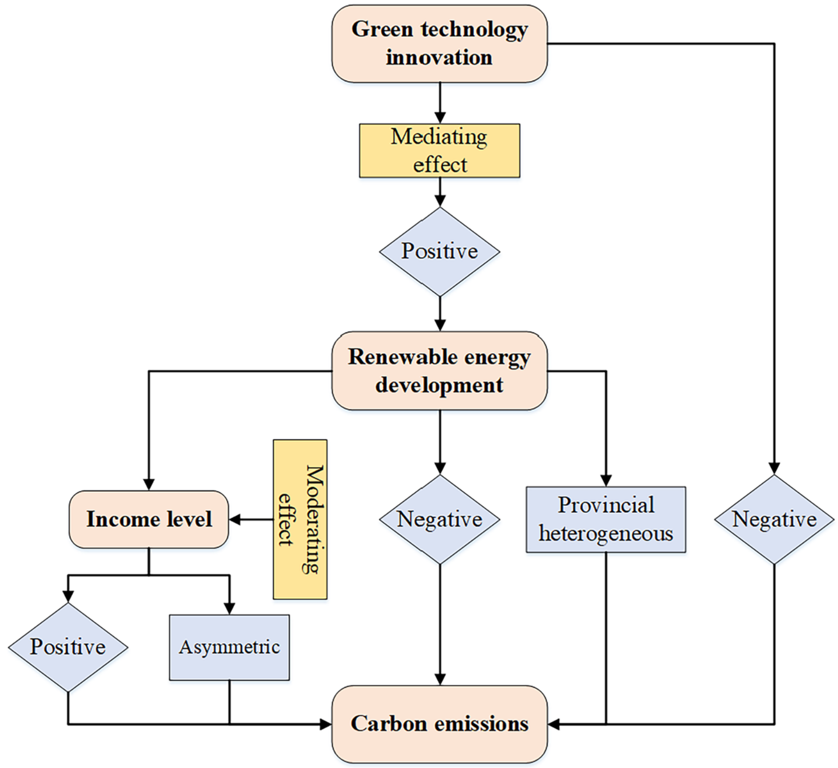
Impact mechanism of green technology innovation

The relationship between green technology innovation, renewable energy, and carbon emissions deserves further study. From the perspective of causality, technological progress is the cause of promoting the efficiency improvement of renewable energy generation, rather than the result of the development of renewable energy. Therefore, this study takes renewable energy as the mediating variable between green technology innovation and carbon emissions to conduct a mechanism analysis. For green technology innovation, the regional green invention patent applications (*GREENPAT1*) and green utility model applications (*GREENPAT2*) are used as proxy variables. The results are shown in Table 5.

The results in columns (1) and (4) of Table 5 show that the two types of green technology innovation variables have a significant inhibitory effect on carbon emissions. For each 1% increase in the number of applications for green invention patents and green utility models, the carbon emissions will be reduced by 0.028% and 0.022% respectively. This indicates that green technology innovation plays a stable role in emission reduction. Moreover, the results in columns (2) and (5) of Table 5 show that the green invention patent has a significant positive effect on the renewable energy, while the green utility model is positive but insignificant, indicating that the green invention patent is the basic driving factor of the renewable energy development. This is consistent with the existing studies (Danish and Ulucak 2021).

Furthermore, the results in columns (3) and (6) of Table 5 show that, first, green technology innovation has a significant inhibitory effect on carbon emissions. Second, the impact of renewable energy on carbon emissions is significantly negative. This means that green technology innovation has significantly reduced carbon emissions by promoting the development of renewable energy. Renewable energy

Fig. 1 Impact mechanism of green technology innovation, renewable energy development and carbon emissions



is an important mediating mechanism for green technology innovation to achieve emission reduction. The explanation is that green technology innovation has promoted the breakthrough of key technologies such as solar photovoltaic panels and wind turbines, thus accelerating the low-cost and large-scale development of renewable energy, and reducing carbon emissions. Moreover, green technology innovation helps to transform the growth momentum of economic and industrial structures into more sustainable renewable energy, thus improving environmental performance (Wang et al. 2020). Therefore, the development and application of green technology innovation should be actively promoted to form a virtuous cycle of environmental improvement (Kuang et al. 2022).

In fact, China's renewable energy has developed significantly in recent years, and the proportion of renewable energy in the energy structure has been constantly increasing. In 2020, non-fossil energy accounted for 15.9% of primary energy consumption, and renewable energy generation accounted for 29.5% of the total electricity consumption (National Energy Administration 2021). The development of renewable energy is the key to achieving the goal of carbon neutrality in the future. Moreover, the results of this study show that renewable energy is also an important carrier of green technology innovation. By promoting the development of renewable energy, green technology innovation could significantly improve the energy consumption structure, reduce carbon emissions, and promote green and low-carbon development. To sum up, in order to clarify the specific influence mechanism between green technology innovation, renewable energy development and carbon emissions in China, Fig. 1 presents the influence path between the variables.

Conclusions and policy implications

China has proposed to achieve carbon neutrality by 2060, promoting the rapid development of renewable energy, and replacing fossil energy is the key path to achieving this goal. Considering that there are significant differences in renewable energy resource endowment, income levels and green technology innovation among various regions in China, identifying the differential characteristics of the relationship between renewable energy and carbon emissions is crucial to formulating renewable energy development strategies. Based on the panel data of 30 provinces in China from 1999 to 2019, this study adopts the system GMM model to investigate the relationship between renewable energy and carbon emissions from the perspective of income levels and green technology innovation. The main conclusions are as follows.

(1) The renewable energy development can significantly reduce carbon emissions. For every 1% increase in renewable energy power generation, the carbon emissions would be reduced by 0.013%. This indicates that developing renewable energy is an effective path for China to achieve carbon

neutrality. However, it is worth noting that the emission reduction effect of renewable energy has not been fully released due to the small amount and proportion of renewable energy. With the substantial development of renewable energy in the future, the resulting emission reduction effect would be further stimulated. Moreover, this study further confirms the inverse U-shaped curve between carbon emissions and economic development. Furthermore, the industrial structure represented by the secondary industry and the energy consumption structure represented by coal has increased carbon emissions. In contrast, foreign trade has a significant negative effect on carbon emissions, which means that closer trade relations are conducive to promoting carbon emission reduction.

(2) The heterogeneity analysis shows that there are significant differences in the emission reduction effects of renewable energy among various regions in China. Renewable energy in most regions can effectively reduce carbon emissions. Specifically, this emission reduction effect is stronger in Yunnan (−0.38), Hainan (−0.23) and Guangxi (−0.19). However, renewable energy in some regions, such as Liaoning, Shanxi, Sichuan, and Xinjiang, plays a significant positive role in carbon emissions.

(3) Regarding the moderating effects of income levels on the relationship between renewable energy on carbon emissions, the results indicate that income levels have a nonlinear effect on the emission reduction effect of renewable energy. When it is at a low-income level, the moderating effect of income levels on the nexus between renewable energy and carbon emissions is significantly positive. Only when economic development reaches the high-income level, the increase in income levels can effectively enhance the emission reduction effect of renewable energy.

(4) For the mechanism analysis between green technology innovation, carbon emission and renewable energy, the study found that, first, the development of green technology can significantly promote the renewable energy. Second, green technology innovation and renewable energy have significantly inhibited carbon emissions. This shows that green technology innovation has significantly reduced carbon emissions by promoting the development of renewable energy. Developing renewable energy is not only the key carrier of implementing green technological innovation but also an important way to reduce carbon emissions.

From the above analysis, the policy implications are as follows.

(1) Renewable energy development is an important measure for China to promote carbon emission reduction and achieve carbon neutrality. On the one hand, it is necessary to increase the installed capacity and power generation of renewable energy. On the other hand, in order to expand renewable energy consumption, a sound green power consumption system should be established. For example, improve the ability of the grid to accept new energy power, promote the integration of energy and digital technology, and improve utilization efficiency. In addition, considering regional heterogeneity, policymakers should formulate differentiating renewable energy development policies based on the regional actual situation to avoid increasing carbon emissions due to blind expansion of power generation infrastructure and equipment.

(2) Due to the significant heterogeneity in the emission reduction effects of renewable energy under different income levels, the government should improve renewable energy development policies in different regions. For low-income regions, on the one hand, provide subsidies and support policies to ensure that they can increase renewable energy consumption at an affordable cost and avoid a rebound in fossil energy consumption. On the other hand, improve public awareness of the clean and environmentally friendly characteristics of renewable energy, thereby reducing dependence on fossil energy and transitioning to renewable energy consumption. Moreover, for high-income regions, the government should expand the scale of renewable energy development in these regions, establish incentive mechanisms to ensure that the emission reduction effect of renewable energy in high-income regions is further expanded, and play a demonstration and leading role.

(3) Green technology innovation significantly reduces carbon emissions by promoting the development of renewable energy. Therefore, governments and enterprises should further increase technological research and development innovation in the field of renewable energy to release the carbon emission reduction potential of renewable energy. In addition, with the help of green finance, accelerate the research and development, promotion and application of green technology innovation. Promote green and sustainable economic growth while promoting the rapid development of renewable energy.

Finally, some shortcomings need to be further improved in the future. First, this study attempts to provide new evidence for the heterogeneous impact of renewable energy and carbon emissions from different income levels and green technology innovation perspectives in China. However, under the income levels, this study only uses dummy variables and fails to determine a specific income level threshold, that is, if the income level exceeds a certain level, the carbon emission reduction effect of renewable energy can be realized. In the next step, we will use the threshold panel model to identify the specific threshold combined with different income level indicators. Second, this study uses dynamic panel models to analyze the carbon reduction effects of renewable energy. However, the production and consumption of renewable energy have a spatial correlation, and the production of a region is not entirely used for its consumption. This requires considering the spatial spillover effects of renewable energy generation. However, China has implemented the “West-East Electricity Transmission” strategy to transmit electricity from the western region to the eastern region. Therefore, the basic settings of the traditional spatial econometric model may not be able to effectively evaluate this spillover effect. In the future, it is necessary to improve the traditional spatial econometric model to analyze the spatial correlation of renewable energy development.

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Declarations

Competing interests The authors declare no competing interests.

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