

The Impact of Renewable Energy Technology Innovation on the Low-Carbon Economic Transformation - Do Climate Risks and Policy Regulations Matter?

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Abstract

In the context of sustainable development, renewable energy technology innovation is not only a vital approach for enhancing energy efficiency but also a critical driver of low-carbon economic transformation. Throughout this process, the importance of climate risks and policy regulations has become increasingly apparent. This paper aims to empirically examine the impact of renewable energy technology innovation on the transition to a low-carbon economy by analyzing panel data from 30 Chinese provinces from 2000 to 2021, with a particular focus on the moderating roles of climate risks and policy regulations. The main findings are summarized as follows: (1) renewable energy technology innovation contributes to low-carbon economic transformation, and this effect remains consistent after a series of robustness tests; (2) climate risk has a negative moderating effect on the transition to a low-carbon economy; (3) policy regulation can significantly promote low-carbon economic transformation. Additionally, we find that renewable energy technology innovation promotes low-carbon economic transformation by reducing air pollution intensity. Renewable energy technology innovation has a more significant effect on the low-carbon economy transition in regions with higher levels of economic development.

Keywords: renewable energy technology innovation, low-carbon economic transformation, climate risk, policy regulation

1.0 Introduction

Renewable energy technology innovation is crucial for the development of renewable energy. In the current economic and social development landscape, non-renewable fossil fuels remain the cornerstone of global energy development and continue to dominate the energy structure (Chen et al., 2021). However, the increasing consumption of fossil fuels leads to a decline in environmental carrying capacity, severely impacting a nation's ability for sustainable development. Therefore, it is imperative for countries to develop renewable energy by leveraging technological innovation to reduce dependency on fossil fuels and achieve an environmentally friendly economic transformation (Shan and Ren, 2023). Although the development of renewable energy is still in the exploratory stage and faces challenges such as technical shortcomings and high costs, achieving technological innovation in renewable energy can optimize the energy structure. This optimization enhances green development and is particularly significant in realizing a low-carbon economic transition (Nepal et al., 2024).

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In the context of sustainable development, achieving a low-carbon economic transition has become a focal point for countries and a key strategy in addressing global emission reduction challenges. It is also seen as a bridge to a sustainable future (Liu et al., 2022). The significant increase in carbon emissions due to economic expansion underscores the urgency of a low-carbon economic transition (Ahmad et al., 2023). Studies indicate that although countries have reached a consensus on the overall goal of reducing carbon emissions, substantial differences exist in their approaches to achieving low-carbon transitions due to varying development characteristics. Therefore, policies tailored to national conditions are necessary to promote low-carbon economic transitions. For developing countries, balancing carbon emission reductions with economic development presents a significant challenge (Tang et al., 2024).

At the same time, addressing climate risks has become an urgent global challenge. The physical risks induced by climate change, such as storms, floods, heatwaves, and droughts, carry significant uncertainty and continue to impact the economy and society (Murphy, 2024). Climate risks negatively affect investments in industries vulnerable to climate change, such as renewable energy, leading to increased investment losses (Sun et al., 2022). This restricts innovation in renewable energy technology and exposes the energy market to downward risks (Chang et al., 2024). However, in the face of these climate risk challenges, achieving innovation in renewable energy technology becomes even more crucial. The sustainable development goals agenda views climate risk as a major factor influencing energy development (Muntasir et al., 2023). Therefore, the impact of climate risks on renewable energy technology innovation cannot be overlooked, and there is an urgent need to explore its impact mechanisms.

On the other hand, effective policy regulation is a crucial means of promoting the transition to a low-carbon economy. To address the negative externalities of environmental quality, achieving low-carbon development requires a combination of governmental power and market mechanisms (Feng et al., 2024). However, overly stringent policy regulations may increase operational costs, affecting the development of a low-carbon economy. Among various policies, the Paris Agreement is considered a significant milestone in global efforts to address carbon emissions and represents the collective efforts of countries in reducing carbon emissions and transitioning to a low-carbon economy (Salman et al., 2022). Nevertheless, the impact and effectiveness of the Paris Agreement's policy regulations remain unclear and require further investigation.

As the world's largest carbon emitter, China proposed its carbon peak and carbon neutrality goals in 2020 (Cao et al., 2024). With significant advancements in renewable energy technology and continuous optimization of its energy structure, China has become a major driving force in the global renewable energy sector. Promoting innovation in renewable energy technology and accelerating the low-carbon economic transition are pressing issues that China currently needs to address. Additionally, this situation provides a valuable context for examining related research.

The structure of this paper is as follows: Section 2 reviews the relevant literature; Section 3 provides theoretical analysis and proposes research hypotheses; Section 4 introduces data

selection and variables, and establishes the model; Section 5 presents empirical results; Section 6 offers further discussion; and Section 7 concludes with policy recommendations.

2.0 Literature Review

2.1. Renewable Energy Technology Innovation and Low-Carbon Economic Transition

Renewable energy technology innovation positively impacts economic and social development. The oil crisis of the 1970s sparked widespread scholarly interest in renewable energy, with research focusing on finding alternatives to fossil fuels. Existing studies indicate that renewable energy technology innovation not only effectively promotes endogenous economic growth (Dong et al., 2023) but also enhances the output level of the renewable energy sector (Liu et al., 2022). Ge et al. (2022) suggest that renewable energy technology innovation plays a positive role in upgrading industrial structures. Additionally, renewable energy technology innovation can significantly improve green productivity (Yan et al., 2020), promote clean production in industrial development (Zhu et al., 2020), and is crucial for reducing carbon intensity and facilitating the transition to a low-carbon economy (Kuang et al., 2022).

Research also finds that renewable energy technology innovation is essential for reducing air pollution and improving air quality (Jordaan et al., 2017). Jacobson and Delucchi (2011) propose that the large-scale application of renewable energy technologies can reduce PM2.5 emissions, decrease pollution intensity, and thus promote the transition to a low-carbon economy.

2.1. Climate Risk

Some studies indicate that climate risks increase the likelihood of disruptions to energy systems, prompting governments and enterprises to intensify their research and development efforts in renewable energy technologies and enhance the resilience of energy systems (Olmos et al., 2012). In regions frequently experiencing extreme weather events, governments are more inclined to implement policies that promote the development of renewable energy and drive technological innovation in this sector (Johnstone et al., 2010). However, some research suggests that climate risks can negatively impact agricultural development (Song et al., 2023), harm the liquidity of the financial sector (Lang et al., 2023), and pose challenges to the development of renewable energy technology projects. These challenges can lead to increased investment uncertainty and a lack of significant improvement in technological innovation capacity (Wei et al., 2023). Therefore, the impact of climate risks on renewable energy technology innovation is complex, and the specific effects remain unclear, necessitating further investigation.

2.3. Policy Regulation

When considering the impact of policy regulation, there are two different perspectives. Some studies suggest that excessive regulation may stifle corporate innovation, increase operating

costs, and negatively impact economic growth (Parise, 2016). Another viewpoint stems from the "Porter Hypothesis" of the 1970s, which posits that stringent environmental regulations can enhance competitiveness by incentivizing innovation. Holmes et al. (2013) argue that environmental regulation can promote the development and application of new technologies, thereby driving innovation in renewable energy technologies. Therefore, the specific impact of policy regulation is complex and requires further validation.

Through a review of the literature, this paper identifies the following gaps: First, existing research seldom focuses on the impact of renewable energy technology innovation on the transition to a low-carbon economy, indicating room for further study. Second, there is no consensus in the current literature on the moderating role of climate risks, necessitating in-depth research to clarify their specific effects. Third, few studies explore the role of the Paris Agreement's policy regulation in promoting the transition to a low-carbon economy through renewable energy, and the significance of policy implementation needs further examination.

3.0 Theoretical Analysis and Research Hypotheses

3.1. The Impact of Renewable Energy Technology Innovation on Low-Carbon Economic Transition

The key to achieving a low-carbon economic transition lies in renewable energy technology innovation. Su et al. (2022) point out that renewable energy technology innovation can optimize regional economic structures, reduce environmental losses caused by industrial upgrades, and improve energy utilization efficiency. This reduces the demand for and consumption of traditional energy sources, lowers pollution emissions, and promotes a green economic transition (Khan et al., 2021). Moreover, enhancing the capacity for renewable energy technology innovation is crucial for reducing carbon dioxide emissions and achieving a low-carbon economic transition (Tambo, 2016; Chatjuthamard, 2024; Ge, 2022). Based on this, the following hypothesis is proposed:

H1: Renewable energy technology innovation promotes the transition to a low-carbon economy.

3.2. The Role of Climate Risks

Climate risks have a significant impact on renewable energy technology innovation. On one hand, climate risks increase the uncertainty of renewable energy technology innovation, reduce technological investment, and thus inhibit the transition to a low-carbon economy. Extreme weather events damage regional infrastructure, cause production disruptions, and increase operating costs, thereby crowding out resources for technological innovation investment (Rao et al., 2023). On the other hand, climate risks can also compel governments to mitigate the impact of climate risks by supporting investment in renewable energy technology innovation (Dietz et al., 2016). On the grounds of these considerations, we put forward the following hypotheses:

H2a: Climate risks negatively moderate the process by which renewable energy technology innovation promotes the transition to a low-carbon economy.

H2b: Climate risks positively moderate the process by which renewable energy technology innovation promotes the transition to a low-carbon economy.

3.3. The Role of Policy Regulation

The study of the impact of environmental policy tools has been a focal point in academic research. Policies can guide relevant industries to reduce their consumption of fossil fuels, optimize energy consumption structures, and promote the transition to a low-carbon economy. The purpose of policy regulations is to control the negative impacts of economic activities within the ecological system's tolerance, ensuring low-carbon economic development (Tang et al., 2023). However, cumbersome policy and regulatory requirements can increase the time and cost of developing renewable energy projects, reducing their development capacity and hindering the transition to a low-carbon economy (Wu et al., 2023). If environmental regulations lack flexibility, they can weaken the incentive effect on low-carbon development, obstructing the transition to a low-carbon economy (Tang et al., 2020). Among various policies, the signing of the Paris Agreement holds milestone significance. Under this framework, countries fulfill their emission reduction responsibilities through nationally determined contributions, marking a new phase in global climate governance (Li et al., 2024). However, the specific impacts of its policies still require further validation. From this basis, we have the following hypotheses:

H3a: Policy regulation positively moderates the process by which renewable energy technology innovation promotes the transition to a low-carbon economy.

H3b: Policy regulation negatively moderates the process by which renewable energy technology innovation promotes the transition to a low-carbon economy.

3.4. The Role of Air Pollution Intensity

Renewable energy technology innovation can reduce air pollution caused by the combustion of fossil fuels (Obiora et al., 2024), decrease industrial pollutant emissions, and lower PM2.5 concentrations, thereby significantly improving air quality (Yu et al., 2023). Air pollution can lead to health problems, reduce labor productivity, and hinder economic development. Therefore, reducing air pollution concentrations can not only improve productivity but also provide an economic foundation for the transition to a low-carbon economy (Jaffe et al., 2004). Economic losses caused by air pollution can also motivate governments and enterprises to increase investments in low-carbon development, further promoting the transition to a low-carbon economy (Fisher-Vanden et al., 2004). Building on these observations, we propose the following hypotheses:

H4: Renewable energy technology innovation promotes the transition to a low-carbon economy by reducing air pollution intensity.

3.5 Renewable Energy Technology Innovation and Low-Carbon Economic Transition in Regions with Different Levels of Economic Development

China's vast territory leads to significant disparities in the development levels of renewable energy across regions (Ge et al., 2022). Economically developed regions have sufficient funding, advanced infrastructure, and abundant human resources, which further promote the adoption of renewable energy technologies (Bai et al., 2024). Conversely, regions with slower economic development face challenges such as inadequate infrastructure and excessive reliance on fossil fuels, making it difficult to achieve a low-carbon economic transition in a short period. Therefore, economically developed regions possess various advantages, making the impact of renewable energy technology innovation on low-carbon transition more significant in these areas. Given these premises, we have the following hypotheses:

H5: The impact of renewable energy technology innovation on the low-carbon transition is more significant in economically developed regions.

4. Data and Variables

This study selects panel data from 30 provincial-level regions in China (excluding Tibet) as the sample, covering the period from 2000 to 2021. Data on renewable energy technology innovation, specifically green patents, are sourced from the China Research Data Service Platform (CNRDS), while other data come from the "China Statistical Yearbook," EPS Database, CEIC, and Chinese Provincial Statistical Yearbooks.

4.1. Dependent Variable

Low-Carbon Economic Transition (CEI): This study measures low-carbon economic transition using carbon emission intensity, following the methodologies of Qiao et al. (2024), Zhang et al. (2024), and Bai et al. (2023). Carbon emission intensity is calculated as the ratio of CO₂ emissions to GDP. A higher CEI indicates slower progress in low-carbon economic transition.

4.2. Key Independent Variable

Renewable Energy Technology Innovation (RETI): Given data availability, this study measures renewable energy technology innovation using the number of green patent applications. Due to the lag in granting green patents, there may be delays in quantifying local technological innovation (Yao et al., 2021). Therefore, using the number of green patent applications as the key independent variable can more accurately reflect the state of renewable energy technology innovation (Yang et al., 2024).

4.3. Control Variables

(1) Foreign Direct Investment (FDI): Measured as the ratio of total import and export value to GDP.

- (2) Urbanization Level (URB): Calculated as the ratio of urban population to total population.
- (3) Industrial Structure (IS): Represented by the ratio of the tertiary industry to the secondary industry.
- (4) Economic Development Level (lnPGDP): Measured as the logarithm of per capita GDP to reflect the economic development level of a region.

4.4. Moderating Variable

Climate Risk (CRI): Climate risk data are derived from daily observations by the National Oceanic and Atmospheric Administration (NOAA) and calculated based on the number of extreme cold, heat, precipitation, and drought days. These are standardized and weighted to form a comprehensive climate physical risk index (Guo et al., 2024).

4.5. Mediating Variable

Air Pollution Intensity (lnAPI): Referring to Jiang et al. (2024), this study introduces the variable of air pollution intensity, measured as the logarithm of the annual average PM2.5 emissions of each province divided by the GDP of the corresponding year.

4.6. Model Specification

To examine the impact of renewable energy technology innovation on low-carbon economic transition, the following baseline regression model is constructed:

$$CEI_{it} = \alpha_0 + \alpha_1 RETI_{it} + \alpha_2 Control_{it} + \varepsilon_{it} \quad (1)$$

In equation (1), CEI_{it} represents the low-carbon economic transition, $RETI_{it}$ denotes renewable energy technology innovation, $Control_{it}$ signifies a series of control variables, and ε_{it} is the random error term.

Furthermore, assuming that CRI moderates the impact of RETI on CEI, the following moderation effect model is established:

$$CEI_{it} = \gamma_0 + \gamma_1 RETI_{it} + \gamma_2 CRI_{it} + \gamma_3 RETI_{it} \times CRI_{it} + \gamma_4 Control_{it} + \varepsilon_{it} \quad (2)$$

In equation (4), CRI_{it} is the moderating variable, representing the climate risk index. γ_1 through γ_4 are the coefficients to be estimated, and the interaction terms are mean-centered.

5. Empirical Analysis

5.1. Baseline Regression

Table 1: Descriptive Statistics

Variables	Observations	Mean	Std. Dev.	Min	Max
CEI	660	0.0256	0.0177	0.00157	0.126
RETI	660	4091	8078	3	67258
URB	660	0.517	0.158	0.139	0.896
FDI	660	0.298	0.364	0.00757	1.721
lnPGDP	660	9.185	0.522	7.887	10.78
IS	660	1.064	0.588	0.494	5.297
lnAPI	660	-5.516	1.134	-8.632	-1.937
CRI	660	43.64	8.74	19.08	84.34

The table shows a significant gap between the minimum and maximum values of CEI, reflecting the disparities among provinces in the transition to a low-carbon economy. The high standard deviation of RETI indicates considerable differences in the number of renewable energy technology innovations among provinces, with the maximum value being 67,258 and the minimum value only 3, further emphasizing the substantial variation in the level of technological innovation development.

As shown in column (5) of Table 2, the estimated coefficient of RETI is negative and significant at the 1% level. The regression results indicate that RETI has a significant negative impact on CEI. Hence, H1 is validated, suggesting that renewable energy technology innovation is conducive to promoting the transition to a low-carbon economy.

5.2. Robustness Checks

The baseline regression results indicate that RETI has a significant negative impact on CEI. To enhance the robustness of the model estimation results, the following tests were conducted: (1) Endogeneity Test: Using the lagged term of RETI as an instrumental variable, a two-stage least squares (2SLS) analysis was performed. In the first stage, the lagged term of RETI was regressed on RETI. In the second stage, the predicted values from the first stage were used as a proxy for RETI to regress CEI. (2) Replacing the Dependent Variable: Referring to Yi et al. (2022), the proportion of carbon emissions to the added value of the secondary industry was used as an alternative variable for low-carbon economic transition.

The results show that renewable energy technology innovation still has a significant negative impact on the low-carbon economic transition, proving the robustness of the results. (3) Excluding Special Years: Considering the impact of the 2008 global financial crisis on China's economy and renewable energy technology innovation, data from the year 2008 was excluded. (4) Handling Outliers: To minimize the impact of outliers on the estimation results, all continuous variables were winsorized at the 1% level at both ends.

Table 2: Baseline Regression results

Variables	(1)	(2)	(3)	(4)	(5)
RETI	-5.44e-07*** (1.56e-07)	-5.20e-07*** (1.52e-07)	-5.11e-07*** (1.50e-07)	-4.48e-07*** (1.39e-07)	-4.47e-07*** (1.38e-07)
URB		0.00708*** (0.00198)	0.00648*** (0.00213)	-0.00580 (0.00820)	-7.95e-05 (0.00822)
FDI			-0.00399 (0.00349)	-0.00387 (0.00414)	-0.00885* (0.00487)
lnPGDP				0.0122** (0.00468)	0.0124*** (0.00415)
IS					-0.00462** (0.00226)
Constant	0.0278*** (0.000638)	0.0241*** (0.00132)	0.0255*** (0.00169)	-0.0809** (0.0390)	-0.0785** (0.0350)
Observations	660	660	660	660	660
R ²	0.106	0.111	0.113	0.138	0.152

Notes: Robust standard errors in parentheses; ***, **, and * denote significance at the 1, 5, and 10 % levels, respectively.

Table 3: Robustness tests

Variables	(1)	(2)	(3)	(4)	
	2SLS (First Stage)	2SLS (Second Stage)	Replacing the explained variable	Excluding specific year	Dealing with outliers
RETI					
L.RETI	0.858*** (0.0101)				
RETI		-6.94e-07*** (8.37e-08)	-9.49e-07*** (3.33e-07)	-5.10e-07*** (1.52e-07)	-5.96e-07*** (1.35e-07)
URB	-2,426* (1,228)	0.0251*** (0.00654)	-0.00638 (0.0240)	-2.53e-05 (0.00888)	-0.00111 (0.00839)
IS	900.0 (669.9)	-0.00694*** (0.00121)	-0.0117** (0.00502)	-0.00461** (0.00223)	-0.00384 (0.00277)
lnPGDP	-2,476*** (743.4)	0.00841*** (0.00264)	0.0245** (0.0111)	0.0112** (0.00426)	0.0113** (0.00432)
FDI	-76.16 (1,419)	-0.0166*** (0.00285)	-0.0126 (0.0117)	-0.00757 (0.00471)	-0.00696 (0.00452)
Constant	23,933*** (6,807)	-0.0500** (0.0216)	-0.141 (0.0928)	-0.0676* (0.0356)	-0.0692* (0.0360)
Observations	630	630	660	630	660
R^2	0.808	0.265	0.110	0.144	0.184

Notes: Robust standard errors in parentheses; ***, **, and * denote significance at the 1, 5, and 10 % levels, respectively.

5.3. The Impact of Climate Risks

To further validate the moderating effect of climate risks, interaction terms between renewable energy technology innovation and climate risks were added to the baseline regression model. The regression results are shown in the table. The coefficient for the interaction term (CRI) is significantly positive, indicating that climate risks hinder the transition to a low-carbon economy and reduce the positive impact of renewable energy technology innovation on this transition. Hence, H2a is validated.

Table 4: The role of climate risk

Variables	Coefficients
RETI	-0.744 (-1.547)
CRI	0.000978*** (3.331)
RETI×CRI	0.0413** (2.281)
URB	0.00884 (1.030)

IS	0.0109*** (3.349)
lnPGDP	-0.0215** (-2.467)
FDI	0.0224** (2.138)
Constant	0.218*** (3.764)
Observations	660
R^2	0.263

Notes: Robust standard errors in parentheses; ***, **, and * denote significance at the 1, 5, and 10 % levels, respectively.

5.4. Analysis of Policy Regulation Effects

Among various policy regulations, the signing of the Paris Agreement holds epoch-making significance. China announced its accession to the Paris Agreement in 2015. To explore the role of policy regulation, this study employs the difference-in-differences (DID) method, using 2015 as the year of policy treatment to analyze the specific role and effect of the Paris Agreement policy in promoting China's transition to a low-carbon economy.

5.4.1. Stability Test

(1) Parallel Trend Test:

The graph shows that before the policy intervention (before 2015), the trends of different groups were roughly the same, satisfying the parallel trend assumption. After the policy implementation, the policy effect significantly decreased, indicating a negative impact on the treatment group. This change in trend suggests that the policy intervention had the intended effect, supporting the validity of the research design. It shows that the difference in trends is primarily due to the policy implementation, rather than other factors.

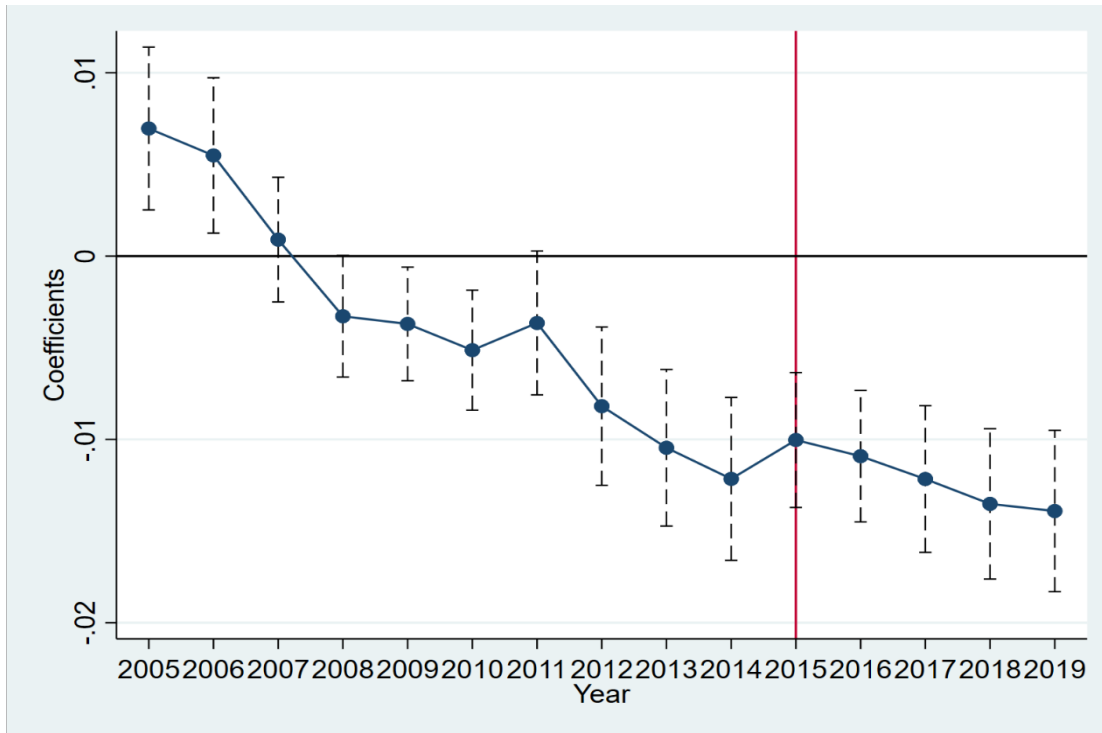


Fig. 1: Parallel trend test.

Combining the importance of the energy industry in the economic structure of each province and the proportion of fossil energy in industrial production, 17 provinces that rely heavily on fossil energy, such as Shanxi, Inner Mongolia, and Shaanxi, are designated as the treatment group. The other provinces serve as the control group. The constructed DID model is shown in equation (3):

$$CEI_{it} = \alpha_0 + \alpha_1 treat_i \times post_t + \alpha_2 Control_{it} + \varepsilon_{it} \quad (3)$$

From the formula, $post_t$ is a time dummy variable, taking the value 0 for the years 2015 and earlier, and 1 for the years after 2015. $treat_i$ is a regional dummy variable, taking the value 1 for provinces that rely on fossil energy and 0 for provinces that do not. The coefficient of the interaction term for policy implementation is -0.00415, which is significant at the 10% level. This indicates that the policy implementation has a significant negative impact on the CEI of the treatment group, suggesting that the policy effectively reduced carbon emissions in regions reliant on fossil energy and promoted the transition to a low-carbon economy. This demonstrates that the policy achieved the expected environmental improvement effect.

(2) Placebo Test:

The placebo test is used to confirm whether there were any significant effects before the policy implementation. In this study, a fictitious policy implementation time was set to 2009, and a regression analysis was conducted. The impact of the placebo treatment variable on CEI was not significant, indicating that the treatment effect observed in the original DID analysis is robust and not due to random causes.

Table 5: Baseline regression results

Variables	(1)	(2)
treat×post	-0.0153*** (0.00184)	-0.00415* (0.00214)
URB		-0.00870 (0.0104)
IS		-0.00626** (0.00242)
lnPGDP		0.00778* (0.00446)
FDI		0.00291 (0.00364)
Constant	0.0281*** (0.000300)	-0.0315 (0.0368)
Observations	660	660
R^2	0.227	0.351

Notes: Robust standard errors in parentheses; ***, **, and * denote significance at the 1, 5, and 10 % levels, respectively.

Table 6: Placebo test

Variables	Coefficient
placebo	2.53e-05 (0.000952)
URB	-5.13e-05 (0.00878)
FDI	-0.0117** (0.00531)
lnPGDP	0.0168*** (0.00403)
IS	-0.00469* (0.00234)
Constant	-0.120*** (0.0336)
Observations	660
R^2	0.088

Notes: Robust standard errors in parentheses; ***, **, and * denote significance at the 1, 5, and 10 % levels, respectively.

In this study, 500 placebo tests were conducted, generating a distribution chart of the regression coefficients for the fictitious treatment variable. The chart shows that the regression coefficients of the fictitious treatment variable are mainly concentrated around 0, exhibiting a normal distribution shape. The fictitious treatment variable has no significant impact on CEI, further validating that the significance of the actual treatment effect is not due to random factors.

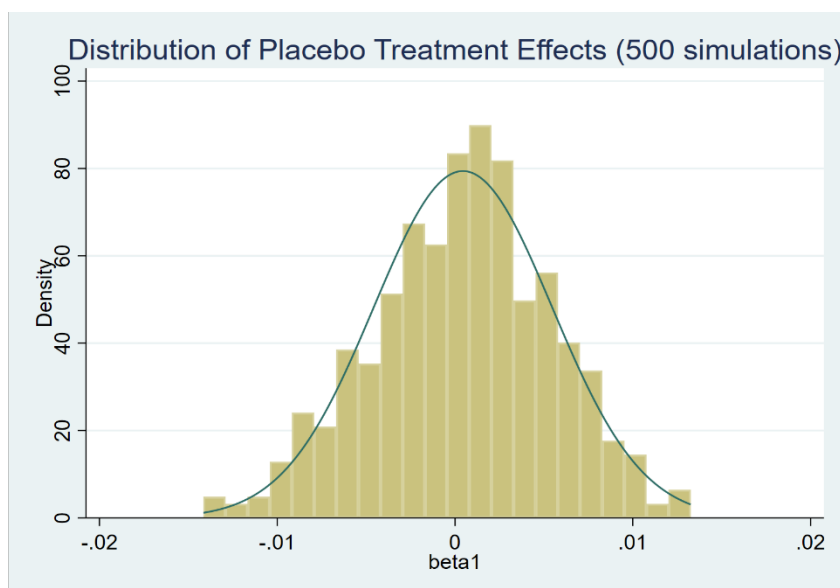


Fig. 2: Placebo test.

(3) PSM-DID (Propensity Score Matching - Difference in Differences):

The analysis results using the PSM-DID method show that the interaction term has a significant positive impact on the low-carbon economic transition. Columns (1), (2), (3), and (4) represent k-proximity matching ($k = 1$), logit matching, radius matching, and kernel matching, respectively. As shown in the table, regardless of the matching method used, the coefficient and significance of the interaction term do not change substantially. This indicates that the Paris Agreement policy effectively promotes the transition to a low-carbon economy.

Table 7: PSM-DID

Variables	(1)	(2)	(3)	(4)
	k-proximity matching	logit matching	radius matching	kernel matching
treat×post	-0.0160*** (0.00217)	-0.0158*** (0.00215)	-0.0149*** (0.00195)	-0.0150*** (0.00210)
URB	-0.00350 (0.0114)	-0.00451 (0.0114)	-0.00787 (0.0100)	-0.00781 (0.0133)
FDI	0.00102 (0.00528)	-0.000552 (0.00594)	-0.00209 (0.00547)	-0.00165 (0.00595)
lnPGDP	0.00892* (0.00493)	0.00924* (0.00479)	0.0122*** (0.00413)	0.0123** (0.00571)
IS	-0.00761* (0.00408)	-0.00724* (0.00380)	-0.00461** (0.00209)	-0.00497* (0.00278)
Constant	-0.0410 (0.0422)	-0.0443 (0.0405)	-0.0743** (0.0339)	-0.0745 (0.0472)
Observations	510	540	660	648
R^2	0.297	0.286	0.267	0.268

Notes: Robust standard errors in parentheses; ***, **, and * denote significance at the 1, 5, and 10 % levels, respectively.

This study also lagged the control variables by one period. The results show that the interaction term is significant at the 1% level. These tests demonstrate that the research findings are robust. Hence, H3a is validated.

6.0 Further Discussion

To understand the mechanism through which renewable energy technology innovation affects the low-carbon economic transition, this study will conduct mediation effect analysis and heterogeneity tests.

6.1. Mediation Effect

Referring to the suggestions by Jiang Ting (2022) on mediation effect analysis, this study addresses the estimation bias issue of the traditional stepwise regression method by focusing on the impact of the core explanatory variable (renewable energy technology innovation) on the mediating variable (air pollution intensity). Therefore, based on the baseline regression model (1), the following mediation effect model is established:

$$\ln API_{it} = \beta_3 + \beta_5 RETI_{it} + \beta_4 Control_{it} + \varepsilon_{it} \quad (4)$$

In equation (4), $\ln API_{it}$ represents the mediating variable, which is air pollution intensity. When both β_1 and β_5 are significant, it indicates the presence of a mediation effect.

The mediating role of air pollution in the impact of renewable energy technology innovation on the low-carbon economic transition cannot be ignored. Existing research has confirmed that renewable energy technology innovation significantly reduces the emission of air pollutants, almost eliminating harmful substances such as sulfur dioxide and PM2.5 (Saidur et al., 2011). It also significantly improves energy utilization efficiency, reduces the demand for traditional energy, and further lowers pollution intensity (Green et al., 2019). Therefore, renewable energy technology innovation plays a significant role in reducing air pollution intensity.

The reduction in air pollution intensity facilitates the low-carbon economic transition in two ways. First, as public awareness of reducing air pollution increases, governments adopt more proactive environmental protection measures and low-carbon development strategies, reducing reliance on high-carbon industries and shifting towards sustainable development (Thomas et al., 2009). Second, reducing air pollution intensity can improve workers' health, increase labor productivity, and enhance economic performance, providing a solid economic foundation for the low-carbon economic transition (Song et al., 2020).

The regression results, as shown in the table, indicate that $\ln API$ plays a significant mediating role between RETI and CEI. An increase in RETI leads to a decrease in $\ln API$, suggesting that renewable energy technology innovation can reduce air pollution intensity. Additionally, $\ln API$ has a significant positive impact on CEI, indicating that a reduction in air pollution intensity is conducive to the transition to a low-carbon economy. Hence, H4 is validated.

Table 8: The role of air pollution intensity

Variables	(1)	(2)
	lnAPI	lnAPI
RETI	-7.12e-05*** (1.55e-05)	-6.33e-05*** (1.42e-05)
URB		-0.0274 (0.499)
IS		-0.481*** (0.117)
lnPGDP		0.972*** (0.206)
FDI		-1.095*** (0.290)
Constant	-5.225*** (0.0636)	-13.34*** (1.707)
Observations	660	660
R ²	0.299	0.358

Notes: Robust standard errors in parentheses; ***, **, and * denote significance at the 1, 5, and 10 % levels, respectively.

6.2 Heterogeneity Analysis

This study continues to investigate the heterogeneous impact of renewable energy technology innovation (RETI) on low-carbon economic transition (CEI) by analyzing the differences in economic development levels. We rank the bottom one-third of the provinces as low economic development regions, the middle one-third as medium economic development regions, and the top one-third as high economic development regions. The results are shown in columns (1), (2), and (3) of Table 9. Column (1) indicates that in regions with low levels of economic development, the impact of renewable energy technology innovation on the low-carbon economic transition is not clear. Column (3) shows that in provinces with higher levels of economic development, renewable energy technology innovation significantly promotes the low-carbon economic transition. Hence, H5 is validated.

Table 9: Heterogeneity test

Variables	(1)	(2)	(3)
RETI	0.0710 (0.3418)	-1.6467*** (-7.5309)	-0.8959*** (-8.0254)
URB	0.0638* (1.6568)	-0.0054 (-0.4657)	-0.0055 (-1.1295)
IS	-0.0038 (-0.3671)	-0.0030 (-0.5443)	0.0003 (0.2551)
lnPGDP	-0.0211 (-1.1442)	0.0118* (1.7608)	0.0039 (1.2137)
FDI	-0.0148	-0.0049	-0.0111***

	(-0.4066)	(-0.5228)	(-3.2873)
Constant	0.2202	0.0152	0.0526*
	(1.3688)	(0.2604)	(1.9414)
Observations	220	220	220
R^2	0.0161	0.2468	0.2843

Notes: Robust standard errors in parentheses; ***, **, and * denote significance at the 1, 5, and 10 % levels, respectively.

7.0 Conclusions and Policy Implications

This study empirically examines the impact of renewable energy technology innovation on the low-carbon economic transition and analyzes the moderating roles of climate risk and policy regulation. The main conclusions are as follows:

- (1) **Baseline Regression Results:** Renewable energy technology innovation significantly promotes the low-carbon economic transition by reducing carbon emission intensity. This conclusion is supported by a series of robustness tests.
- (2) **Moderating Effects:** Climate risks hinder the process by which renewable energy technology innovation promotes the low-carbon economic transition.
- (3) **Difference-in-Differences (DID) Results:** The implementation of the Paris Agreement policy significantly improves the low-carbon economic transition in fossil fuel-dependent provinces, achieving the expected environmental effects. This demonstrates the important role of the Paris Agreement in guiding renewable energy technology innovation and promoting the low-carbon economic transition.
- (4) **Mediation Effects:** Renewable energy technology innovation significantly promotes the low-carbon economic transition by reducing air pollution intensity.
- (5) **Heterogeneity Results:** In provinces with higher levels of economic development, technological innovation significantly promotes the low-carbon economic transition. In contrast, the impact is not significant in regions with lower economic development levels.

This study provides empirical support for the role of renewable energy technology innovation in advancing the low-carbon economic transition and offers the following policy recommendations:

(1) **Strengthen R&D Investment and Collaboration:** The government should increase funding for renewable energy technology innovation, establish special funds, and encourage enterprises and research institutions to conduct R&D in renewable energy. Investments should focus on technologies that improve energy efficiency and reduce carbon emissions. Additionally, the government should encourage collaboration between enterprises and research institutions, optimize the patent application and approval process, and shorten the authorization time for green patents to ensure that innovative achievements can quickly transform into productivity.

(2) **Establish Climate Risk Management Mechanisms:** The government should establish a comprehensive climate risk assessment system, conduct regular assessments of climate risks

in different regions, identify potential risks, and enhance emergency response capabilities to extreme weather events. This will reduce damage to renewable energy projects and ensure the steady progress of renewable energy technology innovation.

(3) Promote Regional Economic Development: Efforts should be made to optimize and upgrade industrial structures, support the development of high-tech, low-pollution industries, and promote the transformation and upgrading of traditional industries to reduce reliance on traditional fossil fuels. Increasing investment in scientific research and development, fostering new technologies, products, and business models, and enhancing economic development levels will create a favorable environment for the development of renewable energy.

(4) Strengthen Environmental Policy Implementation: The government should formulate proactive policy guidance and incentive measures, strengthen the enforcement and supervision of environmental policies, ensure the implementation of environmental protection measures, and create favorable conditions for renewable energy technology innovation.

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