Dual carbon goals and renewable energy innovations

Xuanmei Cheng, Kaite Ye, Anna Min Du, Zhenzhen Bao, Grigoria Chlomou

PII: S0275-5319(24)00199-5

DOI: https://doi.org/10.1016/j.ribaf.2024.102406

Reference: RIBAF102406

To appear in: *Research in International Business and Finance*

Received date: 1 April 2024
Revised date: 20 May 2024
Accepted date: 22 May 2024

Please cite this article as: Xuanmei Cheng, Kaite Ye, Anna Min Du, Zhenzhen Bao and Grigoria Chlomou, Dual carbon goals and renewable energy innovations, *Research in International Business and Finance,* (2024) doi:https://doi.org/10.1016/j.ribaf.2024.102406

Dual carbon goals and renewable energy innovations

Xuanmei Cheng

School of Management, Zhijiang College,

Zhejiang University of Technology

Email: may1981@zjut.edu.cn

Kaite Ye

School of Management,

Zhejiang University of Technology

Email: 1392325576@qq.com

Anna Min Du[1]

The Business School, Edinburgh Napier University

Email: a.du@napier.ac.uk

ORCID: https://orcid.org/0000-0002-1715-8774

Zhenzhen Bao

Zhijiang College,

Zhejiang University of Technology

Email: bmail16@163.com

Grigoria Chlomou

The Business School, Edinburgh Napier University

Email: g.chlomou@napier.ac.uk

This work was supported by the National Social Science Foundation of China (Grant No. 21AJL003, 21BJY262).

Abstract

We examine the impact of renewable energy technology innovation on carbon emissions within the framework of China's ‘dual carbon’ goal, focusing on the role of

[1] Corresponding author.

local (provincial) government innovation competitions and economic competition. Analyzing data across 30 provinces from 2010 to 2019, we investigate the correlation between renewable energy advancements and emission reductions and how local government competition modulates this relationship. Our findings suggest that renewable energy innovations have a significant negative impact on carbon emissions. The study reveals that innovation competition among local governments positively affects emission reductions, while economic competition has a negative impact. These results contribute to understanding how regulatory competition among local governments can support or impede the achievement of dual carbon objectives, emphasizing the need for a competitive yet collaborative regulatory environment to enhance the benefits of renewable energy innovations.

Keywords: renewable energy innovation, carbon emissions, dual carbon goals, sustainable future, regulatory framework

1.Introduction

Carbon emissions have emerged as a critical issue of global concern (Du et al., 2024a; Yang et al., 2024). Notably, China has led in carbon emissions from 2009 to 2022, making the reduction of its carbon footprint a pressing priority. In September 2020, at the 75th session of the United Nations General Assembly, China pledged to adopt "dual carbon" targets, which aim to achieve both "carbon peak" and "carbon neutrality" as part of its strategy to mitigate carbon emissions. This commitment signifies China's dedication to pursuing a path of green and low-carbon development (Yang et al., 2021; Xinhua, 2022). The "dual carbon" goals delineated by China require a substantial decrease in carbon dioxide emissions per unit of GDP by over 65% from 2005 levels by 2030, and an increase in the share of non-fossil fuel energy consumption to more than 80% by 2060. Therefore, it is critical to focus on reducing economic dependence on non-renewable resources (Du et al.,2024a). Realising these ambitious aims necessitates the development of a new energy infrastructure, heavily reliant on renewable energy sources such as wind and solar power. Consequently, carbon reduction has ascended as a foremost objective of governmental policies. Innovation in renewable energy technology plays a crucial role in this energy transformation, marking a significant step towards the creation of new energy systems in China. Such innovations hold considerable promise for reducing energy consumption and, by extension, carbon emissions (Ren et al., 2021).

Climate change has adverse implications on many global aspects (Goodell et al., 2023a) and carbon emissions engender considerable negative externalities, complicating the market's ability to address the efficiency dilemma in resource allocation (Eichner and Pethig, 2013). The theory of market failure argues that the negative externalities that arise in it mean that the actual market conditions do not correspond to the necessary conditions for the pure market economy, conditional market failure. As a result, it is impossible to realize the maximization of efficiency of resource allocation only through market mechanisms. If market failure is due to external negative effects, it is forced to trust the government. Empirical evidence suggests that competition among local governments not only catalyses the infusion of innovative

inputs but also significantly influences the resource distribution mechanisms of both governmental and private sectors. However, the push from the government, though likely, will encourage firms to innovate for environmental management may distort the market of investment and resource allocation efficiency (Du et al.,2024b). Within the ambit of carbon reduction, the strategic orientation of local governments towards effective and judicious policy measures is imperative. Recent shifts in performance evaluation criteria have seen local governmental competition evolve from a predominantly economic paradigm to one embracing innovation (Yang et al., 2023a). In response to the "dual carbon" initiative, local authorities have promulgated policies fostering renewable energy technological innovation as a strategy to mitigate regional carbon footprints (Zhao et al., 2022). Despite the acknowledgment of renewable energy innovation as a pivotal instrument for achieving "dual carbon" objectives, the extent of its impact on carbon reduction remains an area of academic debate, with suggestions of varying regional efficacies (Cheng and Yao, 2021). This ambiguity presents critical inquiries regarding the influence of renewable energy technological advancements on carbon emissions and the potential moderating effect of local government competition. To elucidate these dynamics, this study analyses data from 30 Chinese provinces and regions spanning 2010 to 2019, aiming to delineate the interplay between renewable energy technology innovation and carbon emissions. The empirical study demonstrated that: first, renewable energy technology innovation can inhibit carbon emissions. Second, the inhibition effect caused by “local government economic competition” will be weakened; the inhibition effect caused by the “local government innovation competition” will be strengthened. This investigation seeks to contribute to the theoretical underpinnings necessary for formulating effective strategies to enhance China's carbon emission reduction efforts.

The contributions of this paper are multifaceted, presenting a persuasive narrative on the progression of China towards a "dual carbon" economy. Firstly, by positioning renewable energy technology innovation at the heart of this analysis, the research sheds light on new insights and approaches that are instrumental in mitigating China's carbon emissions. Such innovation is identified as a key instrument for environmental

stewardship, supported by national policies aimed at achieving carbon neutrality and reduction. Secondly, incorporating local government competition into our analytical framework provides a detailed examination of the evolving relationship between renewable energy technology innovation and carbon emissions across different competitive contexts—specifically, those geared towards economic development versus those aiming to encourage innovation. This distinction not only enables a more comprehensive understanding of the effectiveness of policies within diverse regulatory and competitive environments, but also provides practical environmental and economic strategic guidance for the financial sector. Lastly, through an examination of the diversity within China's geographical landscape, this study delivers a more precise evaluation of the emission reduction potential of renewable energy technological innovations. This detailed analysis highlights the significance of tailored strategies in the national strategy for carbon reduction, thus improving the accuracy and impact of policy measures. Together, these contributions lay down a solid theoretical and empirical base for furthering China's dual carbon aims, emphasising the vital importance of renewable energy innovation and local government competition in shaping the future direction of the country's environmental and economic strategies.

2. Literature review

The nexus between technological innovation and carbon emissions has garnered significant scholarly interest as part of a broader quest to tackle global challenges such as climate change and sustainable development. A segment of the academic community recognises the potential of technological innovation to mitigate carbon emissions, citing changes in energy consumption patterns and industrial structure enhancements as pivotal factors (Ma et al., 2021), along with the necessary adjustments within governmental and media frameworks (Liang et al., 2022). On the other hand, some scholars have argued that the direct impact of technological innovation as curtailing carbon emissions may not be direct because most technological innovations are not designed to protect the environment, and instead, it may cause increased emissions (Ganda, 2019).

Within this discourse, renewable energy technology innovation emerges as a critical subset of technological innovation, possessing a more direct influence on energy consumption and environmental conditions (Zhao et al., 2023), and thereby impacting China's carbon emissions profile. In the context of China's "dual carbon" objectives, the efficacy of renewable energy technology innovation in reducing carbon emissions has received increased scrutiny, with a consensus forming around its significant potential to curb emissions. Bai et al. (2020) report that advancements in renewable energy technology have led to reductions in per capita carbon dioxide emissions, particularly at higher income levels.

Despite these findings, the debate regarding the influence of renewable energy technological innovations on carbon emissions persists. Cheng and Yao (2021) observed that more advanced renewable energy technologies exert a minimal impact on carbon emission intensity in the short term, whereas Lin and Zhu (2019) contend that renewable energy technology innovation does not directly affect carbon emissions. This divergence in academic viewpoints underscores the complexity of assessing the relationship between technological innovation and carbon emissions, highlighting the need for further rigorous investigation to elucidate the mechanisms through which renewable energy technology innovation can contribute to carbon emission reduction in the context of global and national sustainability goals.

A plausible explanation for the ongoing debate concerning the influence of renewable energy technology innovation on carbon emissions is the overlooked impact of the regulatory effects stemming from local government competition. The Chinese Government recognises local government competition as a critical determinant in achieving the "dual carbon" objectives. In response, our research incorporates a regulatory variable pertaining to local government competition to delve deeper into this issue. In the era of "dual carbon" targets, there has been a paradigm shift in the performance evaluation metrics for local governments, transitioning from a focus on "economic growth" to the ethos of "green water and green mountains are as valuable as golden mountains and silver mountains". Despite this shift, the persistence of

environmental performance challenges and the protracted nature of sustainability initiatives have led local governments to continue prioritising economic development.

The intensification of economic competition among local governments has a tendency to divert resources away from innovation investments, thereby impeding the potential carbon emission reduction benefits derived from renewable energy technology advancements. Furthermore, the high costs and practical implementation challenges associated with emerging renewable energy technologies (Chen and Lin, 2020) underscore the significance of the innovation ecosystem fostered by local governments. This environment is instrumental in facilitating the development and deployment of cutting-edge renewable energy solutions. Consequently, the degree to which local governments foster an innovation-friendly environment emerges as a pivotal factor influencing the efficacy of renewable energy technology innovation in reducing carbon emissions. This underscores the need for a nuanced understanding of how local government strategies and competition dynamics influence the landscape of technological innovation and its potential to contribute to carbon emission reduction efforts.

The review of extant literature unveils three primary gaps in the current body of research. Firstly, the scholarly focus predominantly rests on the effects of technological innovation on carbon emissions, with particular emphasis on green technology and digital technology advancements (Hunjra et al.,2024; Zeng and Yang, 2023). However, the literature pertaining specifically to the impact of renewable energy technology innovation on carbon emissions is notably limited. Secondly, the discourse surrounding the influence of renewable energy technological innovation on carbon emissions presents divergent viewpoints, leaving the nature of their relationship highly debated and unresolved. Finally, while existing studies have extensively explored the influence of temporal dynamics (Cheng and Yao, 2021), income levels (Yan et al., 2020), and other variables (Danish and Ulucak, 2021) on the carbon emission mitigation potential of renewable energy technology innovations, there is a conspicuous scarcity of research examining the role of local government competitive behaviours. It is our contention that the varying impacts of local government competition merit substantial

consideration and investigation within the discourse on emissions reduction. This oversight underscores a critical need for enhanced scholarly attention to more comprehensively understand how local government competition influences the efficacy of renewable energy technology innovations in reducing carbon emissions.

3. Theoretical analysis and research hypothesis

Natural resources that can naturally recover, such as solar, hydropower, wind, and biomass, can reduce carbon emissions to a certain extent as an energy source alleviating the problem of natural pressure. Renewable energy is not yet universally available because of the natural attributes that make it difficult to store and transport. It can only be realized through the innovative development of renewable energy technologies. However, the process of carbon emissions and the innovation of renewable energy technologies will generate significant externalities. According to the market failure theory of external factors, external factors associated with the production are independent of those involved in the exchange (Claassen, 2016), it may lead to an inefficient market. So, to ensure that the market reallocates resources a local government action is required. Therefore, this article uses local government competition as a moderator variable. This variable aims to explore whether the impact of renewable energy technology innovation on carbon emissions will change with different competition.

3.1 Renewable energy technology innovation and carbon emissions

Renewable energy is abundantly available and more sustainable by far compared to other sources. Thus, it can be considered an excellent constituent for the formation of energy (Yang et al., 2023b; Zheng et al., 2021). Innovations in renewable energy technologies facilitate the advancement and application of industrial processes that significantly contribute to the reduction of carbon emissions and promote sustainable, green development (Goodell et al., 2023b). Examples of such technologies include advancements in solar and hydropower sectors, which offer viable alternatives to non-renewable energy sources. Consequently, the development and integration of renewable energy technologies not only contribute to the diminution of non-renewable energy consumption but also enhance the regional energy consumption architecture. This shift

towards renewable sources plays a pivotal role in reducing dependency on non-renewable energies via energy substitution mechanisms (Habiba et al., 2022), ultimately contributing to the reduction of carbon emissions.

The innovations in renewable energy technology could not only reduce the cost of energy consumption but also make the production pie in a low-carbon manner and a cleaner production offset, which could greatly reduce carbon emissions during the stages of energy development and utilization. For example, carbon dioxide emissions during the production process of solar and wind power are almost nil, and carbon dioxide emissions during the production of hydropower are relatively low, which is completely incomparable to the carbon emissions of conventional oil and coal power plants, which are almost ten times others. Continuous innovation and development of renewable energy technologies could improve energy efficiency and reduce energy consumption per unit of GDP growth (Su and Fan, 2022; Cheng et al., 2024). Furthermore, the refinement of renewable energy technologies can harmonise the relationship between economic development and energy consumption. This synergy potentially culminates in a decrease in carbon emissions generation, illustrating the critical role of renewable energy innovation in aligning economic growth with sustainable energy consumption practices.

From an industrial vantage point, the advent of innovative renewable energy technologies plays a pivotal role in facilitating the integration of renewable energy sources within sectors primed for transition towards green and sustainable development paradigms. These technologies not only have the capacity to advance the development of natural energy sources, such as solar, hydropower, and wind energy, but they also hold the potential for integration with energy-storage technologies to ensure a continuous supply of clean energy. Moreover, the emergence of novel renewable energy technologies can create a feedback loop where technological advancements catalyse the growth of emergent energy sectors, thereby propelling China's shift towards a low-carbon economy (Bai et al., 2020).

Thus, there is a possibility that innovations in renewable energy technology will reduce regional energy consumption by an amount that will at best have low carbon

energy production effects and, at worst, will exacerbate long-run energy trends, reducing energy efficiency and slowing the speed of industrial structural change in a way that would suppress carbon emissions and the generation of electric energy. In light of these considerations, we put forward Hypothesis 1:

Hypothesis 1: Renewable energy technology innovation can reduce the generation of carbon emissions.

3.2 The moderating effect of local government competition

Local government competition encompasses the inter-regional rivalry among local administrative entities within a nation, particularly in aspects concerning the investment climate, legal frameworks, and efficiency of governmental operations to furnish public goods and allure capital, technology, and other critical factors of production. Such competition often has a “weather vane” role in business innovation and environmental governance. In business innovation and carbon emission, the market mechanism often ignores the positive externalities generated by renewable energy technology innovation and the negative externalities generated by carbon emissions in its entirety due to the limitation of evaluation indexes, the impact of information asymmetry, etc. The market cannot play an optimal effect of guiding the carbon emission reduction effect of renewable energy technology innovation. However, synchronizing competition between local governments can make up for the market’s shortcomings in fully considering externalities due to the logical scale of relevant policies. The progressive decentralisation of governance in China has endowed local authorities with augmented discretion over these variables, engendering a diversification in the competitive strategies employed by these governments in the domain of environmental governance （Cheng et al., 2023b). From the perspective of the market failure theory, the described strategies indeed represent a means to correct the existing market failure. However, the strategies described above are not without their stakes in the innovation outcomes in the renewables technology industry and the relevant carbon emissions. Reflecting upon the multifaceted nature of local government competition, this study delineates the concept into two distinct categories: economic competition and innovation competition.

Local government economic competition refers to the inter-regional rivalry amongst local governments aimed at achieving economic expansion. In their quest for growth, local authorities are predisposed towards fostering industrial expansion, gravitating towards sectors known for their rapid yield, substantial tax contributions(Cheng et al., 2023a), and significant output, to expedite production activities. Concurrently, there is a tendency to eschew investments in ventures marked by higher risks and elongated production timelines, such as technological innovation and scientific research initiatives. This approach not only predisposes to an increase in carbon emissions but also to a disproportionate allocation of resources (Ding et al., 2024), engendering a developmental disparity across various industrial sectors. Such disparities can stifle the transformation of the industrial structure and decelerate the transition towards a low-carbon economy, thereby diminishing the potential of renewable energy technology innovations to reduce carbon emissions. Furthermore, in the pursuit of economic objectives, local governments may opt to relax environmental regulatory standards, thereby permitting enterprises to augment their carbon footprint. This relaxation of standards fosters an increased dependency on conventional energy sources, undermining the displacement of non-renewable by renewable energy sources and exacerbating carbon emissions. In light of these considerations, we put forward Hypothesis 2a:

Hypothesis 2a: Economic competition plays a negative regulatory role in the relationship between technological innovation in renewable energy and carbon emissions.

Compared to economic competition, innovation competition among local governments is delineated as the inter-regional rivalry focused on fostering scientific and technological advancements, necessitating significant investment and backing. Governmental interventions, especially through tax incentives and subsidies, serve to mitigate research and development (R&D) expenditures, bolster production capabilities, and enhance the innovation capacity of firms. Such policies provide the requisite financial and infrastructural support essential for the evolution of cutting-edge

renewable energy technologies (Gao et al., 2021), thereby expediting the transition from conventional to renewable energy sources.

Moreover, through the mechanism of innovation competition, local governments can entice further investments in innovative endeavours, and strategically channel subsidies towards enterprises and sectors demonstrating robust innovation potential. This directed support, often referred to as the "visible hand," aids in concentrating innovation resources within high-technology industries, thus influencing the refinement of the industrial structure. Concurrently, the dynamics of innovation competition, coupled with the concept of "top-by-top competition" (Fredriksson and Millimet, 2002; Li and Wen, 2023), empower local authorities to steer pertinent sectors towards adopting low-carbon, green transformation initiatives, culminating in the reduction of energy consumption and carbon emissions. In light of these considerations, we put forward Hypothesis 2b:

Hypothesis 2b: Innovation competition positively regulates the relationship between technological innovation in renewable energy and carbon emissions.

Overall, we have summarized the theoretical model diagram in Figure 1.

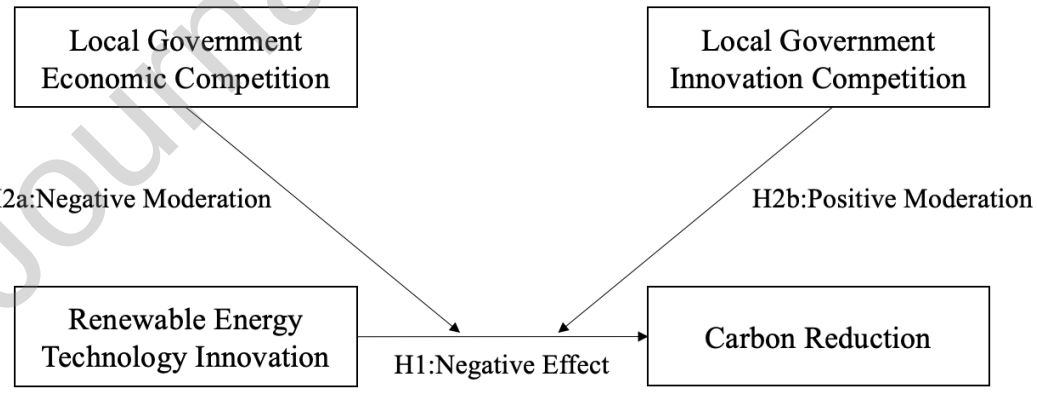


Figure 1 Diagram of the theoretical model

4. MODEL AND DATA

4.1 Model

To examine the impact of renewable energy technology innovation on carbon emissions, we developed a benchmark model:

$$LnCE_{i,t} = \beta_0 + \beta_1 LnRETI_{i,t} + \beta_2 Control_{i,t} + RI + YE + \varepsilon_{i,t} \quad (1)$$

where CE represents carbon emissions; i represents the region; t represents the year; $RETI$ is a key explanatory variable, representing the renewable energy technology innovation knowledge stock; $Control$ is a collection of control variables,including: Government intervention (GOV), Regional economic development (PGDP), Upgrading of industrial structure (IS), Population size (POP), Energy consumption (ESCONS), Urbanization rate (URB); RI is a regional fixed effect; YE is a fixed year effect; β_0 is a constant term; and $\varepsilon_{i,t}$ is the random error.

4.2 Data

Data used to measure the carbon emission index of provinces in mainland China (except Tibet) derived mainly from Carbon Emission Accounts and Datasets (CEADS), with the final required carbon emission data form obtained through consolidation. The database, which was jointly developed by Chinese and foreign research teams, is committed to building a cross-verifiable multiscale carbon emissions accounting system, with the recognition and support of the Department of International Cooperation of the Ministry of Science and Technology of the People's Republic of China and other relevant institutions. Renewable energy technology innovation data were obtained from the patent retrieval and analysis system of the State Intellectual Property Office of China. The year-end resident population, year-end urban population, secondary industry added value, tertiary industry added value, regional GDP, local fiscal expenditure on environmental protection, local fiscal general budget expenditure, regional fiscal expenditure on science and technology, regional total energy consumption, and other data for each province were obtained from the China Statistical Yearbook and the EPS data platform. Based on the availability of the above index data, the research sample interval was set to 2010–2019. Matching different databases permitted sorting of panel databases for 30 provinces and regions across China over that time frame.

Carbon emissions (CE) was set as the explained variable. In 2009, Chinese Premier Wen Jiabao emphasized energy conservation and emission reduction, and beginning with the "12th Five Year Plan", China has proposed to gradually establish a carbon emissions trading market plan, including carbon emissions as a binding

indicator in the national economic and social development planning outline. Therefore, we selected the carbon emissions calculated by the IPCC's accounting method in CEADS as the explained variable.

The primary explanatory variable of this paper is the renewable energy technology innovation knowledge stock index (RETI). Referring to the settings of Popp (2002), RETI is constructed using renewable energy related patent data, calculated as:

$$RETI_{i,t} = \sum_{k=o}^{t} PAT_{i,k} exp[-\eta_1(t-k)] \cdot \{1 - exp[-\eta_2(t-k)]\}$$

where *PAT* represents the number of renewable energy patent authorisations; i represents the province; t represents the year; η_1 and η_2 represent the depreciation rate (0.22) and diffusion rate (0.03), respectively (Popp, 2002). This widely used method takes into consideration knowledge depreciation and diffusion rates. The renewable energy sources analysed in this study include wind, solar, ocean, and biomass energy; energy storage; and hydropower (Lin and Zhu, 2019). Searches and queries for information about these sources encompassed corresponding regions, dates, and international patent classification codes (IPC).

Local government competition was set as the regulating variable, and was divided into economic and innovation competition. Economic competition among local governments is mainly reflected in the competition of regional economic development, not only in comparison neighbouring regions but also to regions with more advanced economic development. As such, we chose the adjacent province and national province parameters to jointly determine the economic competition among local governments in various regions, as this method not only reflects the intensity of economic competition between adjacent provinces but also the relative gap between cities with higher levels of economic development nationwide; essentially, the larger the value, the greater the economic gap between the region and adjacent regions and the more intense the level of economic competition. Regarding the innovation competition of local governments, we selected the ratio of financial expenditure on science and technology in each region to the scale of government expenditure in that region as a measurement index. This approach directly reflects the importance of innovation in local governments. For this

index, higher values indicate greater prioritization by local governments for innovation and more intense innovation competition.

Table 1 provides a full description of all the variables and statistics used in this study. The standard deviations for carbon emissions (CE) and RETI are 0.7258 and 1.2996, respectively, indicating that innovations in renewable energy technologies is more unstable. The average value of local government innovation competition (IC) is 0.0204, and the standard deviation is 0.0145, indicating that local governments' financial investment in innovation is low and needs to be improved.

Table 1

Descriptive statistics and variable definitions

Variables	Description and measurement units	N	Mean	SD	Min	Max
Explained variable						
Carbon emission (CE)	The natural logarithm of total carbon emissions plus one	300	5.57	0.73	3.40	6.84
Core explanatory variable						
Renewable energy technology innovation knowledge stock index (RETI)	The index of renewable energy technology innovation knowledge stock is constructed by using renewable energy related patent data and the natural logarithm of plus one is taken	300	2.81	1.30	0.06	5.55
Regulating variable						
Local government economic competition (ECU)	$\frac{Highest\ GDP\ per\ capita\ in\ neighboring\ provinces}{Per\ capita\ GDP\ of\ the\ province} \times \frac{The\ highest\ per\ capita\ GDP\ in\ China}{Per\ capita\ GDP\ of\ the\ province}$	300	4.11	2.50	0.63	13.44
Local government innovation competition (IC)	The ratio of regional financial expenditure on science and technology to the scale of regional government financial expenditure	300	0.02	0.01	0.004	0.07
Control variable						
Government intervention (GOV)	Ratio of local fiscal expenditure to regional GDP	300	0.26	0.11	0.11	0.76
Regional economic development (PGDP)	The natural logarithm of regional GDP per capita plus one	300	10.71	0.46	9.46	11.99
Upgrading of industrial structure (IS)	Value added of secondary industry as a percentage of regional GDP	300	0.42	0.08	0.16	0.62
Population size (POP)	The natural logarithm of the total resident population of a region at the end of the year plus one	300	8.20	0.74	6.34	9.43
Energy consumption (ESCONS)	Ratio of total regional energy consumption to regional GDP	300	0.87	0.50	0.21	2.34
Urbanization rate (URB)	The ratio of urban population to permanent population at the end of the year	300	0.58	0.13	0.34	0.90

5. RESULTS

To verify the impact of renewable energy technological innovation on carbon emissions according to the panel data model established by Formula (1), we carefully examined the relationship between renewable energy technological innovation and carbon emissions (see Table 2). To ensure robustness of the results, control variables were added. Columns (2)–(7) show the regression results after gradually adding the control variables. Column (1) shows that in the absence of control variables, the regression coefficient of renewable energy technology innovation is -0.102, which is significant at the 10% confidence level, indicating that renewable energy technology innovation has an inhibitory effect on carbon emissions. It can be seen in Table 2 that following the addition of any control variable, renewable energy technology innovation significantly inhibits the generation of carbon emissions. When control variables are added gradually, the significance of the impact of renewable energy technological innovation on the carbon emissions coefficient increases. Column (7) shows that under the influence of additional control variables, renewable energy technological innovation has a significant negative effect on carbon emissions, with a coefficient of -0.131, which is significant at the 1% confidence level. This is consistent with the current research results of most scholars, renewable energy technology innovation can help reduce carbon emissions. Thus, H1 is verified.

Table 2

Benchmark model regression results

Variables	(1) CE	(2) CE	(3) CE	(4) CE	(5) CE	(6) CE	(7) CE
RETI	-0.102*	-0.104*	-0.102*	-0.101*	-0.127**	-0.132**	-0.131***
	(-1.97)	(-1.97)	(-1.98)	(-2.04)	(-2.68)	(-2.73)	(-3.19)
GOV		-0.096	0.234	0.282	0.228	-0.205	-0.324
		(-0.18)	(0.41)	(0.51)	(0.47)	(-0.43)	(-0.72)
PGDP			0.227	0.201	0.192	0.301	0.06
			(1.56)	(0.98)	(0.98)	(1.51)	(0.33)
IS				0.190	-0.219	-0.010	0.123
				(0.29)	(-0.30)	(-0.01)	(0.21)
POP					0.911	0.457	0.423
					(1.27)	(0.69)	(0.72)

ESCONS						0.311**	0.391***
						(2.51)	(3.15)
URB							2.249***
							(3.70)
Constant	5.522***	5.546***	3.144*	3.301*	-3.819	-1.574	-0.116
	(96.03)	(34.95)	(2.01)	(1.73)	(-0.64)	(-0.28)	(-0.02)
YE	yes	yes	yes	yes	yes	yes	yes
RI	yes	yes	yes	yes	yes	yes	yes
Observations	300	300	300	300	300	300	300
Number of id	30	30	30	30	30	30	30
R-squared	0.396	0.396	0.407	0.408	0.446	0.485	0.556

t value in parentheses.

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

This step-by-step addition of control variables provided a preliminary test of the robustness of the results. Further testing was conducted to ensure that results were still robust after changes were made to several parameters, samples, and treatments. These are discussed below.

First, the explained variable is replaced. Replacing the explained variable reduces the reliance on specific data distribution assumptions, making the model more robust and more resilient to deviations from the data distribution. We chose to replace the carbon emission data provided by CEADS, according to the IPCC algorithm, with apparent carbon emissions (ACE). The regression results in Table 3 (1) can be obtained by replacing the explained variables; these results are robust. Renewable energy technology innovation still has a strong inhibitory effect on carbon emissions. Second, it eliminates the sample of municipalities directly under the central government. As regional political and economic centres, municipalities directly under the central government not only have industrial policy support but also have special location advantages. This may interfere with the empirical results. The regression results of column (2) are consistent with the above conclusion. Third, it shortens the sample time frame. Over time, data may be affected by various changes, such as changes in the external environment, policy adjustments, etc. Shortening the sample age can reduce these potential non-robust effects and make robust tests more reliable. The selected sample time range is narrowed by two years, and the regression results of column (3) are still robust, indicating that the above conclusions have high explanatory power for

the research hypothesis. Fourth, the sample was processed by 1% winsorization, and the data after excluding the first 1% and 99% were excluded. This method can reduce the influence of outliers on the model estimation and improve the robustness of the model.The regression results in column (4) are still significant, indicating that renewable energy technology innovation has a strong inhibitory effect on carbon emissions.

Table 3

Robustness test

Variables	Substitution variable ACE	Exclude municipalities directly under the central government CE	Shorten the sample life CE	Winsorization CE
RETI	-0.130**	-0.129***	-0.149***	-0.131***
	(-2.46)	(-2.82)	(-3.61)	(-3.19)
GOV	-0.678	-0.452	-0.017	-0.324
	(-1.25)	(-0.95)	(-0.03)	(-0.72)
PGDP	-0.191	0.061	0.329	0.06
	(-0.66)	(0.30)	(1.41)	(0.33)
IS	-0.753	0.154	-0.199	0.123
	(-0.87)	(0.25)	(-0.35)	(0.21)
POP	0.57	0.586	0.341	0.423
	(0.98)	(0.87)	(0.64)	(0.72)
ESCONS	0.465**	0.388***	0.420**	0.391***
	(2.44)	(3.29)	(2.55)	(3.15)
URB	3.378***	1.990*	1.993***	2.249***
	(3.58)	(1.96)	(3.47)	(3.70)
YE	yes	yes	yes	yes
RI	yes	yes	yes	yes
Observations	300	260	240	300
Number of id	30	26	30	30
R-squared	0.421	0.589	0.592	0.556

t value in parentheses.

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

6. FURTHER STUDY

6.1 The regulatory role of local government competition

To investigate the impact of renewable energy technology innovation on carbon emissions, we further tested the regulatory role of local government competition in the

above relationship, then separated into local government innovation competition and local government economic competition, from which we then developed the following model:

$$LnCE_{i,t} = \beta_0 + \beta_1 LnRETI_{i,t} + \beta_2 ECU_{i,t} + \beta_3 LnRETI_{i,t} \times ECU_{i,t} + \beta_4 Control_{i,t} + RI + YE + \varepsilon_{i,t} \quad (2)$$

$$LnCE_{i,t} = \beta_0 + \beta_1 LnRETI_{i,t} + \beta_2 IC_{i,t} + \beta_3 LnRETI_{i,t} \times IC_{i,t} + \beta_4 Control_{i,t} + RI + YE + \varepsilon_{i,t} \quad (3)$$

Where ECU is a moderating variable representing local government economic competition and IC is a moderating variable representing local government innovation competition. The remaining variables are the same as defined previously.

The results of the regression analysis for the regulatory role of local government competition are shown in Table 4. Column (1) in Table 4 shows that local government economic competition has a negative regulatory effect on the relationship between renewable energy technology innovation and carbon emissions; that is, local government economic competition weakens the inhibitory effect of renewable energy technology innovation on carbon emissions.Thus, H2a is verified. Column (2) in Table 4 shows that local government innovation competition has a positive regulatory effect on the relationship between renewable energy technology innovation and carbon emissions; that is, local government innovation competition strengthens the inhibitory effect of renewable energy technology innovation on carbon emissions.Thus, H2b is verified.

Table 4

Moderating effect test

Variables	Local government economic competition CE	Local government innovation competition CE
RETI*ECU	0.008**	
	(2.07)	
RETI*IC		-2.625**
		(-2.29)
RETI	0.019	0.023
	(0.90)	(1.09)

ECU	-0.002	
	(-0.15)	
IC		1.230
		(0.51)
YE	yes	yes
RI	yes	yes
Control variable	yes	yes
Observations	300	300
Number of id	30	30
R-squared	0.477	0.504

t value in parentheses.

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

In summary, different types and contexts of local government competition have variable regulatory effects on the relationship between renewable energy technology innovation and carbon emissions. Local government innovation competition is more conducive to the carbon emission reduction effect of renewable energy technology innovation due to the enhancement of regional innovation intensity, whereas local government economic competition has the opposite result due to reductions in innovation resources.

6.2 Regional heterogeneity

China is a large country, with substantial variation among its different regions, especially the eastern, central, and western parts of the nation. Will geographical differences lead to heterogeneity in the role of renewable energy technology innovation in carbon emissions? To address this question, we divided China into eastern, central, and western regions. The eastern region included Beijing, Tianjin, Hebei, Liaoning, Shanghai, Jiangsu, Zhejiang, Fujian, Shandong, Guangdong, and Hainan; the central region included Shanxi, Jilin, Heilongjiang, Anhui, Jiangxi, Henan, Hubei, and Hunan; and the western region included Inner Mongolia, Guangxi, Chongqing, Sichuan, Guizhou, Yunnan, Shaanxi, Gansu, Qinghai, Ningxia, and Xinjiang.

Table 5 shows that there is a significant negative relationship between renewable energy technology innovation and carbon emissions in the eastern (coefficient of -2.625, 5% CI) and western (-0.158, 1% CI) regions. In the central region, however, no

significant negative relationship was detected between renewable energy technological innovation and carbon emissions, indicating that the inhibitory effect of renewable energy technological innovation on carbon emissions varies among different geographical locations. This may be because the eastern region has a natural geographic advantage, greater economic development, and more funding sources to support renewable energy technology innovation. At the same time, the greater exposure to and contact with the outside world experienced by the eastern region can attract a large amount of foreign capital, greater access to advanced technology and expertise, and more support for the development of renewable energy technology innovation to curb carbon emissions. In comparison, although its infrastructure and economic development levels are less advantageous than those in the eastern region, the western region has stronger policies favouring development of renewable energy technology innovation for reducing carbon emissions. Finally, relative to the eastern and western regions, the effect on emission reduction was not significant in the central region, most likely because this region lags behind the eastern region in terms of economic development and infrastructure construction, and there is no advantage in resource transfer, making it difficult for the central region to rely on resource advantages to develop renewable energy technology innovation. Moreover, the relocation of industries from the eastern region to the central region has brought greater pressure to upgrade industrial structure and concomitantly increased pressure to substitute carbon-based fuels, further weakening the carbon emission reduction effect of renewable energy technology innovation.

Table 5

Regional heterogeneity testing

Variables	Eastern CE	Central CE	Western CE
RETI	-2.625**	-0.096	-0.158***
	(-2.29)	(-1.16)	(-3.66)
YE	yes	yes	yes
RI	yes	yes	yes
Control variable	yes	yes	yes

Observations	110	80	110
Number of id	11	8	11
R-squared	0.743	0.657	0.759

t value in parentheses.
*** p<0.01, ** p<0.05, * p<0.1

7. CONCLUSIONS AND POLICY IMPLICATIONS

The exploration of renewable energy technology innovation stands as a critical avenue for mitigating carbon emissions. Leveraging data from 30 provinces and cities throughout China spanning the years 2010–2019, our research delves into the influence of renewable energy technology innovation on carbon emissions and delineates the modulatory role played by local government competition. The findings reveal several key insights. First, innovations in renewable energy technology exert a significantly negative effect on carbon emissions. This conclusion persists even after adjustments are made to the variables, exclusion of municipalities directly governed by the central government, reduction of the dataset's temporal scope, and refinement of the analysis to enhance robustness. Second, the dynamic between renewable energy technology innovation and carbon emissions is subject to modulation by local government competition. In particular, competition among local governments in the realm of innovation bolsters the reduction of carbon emissions facilitated by renewable energy technology innovations. Conversely, competition focused on economic outcomes tends to dilute the mitigative impact of renewable energy technology innovation on carbon emissions. Third, the geographical and developmental disparities across China's regions—namely, the eastern region's advanced economic development and infrastructural superiority, and the western region's comprehensive policy support—result in a pronounced variability in the effectiveness of renewable energy technological innovation on carbon emissions. The eastern and western regions of China, as a result of their unique regional attributes, exhibit a more marked response to renewable energy technological innovations in terms of emission reduction. These findings underscore the nuanced interplay between renewable energy technology innovation, local

government competition, and regional characteristics in the broader context of China's carbon emission mitigation efforts.

Drawing upon the insights garnered from our analysis, we advocate for the implementation of three strategic policy interventions to foster the reduction of carbon emissions through renewable energy technology innovation. First, it is imperative to robustly promote the development of renewable energy technological innovations and incentivise their widespread adoption across various industries. Given the substantial mitigative impact of such innovations on carbon emissions, they are pivotal in realising the "dual carbon" objectives. *Second,* the eastern part of China has a high level of economic development accompanied with full infrastructure of technological innovation; thus, it should step up the effort in developing renewable energy technologies by promoting intensive research and development and creating dedicated facilities and platforms to facilitate their application and taking the lead in establishing market-oriented mechanisms to help with the transition to these innovative systems. In response to the unequal effectiveness across space direction of results for renewable energy technological innovation in carbon emission reduction, it is recommended to strengthen regional cooperation. The policy actions represent as follows: relevant actors in different regions adjust policy measures and policy strategies based on the actual situation of their own regions, such as the intensity of network Delphi use; adjust corresponding strategies in regions with less effect. In the area of Central China, regional authorities should improve regional cooperation, learn from successful policies, start the interregional cooperation mode of “industry-university-research integration”, and further promote the use of renewable energy technology in conjunction with it and continuous emission reduction action. Second, the behaviour of local governments should be unified through a standard system to eliminate the requirement for the old-fashion economic path, capital growth, chasing type of conductors, and the innovation competition pattern between the local parties is benchmarked by the old-fashion economic concept. As a result, it should create a corresponding evaluation system suitable to monitor scientific and technological innovation. The empirical results have demonstrated the fact that innovation competition among local governments has been

helping to strengthen the carbon emission reduction capacity of renewable energy technology innovation, while economic competition has been able to reduce the intensity of the effect. In the face of China's western region, local authorities should strengthen innovation competition, and actively practice energy-saving and emission reduction of renewable energy technology innovation. At the same time, the local government shall also provide policy and institutional support to ensure the maximum release of carbon emission reduction benefits brought by renewable energy technology. These recommendations are formulated with the objective of aligning technological advancement in renewable energy with the strategic imperatives of carbon emission reduction, local government competition regulation, and regional cooperation, thereby advancing China's transition to a low-carbon economy.

In conclusion, this study has yielded findings of significant practical relevance, yet it is not without its limitations. Constraints related to data availability and geographical coverage inhibited a thorough examination of how variables such as market conditions, the availability of energy resources, levels of environmental regulation, and technological advancements in the renewable energy sector influence carbon emissions reduction. Future research should address these deficiencies through regional studies to enhance the precision of the conclusions drawn. Additionally, it is imperative to expand the scope of inquiry to explore how the impacts of innovations in renewable energy on carbon reduction may vary across different national contexts, thereby increasing the practical applicability of the research.

References

Bai, C., Feng, C., Yan, H., Yi, X., Chen, Z., Wei, W., 2020.Will income inequality influence the abatement effect of renewable energy technological innovation on carbon dioxide emissions? J. Environ. Manag. 264, 110482. https://doi.org/10.1016/j.jenvman.2020.110482

Chen, Y., Lin, B., 2020. Decomposition analysis of patenting in renewable energy technologies: From an extended LMDI approach perspective based on three Five-Year Plan periods in China. J. Clean. Prod. 269, 122402. https://doi.org/10.1016/j.jclepro.2020.122402

Cheng, X., Yan, C., Ye, K., Chen, K., 2024. Enhancing resource efficiency through the utilization of the green bond market: An empirical analysis of Asian economies. Resour. Policy 89,104623. https://doi.org/10.1016/j.resourpol.2023.104623

Cheng, X., Chen, K., Su, Y., 2023a. Green innovation in oil and gas exploration and production for meeting the sustainability goals. Resour. Policy 87,104315. https://doi.org/10.1016/j.resourpol.2023.104315

Cheng, X., Lyu, Y., Ye, Y., 2023b. Linking organizational exploitation to extra-role behaviors: a conservation of resources perspective. Int. J. Contemp. Hosp. Manag. 35(3), 1109-1124. https://doi.org/10.1108/IJCHM-11-2021-1373

Cheng, Y., Yao, X., 2021.Carbon intensity reduction assessment of renewable energy technology innovation in China: A panel data model with cross-section dependence and slope heterogeneity. Renew. Sustain. Energy Rev. 135, 110157. https://doi.org/10.1016/j.rser.2020.110157

Claassen, R., 2016.Externalities as a basis for regulation: a philosophical view. J. Inst. Econ. 12(3), 541-563. https://doi.org/10.1017/S1744137415000491

Danish, Ulucak, R., 2021.Renewable energy, technological innovation and the environment: a novel dynamic auto-regressive distributive lag simulation. Renew. Sustain. Energy Rev. 150, 111433. https://doi.org/10.1016/j.rser.2021.111433

Ding, X., Liu, H., Zhang, J., Shen, Y., Yang, G., 2024.Does the local government multi-objective competition intensify the transfer of polluting industries in the Yangtze River Economic Belt? Environ. Res. 245, 118074. https://doi.org/10.1016/j.envres.2023.118074

Du, Q. Li, Z., Du, M., Yang, T., 2024a. Government venture capital and innovation performance in alternative energy production: The moderating role of environmental regulation and capital market activity. Energy Econ. 129, 107196. https://doi.org/10.1016/j.eneco.2023.107196

Du, Q., Li, Z., Du, M., Yang, T. 2024b. Venture capital, innovation channels, and regional resource dependence: Evidence from China. J. Environ. Manag. 352, 120034-120034. https://doi.org/10.1016/j.jenvman.2024.120034

Eichner, T., Pethig, R., 2013. Flattening the carbon extraction path in unilateral cost-effective action. J. Environ. Econ. Manag. 66(2), 185-201. https://doi.org/10.1016/j.jeem.2012.12.006

Fredriksson, P. G., Millimet, D. L., 2002.Strategic interaction and the determination of environmental policy across US states. J. Urb. Econ. 51(1), 101-122. https://doi.org/10.1006/juec.2001.2239

Ganda, F., 2019.The impact of innovation and technology investments on carbon emissions in selected organisation for economic Co-operation and development countries. J. Clean. Prod. 217, 469-483. https://doi.org/10.1016/j.jclepro.2019.01.235

Gao, Y., Hu, Y., Liu, X., Zhang, H., 2021.Can public R&D subsidy facilitate firms' exploratory innovation? The heterogeneous effects between central and local subsidy programs. Res. Policy 50(4), 104221. https://doi.org/10.1016/j.respol.2021.104221

Goodell, J. W., Nammouri, H., Saâdaoui, F., Ben Jabeur, S., 2023a.Carbon allowances amid climate change concerns: Fresh insights from wavelet multiscale analysis. Financ. Res. Lett. 55, 103871. https://doi.org/10.1016/j.frl.2023.103871

Goodell, J. W., Yadav, M. P., Ruan, J., Abedin, M. Z., Malhotra, N., 2023b.Traditional assets, digital assets and renewable energy: Investigating connectedness during COVID-19 and the Russia-Ukraine war. Financ. Res. Lett. 58, 104323. https://doi.org/10.1016/j.frl.2023.104323

Habiba, U., Xinbang, C., Anwar, A., 2022.Do green technology innovations, financial development, and renewable energy use help to curb carbon emissions? Renew. Energy 193, 1082-1093. https://doi.org/10.1016/j.renene.2022.05.084

Hunjra, A. I., Zhao, S., Goodell, J. W., Liu, X., 2024. Digital economy policy and corporate low-carbon innovation: Evidence from a quasi-natural experiment in China. Financ. Res. Lett. 60, 104910. https://doi.org/10.1016/j.frl.2023.104910

Li, G., Wen, H., 2023.The low-carbon effect of pursuing the honor of civilization? A quasi-experiment in Chinese cities. Econ. Anal. Policy 78, 343-357. https://doi.org/10.1016/j.eap.2023.03.014

Liang, T., Zhang, Y., Qiang, W., 2022.Does technological innovation benefit energy firms' environmental performance? The moderating effect of government subsidies and media coverage. Technol. Forecast. Soc. Ch. 180, 121728. https://doi.org/10.1016/j.techfore.2022.121728

Lin, B., Zhu, J., 2019. The role of renewable energy technological innovation on climate change: Empirical evidence from China. Sci. Total Environ. 659, 1505-1512. https://doi.org/10.1016/j.scitotenv.2018.12.449

Ma, Q., Murshed, M., Khan, Z., 2021.The nexuses between energy investments, technological innovations, emission taxes, and carbon emissions in China. Energy Policy 155, 112345. https://doi.org/10.1016/j.enpol.2021.112345

Popp, D., 2002.Induced innovation and energy prices. Am. Econ. rev. 92(1), 160-180. https://doi.org/10.1257/000282802760015658

Ren, S., Hao, Y., Wu, H., 2021. Government corruption, market segmentation and renewable energy technology innovation: Evidence from China. J. Environ. Manag. 300, 113686 https://doi.org/10.1016/j.jenvman.2021.113686

Su, Y., Fan, Q., 2022.Renewable energy technology innovation, industrial structure upgrading and green development from the perspective of China's provinces. Technol. Forecast. Soc. Ch. 180, 121727. https://doi.org/10.1016/j.techfore.2022.121727

Xinhua, 2022. Multinationals blaze green path toward China's 'dual carbon' goals, The State Council Information Office, The People's Republic of China. http://english.scio.gov.cn/internationalexchanges/2022-06/22/content_78283961.htm

Yan, Z., Zou, B., Du, K., Li, K., 2020.Do renewable energy technology innovations promote China's green productivity growth? Fresh evidence from partially linear functional-coefficient models. Energy Econ. 90, 104842. https://doi.org/10.1016/j.eneco.2020.104842

Yang, L., Yu, Z., Zhu, N., Wu, X., Jin, Y., 2023a.Local government competition, environmental regulation, and green development in China: Empirical analysis based on regional heterogeneity and path mechanisms. Sustain. Dev. 31(5), 3553-3565. https://doi.org/10.1002/sd.2610

Yang, T., Dong, Q., Du, Q.Y., Du, M., Dong, R., Chen, M., 2021.Carbon Dioxide Emissions and Chinese OFDI: From Perspective of Carbon Neutrality Target and Environmental Management of Home Country. J. Environ. Manag. 295, 113120. https://doi.org/10.1016/j.jenvman.2021.113120

Yang, T., Fang, S., Du, M., Du, Q., 2024.Navigating the Nexus: Geopolitical Risks, Fossil Fuel Price Variability, and European Utility Stocks Performance - Implications for Environmental Management and Energy Security in a Conflict-Ridden Global Landscape. J. Environ. Manag. 352, 120086. https://doi.org/10.1016/j.jenvman.2024.120086

Yang, T., Li, F., Du, M., Huang, M., Li, Y., 2023b. Impacts of alternative energy production innovation on reducing CO2 emissions: Evidence from China. Energy 268, 126684. https://doi.org/10.1016/j.energy.2023.126684

Zeng, J., Yang, M., 2023.Digital technology and carbon emissions: evidence from China. J. Clean. Prod. 430, 139765. https://doi.org/10.1016/j.jclepro.2023.139765

Zhao, C., Wang, J., Dong, K., Wang, K., 2023. How does renewable energy encourage carbon unlocking? A global case for decarbonization. Res. Policy 83, 103622. https://doi.org/10.1016/j.resourpol.2023.103622

Zhao, G., Zhou, P., Wen, W., 2022.What cause regional inequality of technology innovation in renewable energy? Evidence from China. Appl. Energy 310, 118464. https://doi.org/10.1016/j.apenergy.2021.118464

Zheng, H., Song, M., Shen, Z., 2021. The evolution of renewable energy and its impact on carbon reduction in China. Energy 237, 121639. https://doi.org/10.1016/j.energy.2021.121639

CRediT author statement

Xuanmei Cheng: Conceptualization, Investigation, Resources

Kaite Ye: Data curation, Software, Methodology, Writing – original draft

Anna Min Du: Investigation, Project administration, Supervision, Validation, Writing – review & editing

Zhenzhen Bao: Data curation, Formal analysis

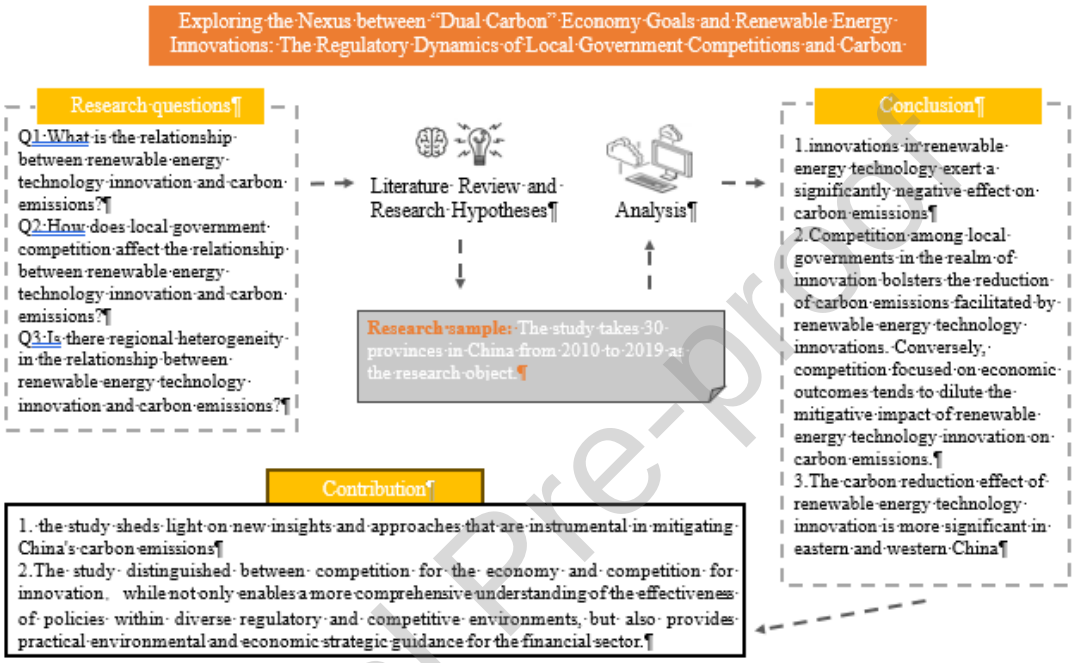
Grigoria Chlomou*:* Writing – review & editing

Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐ The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Graphical Abstract



Highlights

- Renewable energy innovations significantly reduce carbon emissions in China, aiding the "dual carbon" goals.
- Local government innovation competitions boost emission reductions, while economic rivalry can impede progress.
- The study underscores the need for a balanced approach between competition and collaboration among local governments to enhance renewable energy benefits.