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Does environmental regulation affect urban green technology innovation in China? Evidence from the low-carbon city pilot policy

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The Low-carbon City Pilot (LCCP) policy is a new environmental governance model to achieve carbon neutrality, promote low-carbon pilot city development, and address climate change. Taking LCCP policy as an exogenous shock, this paper examines the impact of LCCP policy on urban green technology innovation and its transmission mechanism from 2005 to 2017. Based on the Difference-in-Difference (DID) method, the following results are obtained: The LCCP policy can promote urban green technology innovation, and the results remain robust through a series of robustness tests. Mechanism analysis shows that LCCP improves the level of green technology innovation in two ways, it encourages local governments to increase R&D funds and forces pollution-intensive and energy-consuming industries to upgrade industrial structures. In addition, the conclusion also reveals that the urban location characteristics and the intensity of environmental regulation have a heterogeneous impact on green technology innovation, with the most significant effect on the western region. Therefore, policymakers must mobilize the autonomy of local governments, increase the investment of local government R&D funds, and strive to spread the pilot policy of low-carbon cities to the whole country to promote industrial transformation.

KEYWORDS

low-carbon city pilot policy, environmental regulation, green technology innovation, difference-in-difference method, mediating effect

1 Introduction

Global climate change has become one of the greatest non-traditional security challenges to human development, and the demand and supply of natural resources have changed significantly, which has attracted the attention of the academic community (Khan et al., 2022). According to a report released by the Intergovernmental Panel on Climate Change (IPCC)[1], the current global average temperature has risen by approximately 1°C from preindustrial levels, and when the temperature rise reaches 2°C, the warming will be irreversible, and extreme heat will more frequently reach critical tolerance thresholds for agricultural production and human health. The severe climate problem has prompted a global political consensus and significant action to address climate change. According to the September 2019 report of the United Nations Framework Convention on Climate Change

1 The Intergovernmental Panel on Climate Change (IPCC) is an intergovernmental organization affiliated with the United Nations that specializes in the study of climate change caused by human activities.

(UNFCCC) secretariat, 60 countries around the world have now pledged to achieve zero carbon emissions by 2050 or even sooner, with the European Union leading the way by announcing an absolute emissions reduction target, pledging to reduce greenhouse gas emissions by at least 55% by 2030 compared to 1990 and net zero by 2050, Europe will be the world's first "carbon-neutral" continent[2]. Low-carbon cities promote green urban development through the improvement of energy efficiency, the adjustment of energy structure, the transformation of high-carbon industries to low-carbon industries, and a more environmentally friendly way of resource allocation, while green technology innovation is the key to realizing this development model. However, it is worth noting that while green technology innovation helps enterprises reduce pollution and waste of resources, its "high investment" and "high risk" characteristics make many enterprises flinch. The externalities make enterprises' R&D enthusiasm suffer, which requires the government to play a binding force known as environmental regulation. The emergence of environmental regulation, from the initial pollution cost borne by the whole society to enterprises, must stimulate enterprises' green technology innovation to a certain extent.

The accelerated urbanization and industrialization process has long led to massive energy consumption and excessive greenhouse gas emissions (Zhang et al., 2018). As the world's largest developing country and the largest emitter of carbon dioxide (Luo et al., 2022), China is actively participating in global climate action, formulating an action plan to peak carbon emissions by 2030 and striving to achieve carbon neutrality by2060[3]. Reducing carbon emissions and positively responding to climate change have become important provisions for China's economic transition to high-quality development, and cities have become important actors in low-carbon development and climate change prevention. To ensure that the 2030 greenhouse gas emission control target set by China is met, aiming to address climate change, explore low-carbon development models, and initiate innovative urban development. China's National Development and Reform Commission (NDRC) launched the first low-carbon city pilot (LCCP) policy in 2010, covering eight cities and five provinces. Since then, the second and third batches of pilot work were conducted in November 2012 and January 2017, respectively, with the second batch covering 28 cities and one province and the third batch covering 45 cities[4]. Currently, the LCCP policy includes six provinces, 80 cities, and one region. One of the characteristics of the LCCP policy is that it is a combination of policies. The local governments of each pilot city formulate the Low Carbon City Development Plan program according to the characteristics of the local economic development situation, technology, and industry advantages, which all contain different types of policy tools, such as command-control, market-based, and public participation policies. The policy promotes and strives to promote the decoupling of urbanization from carbon emissions through a combination of different instruments. However, the incentives and constraints of LCCP policy are weak. Unlike previous pilot policies, the central government does not provide financial support and policy benefits to local governments in pilot areas, except for a few capacity-building projects with financial support, which to some extent, weakens the incentives to local governments. At the same time, although the state required the pilot cities to establish a CO2 emission target assessment system with local conditions and set CO^2 emission peak, it did not establish a strict assessment mechanism, which reduces the constraints on local governments. In short, whether the LCCP policy can maximize its benefits still needs the support of multiple means.

Currently, high priority is given to the pilot work at the national level, and the pilot scope's gradual expansion demonstrates the pilot policy's importance in promoting green and low-carbon development in China. Each pilot city has issued a low-carbon city development plan based on its industrial structure, resource endowment, and technological advantages, and most of the plans explicitly promote low-carbon urban development by promoting technological innovation. As the requester of natural resources and the core carrier of creating social and economic wealth, green technology innovation can not only enable enterprises to make low-carbon transformations and reduce environmental pollution but also can significantly change the traditional production technology of high input, low output, high pollution, and high energy consumption, promote enterprises to produce green differentiated products, stimulate new market demand, and improve the green competitiveness of enterprises. Therefore, whether the LCCP policy and green technology innovation, as the realization path and important driving force of high-quality urban development, can achieve the synergistic effect of the two grasps determines the path model and time sequence of China's green transformation. Therefore, the examination of the implementation effect of the pilot policy can provide a reference for further effectiveness of the policy and the construction of subsequent low-carbon pilot cities.

This paper examines the impact of the LCCP policy on urban green technology innovation by using panel data from 276 prefecture-level cities in China from 2005 to 2017 through the DID method. This paper may have the following three marginal contributions. First, under the political system with Chinese characteristics, the LCCP policy is a targeted policy enacted by the Chinese government to address the climate problem and reduce carbon emissions. This policy can reduce the city's carbon intensity and total carbon emissions and even promote relevant subjects to upgrade technology and realize the "Porter hypothesis". This is conducive to promoting the follow-up pilot work of low-carbon city construction and provides effective references for environmental regulation practices in developing countries and even globally to deal with the greenhouse effect. Second, this paper further explores the mechanisms underlying the LCCP policy that influence urban green technology innovation. As a kind of weak incentive and weak constraint environmental regulation policy, LCCP improves the level of green technology innovation in two ways, first by encouraging local governments to increase R&D funds and then by forcing pollution-intensive and energy-consuming industries to upgrade industrial structures. Finally, the LCCP policy is a local policy experiment in China, in which the central government mainly sets policy goals, local governments set specific experimental methods according to their own actual conditions, and they have greater autonomy. In this process, regional differences and different implementation efforts of local governments will lead to different

2 From the "State of the Union Address" delivered by the European Commission President von der Leyen on 16 September 2020.

3 From the 14th Five-Year Plan of the National Economic and Social Development of the People's Republic of China and the Outline of Vision 2035 (the "14th Five-Year Plan").

4 Three batches of pilot specific time and pilot areas see Appendix A.

policy effects. Therefore, through the analysis of regional heterogeneity, we found that the western region has the most significant impact. This paper aims to help the policymakers find specific pilot areas, form a demonstration effect, and then promote the implementation according to local conditions.

The rest of this study is organized as follows: Section 2 presents the literature review and hypothesis. Section 3 describes the methodology and data. Sections 4and 5 present a discussion of the empirical findings. Section 6 summarizes the results and discusses some policy implications.

2 Literature review and hypothesis

2.1 Literature review

Economic research has always focused on the relationship between environmental regulation and green technology innovation. At the micro-level, there are three main aspects: First, part of the research follows the “Porter Hypothesis”, which affirms the positive role of environmental regulation in improving green technology innovation. Scholars led by Porter and Van der Linde (1995) think that the relationship between environmental protection and economic development cannot simply be divided into two opposites. They argue that appropriate environmental regulation can lead to more innovation by firms, thus offsetting the costs of environmental protection and increasing the profitability of firms in the markets (Porter and Van der Linde, 1995; Zhao and Sun, 2016; Ramanathan et al., 2017; Cohen and Tubb, 2018). According to the “Porter hypothesis”, some studies believe that environmental regulation can promote green technology innovation (Costantini and Mazzanti, 2012; Wang et al., 2020). Second, another part of the research follows the “cost increase hypothesis”, which believes that environmental protection policies can raise private production costs and reduce the competitiveness of firms, thus offsetting the positive effects of environmental protection on society and harming economic growth. Some scholars have concluded that environmental regulation disincentives green technology innovation (Yuan and Xiang, 2018; Shen et al., 2020). Third, some scholars have found that the impact of environmental regulation on green technology innovation is uncertain, and it may form an Inverted-U Relation. Song et al. (2020a) proved that the effect of green technology innovation gradually changes from inhibition to promotion under the circumstance of increased environmental supervision. Discussed that there is an inverted “U” relationship between environmental regulation and green technology innovation in China’s central and central coast regions. In comparison, the north area, southern coast, and southwest region exhibit a “U” relationship between the two. However, some scholars believe that the impact of environmental regulation on green technology innovation will vary according to the type of environmental regulation, industrial structure, and the stage of economic development (Feng and Chen 2018; Guo et al., 2018; Li et al., 2020; Du G. et al., 2021; Zhu et al., 2021).

Cities are considered the major contributors to carbon emissions due to their high population density, economic activity, and energy consumption. Nations and organizations around the world have initiated many city-level low-carbon programs to reduce carbon emissions. As the world’s largest carbon emitter, China has initiated the LCCP policy as a city-level mitigation strategy for carbon emissions. LCCP policy has gradually become an important approach and means of environmental governance. Therefore, scholars turned their research perspective to LCCP policy. The existing research on LCCP policy is mainly divided into three types: first, some studies evaluate and analyze the impact of low-carbon city pilot policy on innovation. At the micro-level, some scholars believe that the LCCP policy will promote the technological innovation of enterprises (Ma et al., 2021), and technological innovation impacts carbon emissions (Wahab et al., 2022). At the macro level, some scholars believe that LCCP policy significantly impacts urban green total factor productivity (Cheng et al., 2019; Guo et al., 2021; Qiu et al., 2021). Second, some research studies focused on the effect of LCCP policy on emission reduction. Some scholars believe the LCCP policy will help reduce carbon emissions (Fu et al., 2021; Chen, S. et al., 2021). Third, researchers paid attention to the impact of LCCP policy on industrial structure, FDI, and urban ecological efficiency (Song et al., 2020b; Zhao and Wang, 2021; Zheng et al., 2021)

Existing studies focus on the impact of LCCP policy on green technology innovation, mainly concentrating on enterprises or industries, and the literature on the role of environmental regulation from the perspective of regional green technology innovation is lacking (Zhang et al., 2020). The existing literature also does not pay attention to the impact of LCCP policy on green technology innovation at a regional level, nor does it reveal the causal relationship and impact mechanism between LCCP policy and regional green technology innovation. With the increasing abundance of relevant data and the maturity of measurement techniques, scholars need to measure the effect of LCCP policy from the perspective of regional green technology innovation to more accurately evaluate LCCP policy.

2.2 Theoretical hypothesis

In order to implement China’s climate goals, the NDRC has proposed an LCCP policy. As a type of weak incentive and weak constraint environmental regulation policy, the LCCP policy does not set specific targets for pilot cities but rather adopts a decentralized governance model with differentiated initiatives for different regions, and each pilot city can promote low-carbon work according to its own situation. LCCP policy aims to achieve the low-carbon goal by controlling the pollution emissions of energy-consuming and high-emission industries in the city. This process will bring about the improvement of energy efficiency, energy conservation, and emission reduction in the production process, as well as the transformation and upgrading of industries in the low-carbon direction, prompting relevant entities to upgrade existing technologies and develop green technologies that meet the needs of low carbon program, that is, to realize the “Porter hypothesis”. It must be accompanied by green technology innovation at the city level. Accordingly, hypothesis 1 is proposed in this paper.

Hypothesis 1: The LCCP policy will promote urban green technology innovation.

LCCP policy promotes the transformation of existing production models of cities and ultimately achieves a “win-win” of low-carbon emissions and green technology innovation. Simultaneously, it may go through a series of transmission mechanisms, such as increasing government policy-based R&D investment and advancing industrial structure optimization.

LCCP policy requires local governments to "Actively explore institutional innovation in combination with local conditions and plan and build urban infrastructure in accordance with the low-carbon concept", which means that local governments should play an important role in policy guidance and introduce financial support policies that are more suitable for low-carbon development. The LCCP policy may encourage local governments to pay more attention to investment in scientific and technological innovation for the following reasons: frontier scientific and technological innovation has the characteristics of a long cycle, strong uncertainty, and large market risk. It often makes it difficult for innovative subjects to obtain external funds. On the one hand, the scientific and technological fund support of government departments is conducive to easing the financial constraints faced by innovation subjects, reducing innovation costs, and sharing innovation risks, so as to improve the enthusiasm of innovation subjects; On the other hand, the government subsidies or guidance funds will release a positive signal that the government encourages innovation, which is conducive to the relevant subjects to obtain more social risk capital investment. Therefore, government policy-based R&D investment is an effective institutional arrangement for local governments to achieve scientific and technological development in the construction of low-carbon cities, which is particularly important in improving urban green technology innovation.

In addition, the LCCP policy requires "to establish a low-carbon industrial system characterized by low-carbon, green, environmental protection, and recycling. It is necessary to vigorously develop low-carbon strategic emerging industries and modern service industries in combination with regional industrial characteristics and development strategies." According to the policy instructions, developing low-carbon strategic emerging industries and modern service industries to achieve industrial structure upgrading is one of the priorities of low-carbon pilot policy construction. With the gradual promotion of the LCCP policy, pollution-intensive and high energy-consuming industries bear higher environmental costs. Due to increased costs, some polluting enterprises will be forced to withdraw from the market. Modern manufacturing industry dominated by technological innovation and the tertiary industry dominated by services will gain comparative advantages. Therefore, the LCCP policy will promote upgrading the overall industrial structure. From the perspective of the impact of industrial structure on urban green technology innovation, upgrading the industrial structure provides a good foundation for innovation and is conducive to improving the quality and efficiency of green technology innovation. The reasons are as follows, first, the upgrading of industrial structure is realized in the sequential evolution of labor-intensive, capital-intensive, and technology-intensive industries. In this process, the requirements for green technology innovation are gradually raised, providing a continuous and huge market demand for the application of new technologies. The adjustment of industries forces the improvement of urban green technology innovation. Second, the upgrading of industrial structure makes the industries with high innovation levels gradually replace the industries with low innovation levels, and the allocation of innovation resources is more reasonable, thus improving the efficiency of green technology innovation. In summary, the following research hypothesis can be drawn:

Hypothesis 2: The LCCP policy will increase the government's policy-based R&D investment and force the upgrading of the industrial structure to improve the level of urban green technology innovation.

3 Model and data

3.1 Model setting

Based on the pilot city list announced by the NDRC in July 2010 and 2 November012[5], a difference-in-differences (DID) approach is employed to assess the causal relationship between the LCCP policy and urban green technology innovation[6]. The provinces and cities included in the pilot scope are the experimental groups, and the remaining regions are the control group, and the impact of the LCCP policy on urban green technology innovation is identified by comparing the experimental and control groups. Since low-carbon pilot cities were approved at different times, this paper identifies them by constructing a multi-period DID model, which is set below:

$$G\_innov_{it} = \alpha_0 + \alpha_1 Pilot_i \times Post_t + \sum Control_{it} + \mu_i + \delta_t + \varepsilon_{it} \quad (1)$$

In the above equation, G_innov_{it} is a measure of urban green technology innovation in city i in year t, $Pilot_i \times Post_t$ indicates a dummy variable that is equal to one if city i become a low-carbon pilot city in year t and zero otherwise. $Control_{it}$ is a set of time-varying city-level control variables, μ_i is city fixed effects controlling unobserved city characteristics that may affect urban green technology innovation, δ_t is year fixed effects controlling nationwide shocks and trends that affect urban green technology innovation; ε_{it} is the error term allowing for city-level clustering.

In the benchmark analysis, we focus on the coefficient of the $Pilot_i \times Post_t$, α_1. This coefficient reflects the impact of the LCCP policy on urban green technology innovation after differencing between pilot and non-pilot regions before and after the implementation. A positive and significant α_1 suggests that the LCCP exerts a positive effect on urban green technology innovation, while a negative and significant α_1 indicates that the LCCP policy has a dampening effect on urban green technology innovation.

Based on the benchmark model, in order to test the mechanism of the LCCP policy in influencing urban green technology innovation, this paper uses a three-step mediation regression analysis based on the Sobel test to further construct the following recursive model on the basis of the model (1).

$$mediator_{it} = \lambda_0 + \lambda_1 Pilot_i \times Post_t + \sum Control_{it} + \mu_i + \delta_t + \varepsilon_{it} \quad (2)$$

5 The pilot city list in each batch is in Appendix A.

6 Since 2010, NDRC has launched the pilot program of low-carbon cities. The first batch of LCCP program was launched in July 2010, and the second batch of LCCP program was launched in November 2012. Therefore, when setting and processing dummy variables ($Pilot_i$), this paper sets the selection time of the first batch of low carbon cities as 2010, and the second batch as 2013, that is to say, the approval time is in the first half of the year, the set year starts to become low carbon cities, and the approval time is in the second half of the year, It is set to become a low-carbon city next year.

TABLE 1 Descriptive statistics of main variables.

Variable	Definition	Obs	Mean	Std.Dev	Min	Max
G_innov	urban green technology innovation	3588	13.9557	23.0483	0	146
$Pilot_i \times Post_t$	Whether to be selected as a low-carbon city	3588	0.1572	0.364 0	0	1
Lgdp	Level of economic development	3588	4.6037	1.0338	1.5014	8.0272
Lhc	Human capital development level	3588	10.3424	1.3769	5.4424	13.8807
Lpeoden	Population density	3588	5.7143	0.91782	1.54748	7.8513
Linfrastr	Infrastructure Development Level	3588	2.2235	1.0222	−4.6052	5.6985
Finan	Financial Correlation Rate	3588	5.6026	4.1700	0.5600	102.2820
Lfdi	External opening level	3588	6.8969	2.0137	−2.0189	11.9712
Lngovsoci	policy-based R&D funding	3588	9.4574	1.7108	3.5264	15.2106
Industry	industrial restructuring and upgrading	3588	0.9024	0.4768	0.1011	4.6057

$$G\_innov_{it} = \eta_0 + \eta_1 Pilot_i \times Post_t + \eta_2 mediator_{it} + \sum Control_{it} + \mu_i + \delta_t + \varepsilon_{it} \quad (3)$$

where the coefficient λ_1 is the degree of influence of the LCCP policy on mediating variables, and the coefficient η_1 is the degree of influence of the LCCP policy on urban green technology innovation after adding mediating variables. If the coefficients λ_1 and η_2 are significant and the significance of η_1 decreases or the value of the coefficient is less than α_1, it shows that the increase of mediating variables reduces the impact of LCCP policy, and there is a partial mediating effect; If η_1 is not significant, the LCCP policy works exclusively through mediating variables; if only one of λ_1 and η_2 is significant, the Sobel test must be used, and a significant Sobel test would indicate that a mediating effect does exist.

3.2 Data

This section presents the datasets. All the variables constructed from the raw data and used in the figures and tables are defined sequentially throughout the article. This paper eliminated cities with inconsistent administrative divisions and serious data loss. Based on the limitations of the sample data, the panel data of 276 prefecture-level cities in China from 2005 to 2017 were finally selected for analysis, and 88 cities were included in the low-carbon city pilot sites. The patent grant data used in this paper for measuring urban green technology innovation are obtained from the China Intellectual Property Office (IPO), and other urban-level data come from the China Urban Statistical Yearbook over the years. The missing data are filled by interpolation. Table 1 provides definitions of all the variables and their descriptive statistics.

3.2.1 Low-carbon pilot cities

This paper conducts a quasi-natural experiment with the LCCP policy as an exogenous shock. $Pilot_i$ indicates the intergroup dummy variable equal to one if the city becomes a low-carbon pilot city and zero. $Pilot_i$ is a time dummy variable that is set to one after being selected as a low-carbon city and zero before. The interaction term between the intergroup dummy variable and the time dummy variable is used as the policy variable to construct the independent variable $Pilot_i \times Post$.

3.2.2 Urban green technology innovation

The dependent variable of this paper is urban green technology innovation (G_innov_{it}), which is measured by the number of green patents granted in cities. Although a lot of research has been done on the impact of environmental regulation on green technological innovation, there is no unified standard for the measurement of green technological innovation, and many empirical papers focus on R&D expenditure or green total factor productivity (Hamamoto, 2006; Wang et al., 2018; Hu and Liu, 2019; Li et al., 2021; Lv et al., 2021). With the improvement of data availability and the unification of patent classification standards, scholars can dig deeper into patent information, and the advantages of patent data make it a key indicator for measuring green technology innovation (Wang et al., 2019). In September 2010, the World Intellectual Property Organization (WIPO) defined the classification number of the International Patent Classification Green Inventory (IPC Green Inventory). All patents can be scientifically classified into green and non-green patents according to the characteristics of the technical field shown in the IPC classification number, which is internationally common and authoritative. Based on this, many scholars have started using patent data to measure green technology innovation (Przychodzen et al., 2020; Du K. et al., 2021; Maasoumi et al., 2021).

As mentioned earlier, the patent data provided by Inspiro are used as an agent variable for urban innovation. The database contains the information on each patent published by the State Intellectual Property Office of China (CNIPA) since 1985, including the application address of inventors, the application year, the granted year, the patent's technology class, and the International Patent Classification (IPC) code. Based on the research by Johnstone et al. (2010), this paper considers the patents of IPC code in WIPOIPC green list 1 as green patents. The annual green patents are retrieved from the China Intellectual Property Office by year and IPC code and then matched with the city data according to the retrieved address of the patent applicant.

TABLE 2 Baseline regression results.

	(1) G_innov	(2) G_innov
$Pilot_i \times Post_t$	1.8803* (1.0664)	2.3305** (1.0533)
Cons	13.6601*** (0.1676)	68.3894 (47.7440)
Control Variable	Yes	Yes
CITY FE	Yes	Yes
TIME FE	Yes	Yes
N	3588	3588
F	3.1090	1.7004
r2_a	0.5416	0.5421

The table shows estimations of the impact of the LCCP, on urban green technology innovation. The number of observations in each regression corresponds to 276 cities during 13 years between 2005 and 2017. All regressions control for city and year fixed effects. There are no other control variables in column (1), while *lgdp*, *lhc*, *lpeoden*, *linfrastr*, *finan* and *lfdi* are controlled in column (2), Standard errors are clustered at the city level and appear in parentheses. *, **, and *** indicate statistical significance at the 10%, 5% and 1% levels, respectively. The same below.

3.2.3 Control variables

Some variables with city-specific, time-varying sociodemographic characteristics may affect urban green technology innovation. Level of economic development (*lgdp*), measured using the log of urban GDP; Human capital development level (*lhc*), measured by the log of the number of general higher education students per 10,000 people; Population density (*lpeoden*), measured by the log of the number of people per unit land area; Infrastructure development level (*linfrastr*), measured by the log of urban road area *per capita*; The level of financial development of the city (*finan*), measured by the financial correlation rate; The level of openness of the city to the outside world (*lfdi*), measured by the log of the total amount of actual foreign capital utilized.

3.2.4 Mechanism variables

As explained in the previous theoretical mechanism, the LCCP policy will have an impact on urban green technology innovation in two ways: local government policy-based R&D funding and industrial restructuring and upgrading. Therefore, local government policy-based R&D funding and industrial restructuring and upgrading are selected as mediating variables. For policy-based R&D funding (*lngovsoci*), this paper measures it by taking the natural logarithm of city government science and technology expenditure. For industrial transformation and upgrading (*industry*), this paper measures it by the ratio of tertiary industry output value to the secondary industry output value.

The summary statistics are presented in Table 1. The means of urban green technology innovation suggest that the series is concentrated at 13.9557. However, there is a large difference between the minimum and maximum values, which can also be seen from the standard deviation that the values are not concentrated. The ($Pilot_i \times Post_t$) is 0–1 variable, so it is no need to analyze. Among the other variables, since the Financial Correlation Rate or industrial restructuring and upgrading are ratios, the rest are descriptive statistics after logarithm. It can be seen from the standard deviation that there is no large fluctuation, and subsequent tests can be conducted.

4 Empirical results

4.1 Main results

Based on the baseline model (1), the impact of the LCCP on urban green technology innovation is assessed with two regression specifications, and the results are presented in Table 2. In column (1), the regressions simply condition on city and year fixed effects, $Pilot_i \times Post_t$'s coefficient was significantly positive at the level of 10%. Column (2) also includes control variables, $Pilot_i \times Post_t$'s coefficient is significantly positive at the level of 5%, and the degree of impact is greater than the former, which shows that, on the whole, the LCCP policy has a significant positive impact on urban green technology innovation, To some extent, the LCCP policy promotes urban green technology innovation, and after controlling other factors that may affect the city's green technology innovation, the positive impact of the LCCP policy on urban green technology innovation is more significant. So far, Hypothesis 1 has been verified. The regression results also show that environmental regulation can significantly promote urban green technology innovation (Costantini and Mazzanti, 2012; Wang et al., 2020). The results of benchmark regression confirm hypothesis 1.

4.2 Robustness test

The baseline specification is reported in Table 2 above. In this section, various refinements will be considered to check the robustness of the regression.

4.2.1 Dynamics of the LCCP and urban green technology innovation

The dynamics of the relationship between the LCCP policy and urban green technology innovation should be examined. Following Beck et al. (2010), a series of dummy variables in the baseline regression are included to delineate the year-by-year effects of the LCCP on *G_innov*:

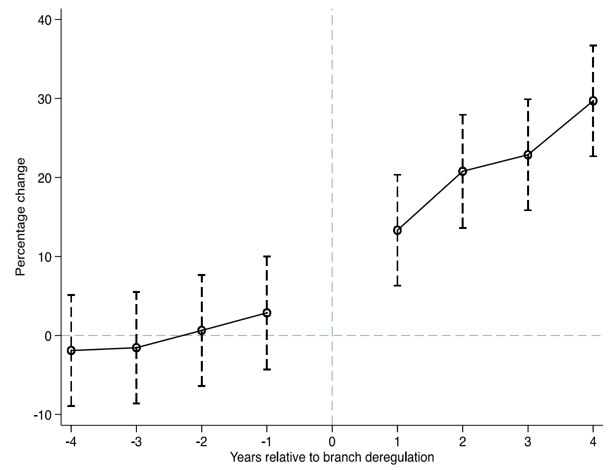

FIGURE 1
Dynamic impact of the LCCP policy on urban green technology innovation. Notes: The figure plots the impact of the LCCP on urban green technology innovation. The dependent variable is the natural log of the green patents granted in cities (*G_innov*), with an 8-year window spanning from 4 years before the LCCP policy until 4 years after the LCCP policy. All observations are at the city-year level. The dashed lines represent 95% confidence intervals adjusted for city-level clustering.

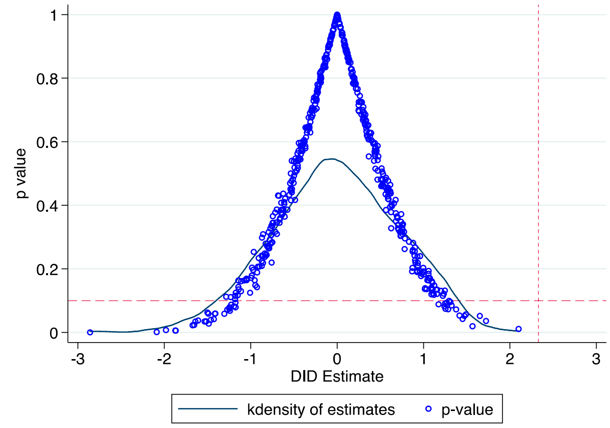

FIGURE 2
Placebo test of the LCCP policy on urban green technology innovation. Notes: The figure plots the results of the placebo test. The dependent variable is the natural log of the green patents granted in cities (*G_innov*). All observations are at the city-year level. The estimation model is Eq. 1. The figure shows the cumulative distribution density of 500 pseudo-estimations. The vertical line presents the results of columns (2) in Table 2.

$$G\_innov_{it} = \beta_0 + \beta_1 D_{it}^{-4} + \beta_2 D_{it}^{-3} + \ldots + \beta_8 D_{it}^{4} + \sum Control_{it} + u_i + \delta_t + \varepsilon_{it} \tag{4}$$

where the LCCP policy dummy variables, the "D's," equal zero, except as follows: D^{-j} equals one for cities in the j^{th} year before becoming low-carbon pilot cities, while D^{+j} equals one for cities in the j^{th} year after becoming low-carbon pilot cities. We exclude the year of LCCP policy was launched, thus estimating the dynamic effect of the LCCP policy on urban green technology innovation relative to the year of LCCP policy. μ_i and δ_t are vectors of city and year dummy variables, respectively. In Eq. 2, D_{it}^{-4} equals one for all years that are four or more years before the year the city becomes a low-carbon pilot city, D_{it}^{+4} equals one for all years that are 4 years or more after the city becomes a low-carbon pilot city. Figure 1 plots the results and the 95% confidence intervals, which are adjusted for city-level clustering.

As shown in Figure 1, the coefficients on the LCCP policy dummy variables are insignificantly different from zero for all years before the cities obtained the LCCP policy with no trends. Additionally, *G_innov* increases immediately after the LCCP policy has been launched. In sum, the results show that there is no significant difference between the treatment group and the control group before the implementation of the LCCP policy, which meets the parallel trend hypothesis. After the implementation of the LCCP policy, the impact on urban green technology innovation materializes very quickly. Thus, detecting the mechanisms connecting the LCCP policy with urban green technology innovation is essential.

4.2.2 Placebo test

A placebo test was performed to exclude the effects of other unobservable factors further and verify that implementing the LCCP policy brings about urban green technology innovation [63]. To make the impact of the LCCP policy on specific regions random, this paper randomly selects the treatment and control groups among all samples, and the process is repeated 500 times to obtain 500 pseudo-city samples. The baseline regression, as shown in Table 2 Column (2), was performed in each of these pseudo-city samples, and the relevant coefficients were saved. Finally, the coefficients from the actual city sample are compared with those from these pseudo-city samples. The distribution of the 500 pseudo estimations and *p*-values is shown in Fig. 3.

The solid black line is the estimated coefficient distribution of the placebo test, the blue scatter is the *p*-value corresponding to the estimated coefficient of the placebo test, the horizontal dotted line is the significance level of 10%, and the vertical dotted line is the real estimated coefficient of the benchmark regression. It can be seen from Figure 2 that, on the one hand, most regression coefficients fall within the range of [- 3, 2], It is smaller than the benchmark regression coefficient 2.3305. On the other hand, the regression coefficient roughly follows the normal distribution with the mean value approximating to 0, and the corresponding *p*-value is mostly greater than 0.1, which is statistically consistent with the expectation of the placebo test, suggesting that there is no effect with the randomly constructed city sample. In general, the results of the placebo test suggest that the positive and significant effect of the LCCP on urban green technology innovation is not driven by unobserved factors or unmeasured time trends, which strengthens the credibility of the results.

4.2.3 Propensity score matching-difference in difference

In order to avoid possible self-selection problems in the trend of the experimental groups and control groups leading to bias in the regression results, the PSM-DID method is used in this paper for robustness testing. Propensity score matching uses propensity score as a distance function for matching, and there are three specific matching methods: Neighbor Matching, Radius Matching, and Kernel Matching. In order to make the evaluation results more robust, this

TABLE 3 PSM-DID regression results.

	Radius matching	Neighbor matching	Kernel matching
	G_innov	*G_innov*	*G_innov*
$Pilot_i \times Post_t$	2.5972**	2.3305**	2.2477**
	(1.0823)	(1.0533)	(1.0614)
Control Variable	Yes	Yes	Yes
TIME FE	Yes	Yes	Yes
CITY FE	Yes	Yes	Yes
N	3524	3588	3576
F	1.5980	1.7004	1.5155
r2_a	0.5410	0.5421	0.5408

The table presents the PSM-DID, results of the impact of LCCP, on green technology innovation. All regressions control for year and city-fixed effects. Standard errors are clustered at the city level and appear in parentheses. *, **, and *** indicate statistical significance at the 10%, 5% and 1% levels, respectively.

TABLE 4 Results of heterogeneity analysis.

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
	Eastern region	Middle region	Western region	High level of economic	Low level of economic	High environmental regulation intensity	Low environmental regulation intensity
	G_innov	*G_innov*	*G_innov*	*G_innov*	*G_innov*	*G_innov*	*G_innov*
$Pilot_i \times Post_t$	2.1875 (1.4870)	0.7391 (2.4894)	4.1043* (2.2748)	1.7611 (1.6566)	4.2312** (1.8692)	2.6553** (1.1703)	0.0134 (2.5310)
cons	153.0191 (94.2875)	164.9604 (117.418)	41.3673 (77.8929)	58.8280 (78.4432)	111.8354 (84.5302)	38.7964 (56.7740)	76.1018 (89.8325)
Control Variable	Yes	Yes	Yes	Yes	Yes	Yes	Yes
TIME FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes
CITY FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes
N	1300	1261	1027	1759	1803	390	3122
F	2.8722	1.3000	1.8499	0.3074	1.5880	1.1878	1.4565
r2_a	0.5721	0.2477	0.5051	0.5124	0.5290	0.5763	0.5335

The table presents estimates of the heterogeneity impact of LCCP, on green technology innovation. All regressions control for year and city-fixed effects. Standard errors are clustered at the city level and appear in parentheses. *, **, and *** indicate statistical significance at the 10%, 5% and 1% levels, respectively.

study uses the above three ways of matching respectively and finally comes up with a robust estimation result. The results in Table 3 show that whether Neighbor Matching, Radius Matching, or Kernel Matching, the DID tests are significantly positive and consistent with the baseline regression result. This indicates that the estimation results of this paper are robust.

5 Discussion

5.1 Heterogeneity analysis

The baseline regression results show that the LCCP policy significantly enhances urban green technology innovation, but due to differences in resource endowments and early national development strategies, China's regions' development is uneven. In addition, when the central government assigns the emission reduction task because local governments have certain discretion, different local governments may have different governance motives, resulting in different environmental regulation intensities. In this context, does the LCCP policy have differential impacts on urban green technology innovation depending on the locational characteristics or the intensity of environmental regulation? Exploration of this issue helps understand the mechanisms underlying the LCCP policy that influence urban green technology innovation from a new perspective.

5.1.1 Heterogeneity of regional differences

Given the vast size of China and the great differences in resource endowments and economic development among different regions, the impact of the LCCP policy on green technology innovation may be different in regions. In view of this, we respectively analyze the heterogeneity of regional characteristics and economic development levels.

This paper introduces the Chinese city location classification index to test the heterogeneous effects of the LCCP policy on urban green technology innovation in the eastern, middle, and western regions. According to the regression results of columns (1)–(3) in Table 4, the LCCP policy has promoted green technology innovation in the western regions more than in the eastern and central regions. Li et al. (2022) also found that LCCP policy plays a more important role in improving the carbon governance efficiency of cities in Western regions. This is most likely due to the backward economic conditions in the early development of the western region and the relatively low land and labor costs in the western region, which led to the transfer of pollution-intensive industries from the eastern region to the western region, making the western region gather large numbers of pollution-intensive industries and becoming a "pollution haven" (Hu et al., 2022). When the government implements environmental regulations, it changes local industrial enterprises' production patterns, forcing them to shift to cleaner production, and promoting urban innovation. Accordingly, when selected as a pilot city, the strong willingness of local governments to govern the environment will force local industrial enterprises to change their production patterns, leading to more significant green technology innovation. Wen et al. (2022) thought that the LCCP has a better carbon efficiency improvement effect in resource-based cities. However, in eastern cities, the level of green technology innovation is relatively high, and the stimulating effect of the LCCP policy is smaller. For central cities, the LCCP policy impact on green technology innovation is not significant.

Different regions have different levels of economic development. The better the local economic development is, the more conducive to implementing the policies formulated by the local government. On this basis, according to the economic development level of different cities, this paper defines cities higher than the mean value of *per capita* GDP as high levels of economic cities and cities lower than the mean value of *per capita* GDP as low levels of economic cities. Based on this, the heterogeneity of the urban economic level is analyzed. The results of columns (4)–(5) in Table 4 show that the LCCP policy significantly promoted green technology innovation for cities with low economic development levels. This may be because the existing factor market operates inefficiently in low-economic development cities. LCCP policy has more significant guidance for green technology innovation and a greater promotion effect on green technology innovation. However, for cities with high economic development levels, the role of LCCP policy in driving green technology innovation is not significant, which further indicates that LCCP policy plays a greater role in radiating and driving green technology innovation in cities with low economic development levels.

5.1.2 Heterogeneity of environmental regulation intensity

In addition, we further analyze whether the impact of the LCCP policy on urban green technology innovation varies according to the intensity of environmental regulation. This paper takes the ratio of the total investment in environmental pollution control (million) to the city's GDP (million) in the initial period of the sample, that is, in 2005, which was not affected by the policy, as the proxy index of the intensity of the environmental regulation. If the level of urban environmental regulation is higher than the mean value, it is considered high environmental regulation intensity, and if the level of urban environmental regulation is lower than the mean value, it is considered weak environmental regulation intensity. The regression results of columns (4)–(5) in Table 4 suggest that the effect of the LCCP policy on urban green technology innovation is greater in cities with high environmental regulation intensity. This means that the effectiveness of the implementation of the LCCP policy depends not only on the region where it is implemented but also on the strength of its implementation. Safi et al. (2022a) also revealed that policies aimed at institutional quality, ecological innovation and energy productivity significantly affected CO2 emissions and contributed to improving environmental quality.

5.2 Underlying mechanisms

This paper verifies that there is a significant positive effect of the LCCP policy on urban green technology innovation through benchmark regressions and a series of robustness tests. Then, what mechanism will the LCCP policy impact urban green technology innovation? According to the theoretical mechanism analysis in the previous section, it is found that local government policy-based R&D funding and industrial transformation and upgrading play a mediating role in the LCCP policy to promote urban green technology innovation, and the mediating effect will be tested in this section. The regression results are shown in Table 5.

The regression results of columns (1)–(3) indicate that the LCCP policy improves the level of green technology innovation by increasing local government policy-based R&D funding, and the $Pilot_i \times Post_t$ coefficient in column (3) is significantly positive, and the coefficient decreases compared to the result of the baseline regression, but the coefficient of *lngovsoci* is not significant, and the Sobel test is needed. The Z value of the Sobel test is 4.9150, which is greater than the critical value of 2.58 at the 1% level, proving that the test result is significant, which also indicates that the mediating effect of the LCCP policy on urban green technology innovation through local government policy-based R&D funding investment does exist. This result indicates that the LCCP policy can effectively motivate local governments to introduce financial support policies that are more in harmony with low-carbon development goals to fully play the role of policy leadership, which also fully reflects the inherent incentive of central government policies on local governments under the Chinese political system. Many research studies support this conclusion. Wang et al. (2022) considered that LCCP policy mainly relies on technological progress rather than technological efficiency to promote urban green productivity. Ma et al. (2021) believed that LCCP stimulates the green technological innovation of enterprises, as manifested in their application of green invention patents.

The regression results of columns (4)–(5) show that the LCCP policy improves green technology innovation by promoting industrial structure upgrading. Similarly, the coefficient of $Pilot_i \times Post_t$ in column (5) is significantly positive, but the coefficient of the industry is not significant, and the Z value of the Sobel test is 6.3340, which is greater than the critical value of 2.58 at the 1% level, proving that the test result is significant, which also indicates that the mediating effect of LCCP policy affecting urban green technology innovation through industrial transformation and upgrading does exist. This result indicates that with the gradual promotion of the LCCP policy, pollution-intensive and energy-consuming industries will be forced

TABLE 5 Mechanistic analysis.

	(1)	(2)	(3)	(4)	(5)
	G_innov	*Lngovsoci*	*G_innov*	*industry*	*G_innov*
$Pilot_i \times Post_t$	2.3305**	0.0162*	2.2992**	12.7416*	2.3184**
	(1.0533)	(0.0088)	(1.1127)	(7.0078)	(1.1128)
Mediator			2.5951		0.0018
			(2.1931)		(0.0028)
_cons	68.3894	0.0433	63.7564	−1.7e+02	64.1697
	(47.7440)	(0.3128)	(39.3642)	(248.0510)	(39.3727)
Control Variable	Yes	Yes	Yes	Yes	Yes
TIME FE	Yes	Yes	Yes	Yes	Yes
CITY FE	Yes	Yes	Yes	Yes	Yes
N	3588	3588	3588	3588	3588
F	1.7004	12.6430	1.84	1.2421	1.4900
r2_a	0.5421	0.9425	0.5423	0.8741	0.5266

This table shows the results of the mechanism of LCCP, on green technology innovation. All regressions control for year and city-fixed effects. Standard errors are clustered at the city level and appear in parentheses. *, **, and *** indicate statistical significance at the 10%, 5% and 1% levels, respectively.

out of the market due to the increase in costs. In contrast, modern manufacturing industries with technological innovation as well as service-oriented tertiary industries will gain comparative advantages, and the industrial structure will be transformed and upgraded, thus further driving the level of green technological innovation in cities. In summary, it confirms hypothesis 2.

6 Conclusion

This paper assesses the impact of LCCP policy on urban green technology innovation using the DID method. The findings are as follows: (1) The LCCP policy can promote urban green technology innovation, and the results remain robust through a series of robustness tests. The implementation of the LCCP policy reduces the carbon intensity and total carbon emissions of the city, and this process led to the upgrading of existing technologies and the development of green technologies that meet the needs of low-carbon development (2) The mechanism analysis shows that the LCCP policy can promote urban green technology innovation by increasing local government policy-based R&D funding. LCCP policy has increased the enthusiasm of local governments to invest in scientific and technological innovation, which improves innovation subjects' enthusiasm. (3) Another way for LCCP to increase green technology innovation is to upgrade the industrial structure. With the gradual promotion of the LCCP policy, pollution-intensive and energy-consuming industries must bear higher environmental costs. Some polluting enterprises need to be forced out of the market due to the increase in costs, while technological innovation gains comparative advantages that dominate the industries. (4) Urban location characteristics, as well as the environmental regulation intensity, have heterogeneous effects on green technology innovation. The LCCP policy improves the green technology innovation level of eastern and western cities and has a greater impact on the western region. For middle cities, the LCCP policy impact on green technology innovation is not significant.

Based on the above findings, the following policy suggestions are proposed: (1) The government should expand the scope of low-carbon policy pilots and promote LCCP policies nationwide. The research shows that the pilot policy of low-carbon cities can improve the green technology innovation of enterprises, so the government should constantly strengthen the constraint and incentive of the policy and boost the green technology efficiency of manufacturing enterprises through policies, financing, supervision and other ways (Amin et al., 2022; Safi et al., 2022c). Especially for enterprises in resource-based cities, the government can change the traditional policy development model, stimulate enterprises' innovation vitality, eliminate the path dependence of extensive growth from the root, and realize the development of low-carbon and clean industries. (2) Considering that local government policy-based R&D funding and promoting industrial transformation and upgrading are important channels for the LCCP policy to play a long-term impact of the LCCP policy on green technology innovation. On the one hand, the central should mobilize the independent forces of local governments, increase local government R&D funding investment and make good infrastructure construction and other supporting facilities to provide better innovation guarantees. Safi et al. (2022b) also showed that fiscal decentralization improves environmental quality. On the other hand, the government should fully play the fundamental role of market allocation of resources, adopt a new road of industrialization, promote the integration of information technology and industrialization, and enhance the transformation and upgrading of industrial structure. (3) There are huge differences in resource endowment, industrial structure, and other aspects among provinces in China. When assessing the carbon emission reduction effect of pilot policies for low-carbon cities, full consideration should be given to the fairness between regions. Meanwhile, the intensity of environmental regulations should be moderately strengthened, and the monitoring and evaluation mechanism for implementing low-carbon emission reduction tasks in pilot cities should be improved. Financial and resource support should be given to areas with good implementation to form a model effect; pilot areas with insufficient implementation should be given more accountability, and a withdrawal mechanism should be established.

7 Limitation

Due to the limitation of data availability, this paper uses the number of granted green patents to measure the level of green technology innovation in cities. However, it may not reflect the quality of green patents, and thus the measurement of urban green technology innovation in cities may be biased. In the future, we expect to improve the data related to environmental protection in China to add indicators reflecting the quality of patents and thus have a more comprehensive and scientific measurement of urban green technology innovation.

This paper only makes a preliminary judgment and brief analysis of the impact mechanism of the LCCP policy on urban green technology innovation and does not further reflect the mechanism from the micro-level. Subsequent research can further be studied by collecting firm-level data.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

All authors wrote the whole manuscript. ZL—conceptualization, data curation, project administration, writing—review and original draft preparation. ZL—formal analysis, methodology, results, results interpretation, visualization, resources. All authors read and approved the final manuscript.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

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Appendix A: The low-carbon city pilot policy batch time and pilot cities

The LCCP policy is divided into three batches: the National Development and Reform Commission (NDRC) launched the first batch of pilot work in July 2010, with a pilot area of eight cities and five provinces. Then, the second and third batches of pilot work were conducted in November 2012 and January 2017, respectively. The second batch of pilot work covered 28 cities and one province, and the third batch of pilot work covered 45 cities. The specific pilot cities are as follows.

The first batch of pilot areas: Guangdong, Liaoning, Hubei, Shaanxi, Yunnan five provinces and Tianjin, Chongqing, Shenzhen, Xiamen, Hangzhou, Nanchang, Guiyang, Baoding eight cities.

The second batch of pilot areas: Beijing, Shanghai, Hainan Province, Shijiazhuang, Qinhuangdao, Jincheng, Hulunbeier, Jilin, Daxinganling area, Suzhou, Huai'an, Zhenjiang, Ningbo, Wenzhou, Chizhou, Nanping, Jingdezhen, Ganzhou, Qingdao, Jiyuan, Wuhan, Guangzhou, Guilin, Guangyuan, Zunyi, Kunming, Yan'an, Jinchang, and Urumqi.

The third batch of pilot areas: Wuhai, Shenyang, Dalian, Chaoyang city, Sunk County, Nanjing, Changzhou, Jiaxing, Jinhua, Quzhou, Hefei, Huaibei, Huangshan, Liuan, Xuancheng, Sanming, Gongqingcheng, Ji'an, Fuzhou, Jinan, Yantai, Weifang, Changyang Tujia Autonomous County, Changsha, Zhuzhou, Xiangtan, Chenzhou, Zhongshan, Liuzhou, Sanya, Qiongzhong Li Miao Autonomous County, Chengdu, Yuxi, Pu'er Simao District, Lhasa, Ankang, Lanzhou, Dunhuang, Xining, Yinchuan, Wuzhong, Changji, Yining, Hotan, First Division Alar.