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Research article

Innovation or introduction? Impacts of the low-carbon city pilot policy on the pathways toward green technology progress

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ABSTRACT

To examine whether the low-carbon city pilot (LCCP) policy influences the green technology innovation (GTI) or embodied technology introduction (ETI), two different pathways to green technology progress, in manufacturing enterprises in China, this study employs a staggered difference-in-difference (DID) model to evaluate the effects of the policy. The findings suggest that the LCCP policy has stimulated an increase in the quantity of GTI and ETI among enterprises, but reduced the quality of innovation. Large, high-carbon-intensity, and state-owned enterprises are more likely to engage in GTI, while small, low-carbon-intensity, and non-state-owned enterprises prefer ETI. The policy is effective in alleviating financing constraints and improving environmental concerns. Both GTI and ETI play a crucial role in economic performance, while the latter also promotes environmental and ESG performance. Accordingly, we recommend establishing a policy-compatible evaluation system, strengthening mandatory and incentive measures, and cultivating a green innovation ecosystem, etc., to improve the performance of the LCCP policy.

1. Introduction

Rapid industrialization in China, driven by extensive energy consumption and carbon emissions, has given rise to significant resource and environmental challenges, profoundly impacting the sustainable development of the economy. From 2000 to 2021, China's energy consumption in the manufacturing sector witnessed a substantial increase from 8091.4 million tons to 2930.65 million tons of standard coal, a growth of 3.62 times. Concurrently, carbon dioxide emissions also significantly rose by 3.53 times.[1] Under these circumstances, the "14th Five-Year Plan for Modern Energy System" explicitly states that the key to achieving carbon neutrality and accelerating the green transformation of manufacturing lies in advancements in green technology. The Jointly Released Implementation Plan for Enhancing the Market-oriented Green Technology Innovation System (2023–2025) by the National Development and Reform Commission (NDRC) and the Ministry of Science and Technology (MST) emphasizes the necessity to enhance regulatory measures to stimulate market-driven innovation in green technology. As a crucial component of the green and low-carbon policy framework, the low-carbon city pilot (LCCP) policy serves as a prime example of environmental protection policies in China. Assessing the effectiveness and analyzing the challenges of the LCCP policy hold significant practical implications for optimizing policy measures. Therefore, this study aims to examine the impacts of the LCCP policy on the pathways towards green technology progress within

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[1] Source: China Energy Statistical Yearbook (CESY) of the year 2022.

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manufacturing enterprises.

The LCCP policy has attracted increasing attention since its inception. The policy was initially launched by the NDRC in 2010, and then successively expanded in 2012 and 2017, encompassing three batches of low-carbon pilots and covering six provinces and 81 cities. According to the LCCP policy, each pilot city is mandated to formulate low-carbon development plans based on local resource conditions and industrial structure, and to clearly define the objectives of its low-carbon pilot initiatives to actively promote green and sustainable lifestyles and consumption patterns [1,2]. As a flexible pilot policy, the LCCP can be timely adjusted and rectified during the process of "pilot diffusion" to effectively mitigate potential policy failures [3,4]. Existing research in this field can be broadly categorized into the following four categories: (i) environmental impacts, mainstream literature suggests that the LCCP policy promotes industrial structure optimization and enhances energy efficiency, reducing carbon emission intensity in pilot cities and improving urban air quality [5,6]; (ii) social effects, the LCCP policy can enhance residents' awareness of low-carbon practices and motivate their adoption of low-carbon products [7], improve enterprises' ESG performance and stimulate employment through the effects of increased output and factor substitution [8–10]; (iii) economic impacts, the LCCP policy alleviates financing constraints, improves resource allocation efficiency and TFP, therefore enhancing enterprise economic efficiency [11–13]; (iv) green innovation effects, previous research reveals that the LCCP policy facilitates GTI at an organizational level, supporting the Porter hypothesis, particularly for high-carbon enterprises [14,15]. Our investigation into the impacts of the LCCP policy on green technology progress bears much more similarity with the fourth category.

Under the LCCP policy, manufacturing enterprises strategically pursue diverse paths towards green technology progress, either internal green technological innovation (GTI) by the enterprise itself or external embodied technological introduction (ETI) from outside sources. Specifically, GTI refers to the innovative technological means that actively seek to reduce or minimize environmental pollution, conserving precious resources and energy [16,17]. ETI typically refers to the technological progress of the introduced elements, particularly newly implemented machinery and other capital assets [18,19]. From 2001 to 2021, even in the face of increasingly severe technology blockades from developed countries, the value of foreign technology introduction contracts in China surged from US$9.091 billion to US$36.706 billion, accounting for 7.71% of the total value of R&D and technology introduction costs,[2] highlighting technology introduction as an effective complement to enterprises' independent innovation. Generally, enterprises with stronger R&D capability are likely to achieve green technological advancements through increased R&D investment [20,21], while those with limited factor endowments and innovation resources prefer to introduce advanced equipment. Yet, the question of whether the LCCP policy would impact the preferences of different enterprises in pursuing green technology progress remains unanswered.

Relevant literature generally focuses on green innovation and neglects the crucial role of ETI, resulting in a one-sided and underestimation of enterprise green technology progress. The objective of this paper is to address this research gap. Previous studies commonly use the quantity of patent applications and TFP [22,23] as indicators to evaluate green innovation or technological progress [24]. Such measurement need to be optimized and improved: On the one hand, the current authorization rate of invention patents in China is relatively low, and a significant proportion of green patent applications consist of low-quality patents, which fail to accurately reflect enterprises' green technological innovation [25]. On the other hand, this measure fails to account for the technological improvement facilitated by the introduction of advanced machinery and equipment [26,27], commonly referred to as ETI [28], thereby resulting in an underestimation of firms' actual technological progress. As the discourse in Lin and Ren (2007) [29] on East Asia's economic development model proposed, developed countries typically pursue independent R&D to achieve technological progress, while developing countries primarily attain technological progress through the adoption of machinery and equipment embedded with advanced technologies during their initial stages [30,31].

In general, advanced machinery and equipment are considered high-tech products that effectively contribute to the reduction of energy consumption and pollution emission intensity in enterprises [32]. Moreover, they catalyze to stimulate enterprises to improve their green technology capabilities through the adoption of imitation and "reverse engineering" practices [33,34]. This approach is particularly effective for firms with limited independent R&D capacity [35], as it facilitates the achievement of green technology progress through the introduction of advanced equipment. Admittedly, the technology introduction also includes the acquisition of external patents. However, it should be noted that in most cases, the transferred technologies tend to be mature or obsolete as a strategic measure to maintain their own technological advantages and monopolistic position. These technologies have limited effectiveness in promoting green technology progress within technology-importing enterprises [36]. Therefore, this paper assesses GTI by examining both the quantity and quality of granted green invention patents of manufacturing enterprises. It also uses the introduction of new equipment as a measure of ETI and focuses on analyzing the impact of LCCP policy on GTI and ETI.

The marginal contribution of this study is as follows: (i) The prevailing literature predominantly supports the "compensation effect" of environmental regulation, such as the LCCP policy, on firms' green innovation while overlooking the potential occurrence of a "race to the bottom" phenomenon and a "green innovation bubble" driven by policy incentives. As a result, the impact of LCCP policy on enterprises GTI has been overestimated. Given this, our study contributes to revealing that the LCCP policy inhibits the GTI quality and causes "green innovation bubbles" based on firms' "subsidy seeking" and "greenwashing." (ii) This study investigates the heterogeneous impacts of the LCCP policy on firms with different ownership structures, sizes, and carbon emission intensities, to optimize the LCCP policy and establish a comprehensive evaluation system for GTI. (iii) This paper examines the mechanism of the policy on firms' green technology progress, taking into account factors such as relative financing constraints, commercial credit constraints, and public and government environmental concerns, and explores the economic, environmental, and ESG performance of different pathways. In doing

[2] Source: China Statistical Yearbook on Science and Technology (CSYST) of the year 2022.

so, our work provides theoretical support for further facilitating green and low-carbon production.

The rest of this paper is structured as follows. Section 2 outlines the theoretical framework and the hypothesis in the context of the LCCP policy. Section 3 presents the model, variables, and the data used in the empirical tests. Section 4 presents the empirical results and a series of tests for robustness and heterogeneity tests. Section 5 presents the potential mechanism and the performance analysis. Section 6 concludes and limitations.

2. Theoretical analysis and hypothesis

As a comprehensive environmental policy, the LCCP combines command-and-control measures (such as eliminating outdated production capacity and implementing vehicle emission standards), market-based incentives (including carbon trading mechanisms and energy-saving pilots), and voluntary initiatives (such as low-carbon industrial parks and transport pilots) [37,38]. For one thing, the LCCP policy sets limits on carbon emissions, requires manufacturing enterprises to upgrade and transform to cleaner production and improve resource utilization efficiency, sets up market access thresholds for energy conservation and environmental protection, and uses market mechanisms to control the excessive growth of industries with high pollution and energy consumption [39,40]. For another thing, it supports R&D of low-carbon technology through tax subsidies, financial support, and other measures, while upgrading conventional technologies. In addition, compared with non-pilot cities, LCCP areas have access to more special funds, industrial financial subsidies, and other financial support from central and local governments during the development of the low-carbon economy. In this case, enterprises can afford to carry out transformation, upgrading, and green innovation [41]. This is the well-known “innovation compensation” effect, which can alleviate or offset to some extent the “cost compliance” effect of environmental regulation proposed by neoclassical economic theory [41,42] and existing research [43,44], and consequently promote the progress of green technology.

However, under the incentive of the LCCP policy, some enterprises may engage in speculative behavior such as “seeking subsidies” and "green-washing", and attract more external resources through the “gimmick effect” of green innovation [45,46], resulting in a green innovation bubble. In the evaluation of green innovation, information asymmetry exists between the government and enterprises due to the imperfect technology evaluation system and information disclosure system, so the government cannot accurately evaluate the quality of green innovation in enterprises, and provide subsidies according to the number of granted patents. This may lead to an increase in low-quality green patents that are used to defraud subsidies [47,48]. Accompanied by the increasing emphasis on ecological and environmental assessment in the performance evaluation of local officials’ promotion tournaments, there may be a mutual exchange of rent-seeking activities between them and entrepreneurs in pilot cities to acquire resources and policy preferences from the central government, as well as gain more advantages for promotion [49]. To promote the implementation of the LCCP policy, pilot cities will be motivated to encourage manufacturing enterprises to vigorously carry out green innovation activities through financial subsidies and tax incentives. Enterprises will also be motivated to launch a large number of low-quality green innovations to meet policy needs and receive more policy financial support. Accordingly, it is proposed that.

Hypothesis 1. The LCCP policy is conducive to promoting the quantity of green innovation but inhibiting the quality.

The long-term nature of the R&D and the uncertain outcomes of the innovation determine that ETI is better suited to the short-term interests than independent innovation, as ETI can promote green transformation and improve the technical equipment of firms in a relatively short period of time, help polluters to reduce pollution and increase efficiency, and quickly meet the requirements of environmental regulations [28]. At the same time, the ETI helps reduce the cost of green R&D and encourages firms to adopt environmentally friendly innovations through the spillover effects of external technologies [50]. After the launch of the LCCP policy, local governments are motivated to encourage and guide enterprises to install new pollution control and production equipment to realize the policy goal in the short term. Meanwhile, for manufacturing enterprises, the installation of pollution control equipment according to their pollution discharge conditions can effectively reduce the amount of final pollution discharge. In addition, the new machinery and equipment can also improve energy utilization and production efficiency during the production process, and further reduce the pollution emission intensity [51]. Therefore, we propose that.

Hypothesis 2. The LCCP policy is conducive to the ETI of manufacturing enterprises to green technology progress.

Innovation theory suggests that the availability of capital plays an important role in technological innovation. However, advances in green technology require a certain level of technological expertise and knowledge, and the creation of production capacity from technological innovation is highly uncertain and may be limited by severe capital constraints [52]. To ensure the positive effects of the LCCP policy, the pilot cities are trying to increase financial support for manufacturing enterprises through measures such as financial subsidies, tax and fee reductions, and special funds, thereby releasing the signal of the government’s implicit guarantee to financial institutions and lowering the financing threshold for such enterprises [53]. Such support from the government and financial institutions can effectively ease the financing constraints. The funds or subsidies received by enterprises can be used to purchase new machinery and equipment to improve the existing production process and technical equipment, and then promote green technology progress in manufacturing. Accordingly, we suggest that.

Hypothesis 3. The LCCP policy can promote green technology progress by easing the financing constraints.

With the implementation of the LCCP policy, the environmental concerns and awareness, as well as the participation in environmental monitoring and management, of the public and the government in the pilot cities have been significantly improved. The Public’s concern and participation can provide timely and accurate first-hand information for environmental governance, and effectively reduce the information asymmetry in environmental regulation [54]. As consumers and investors, the public can "vote with their feet" to support environmentally friendly products and enterprises in the goods and capital markets, and impose "market penalties" on environmentally unfriendly enterprises [55]. In addition, the last two batches of low-carbon pilot cities are generated by the "declaration + selection" method, which indicates that the governments of the selected pilot cities have a relatively higher level of environmental concern. Moreover, after the implementation of the LCCP policy, the public demand for environmental improvement increases, which would eventually affect the government's environmental regulation efforts [56]. From this perspective, we suggest that.

Hypothesis 4. The LCCP policy promotes green technology progress in businesses by raising public and government environmental awareness.

The theoretical framework of this paper can be illustrated in Fig. 1.

3. Methodology

3.1. Model specification

The difference-in-differences (DID) model is commonly used in mainstream literature to evaluate the effect of policy implementation in recent years. In the model, the policy is treated as a "quasi-natural experiment" exogenous to the economic system. Referring to Zeng et al. (2023) [57], we also take LCCP policy as a quasi-natural experiment, setting 2010, 2013 and 2017 as the starting years of the three policies implementation respectively, to examine the impact of the policy on the pathways towards green technology progress manufacturing enterprises. The DID model can be expressed as equation (1):

$$(GTI_{ict}, ETI_{ict}) = \alpha + \beta LCCP_{ict} + \gamma \boldsymbol{X}_{ict} + \mu_i + \sigma_c + \lambda_t + \varepsilon_{ict} \quad (1)$$

Where, GTI_{ict} and ETI_{ict} represent the green technology innovation and introduction of firm i in city c in t years, and GTI is further divided into two aspects: the quantity (GTI_qn) and the quality (GTI_ql). $LCCP_{ict} = policy_{ic} * post_t$ is the DID variable, where $policy_{ic}$ denotes the dummy variable of firm i in city c, which equals 1 if c is the pilot city, then the firms in city c are in the experimental group, or 0 and the control group. $post_t$ is the dummy variable before or after the implementation of the LCCP policy, post is 1 from the year when the policy starts to be implemented, otherwise 0. β is the coefficient reflecting the impact of the LCCP policy on green technology progress. If the policy does indeed facilitate both GTI and ETI, the estimates should be significantly positive. $\boldsymbol{X}$ represents a set of covariates that may affect firms' green technology progress, and μ_i, σ_c, λ_t represent the firm, city, and time-fixed effects, respectively, to capture any individual characteristics that vary across cities and years. ε_{ict} denotes the random disturbance term. Standard errors are clustered at the city level.

3.2. Variables

GTI is generally measured by the number of granted patents for green inventions. The main consideration in using enterprises' patented green inventions is that the invention patents have more substantial innovation than the utility model patent. In addition, as mentioned above, the approval rate rate of invention patents in China is relatively low, and the process from R&D investment to patent application, and to putting into use is full of uncertainties. Therefore, compared with applied patents, granted patents can minimize the uncertainty of the intermediate link and reflect the innovation at the firm level as accurately as possible. In addition, there is a certain time lag from the application to the approval of invention patents, the data of approved green invention patents cannot accurately reflect the technological innovation. The further analysis of the application date and public announcement date of invention patents, we find that the average time interval from application to approval of invention patents is 2.81 years. Therefore, we chose the patented green innovation after 3 years to evaluate the quantity of GTI (GTI_qn).

As for the GTI quality (GTI_ql) at the firm level, the knowledge width method was used, referring to Aghion et al. (2005) and Mao et al. (2019). Specifically, according to the IPC of green patents and the way of Herfindahl-Hirschman index (HH), the degree of

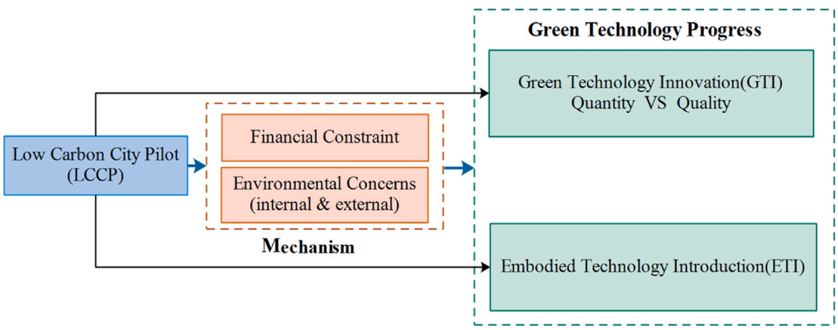

Fig. 1. Theoretical framework.

disparity of IPC numbers among large groups of green patents is calculated according to equation (2):

$$patent_{width} = 1 - \sum \alpha^2 \quad (2)$$

Where α represents the proportion of each major group based on IPC, $patent_{width}$ denotes the knowledge breadth, i.e. the difference between the number of patent classifications at the large group level. The larger the $patent_{width}$, the more comprehensive the patent is and the higher the quality. To obtain the *GTI_ql* at the firm level, we use the median method to sum the information on the green patent width.

ETI is measured by " the ratio of the cash paid for the acquisition and construction of property, plant and equipment, intangible assets, and other long-term assets to the total assets" according to Wan et al. (2021) [51]. This proxy variable can also reflect the expenditure on intangible assets such as patents and unpatented technologies, so it is inherently reasonable to use this indicator.

Control variables. Other intrinsic characteristics of firms may also influence their progress in green technology. In line with existing research [41,58,59], we consider several firm-level variables: (1) firm size (LnScale), (2) firm age (LnAge), (3) firm revenue (LnReven), (4) the number of employees (LnEmp), (5) the liquidity ratio (Liqu), (6) the fixed assets ratio (Fix_rate), (7) the return on assets (ROA), (8) the capital structure (*Lev*), (9) the cash flow ratio (*Cashflow*). The description of variables is presented in Table 1.

3.3. Data source and description

Given the changes in accounting methods brought about by the adjustment of accounting standards in 2007, as well as the profound impact of COVID-19 in 2020 on the management and operation of enterprises in China, this paper mainly examines manufacturing A-share listed companies in Shanghai and Shenzhen from 2007 to 2019. The financial data of listed companies are generally from the CSMAR database, and the price index is from the CEInet statistical database. Green patent data are from the China National Intellectual Property Administration and the CNRDS database. Green invention patents are identified by matching the downloaded patent IPC codes with the "IPC Green List" published by the World Intellectual Property Organization. Following the main research on listed companies, the companies marked with ST, *ST, and PT and those with large missing values were deleted. In addition, the 1% double-tailed treatment was applied to all continuous variables to minimize the impact of extreme values. To eliminate the influence of price fluctuations, we take 2007 as the base period and adjust total assets, cash payments such as construction of fixed assets, depreciation of fixed assets, and total main income of listed companies. Finally, we obtained the unbalanced panel observation data including 795 manufacturing companies. The statistical description of the main variables is reported in Table 2.

4. Results and analysis

4.1. Baseline tests

Table 3 presents the impact of *LCCP* policy on green technology innovation and ETI. Column (1) for *GTI_qn* is estimated with *LCCP* policy dummy variables only, and column (2) adds all the control variables on this basis. We obtain columns (3)–(6) for *GTI_ql* and ETI in the same way. As in columns (1)–(2), the positive and significant point estimates of LCCP indicate that the LCCP policy is conducive to increasing the number of green patents granted to manufacturing enterprises and promoting GTI, which is consistent with the conclusions of mainstream studies [37]. Similarly, the positive point estimates of LCCP in columns (5) and (6) imply that the LCCP policy can promote more ETI in manufacturing firms. Columns (3)–(4) show that the coefficient of LCCP is significantly negative, suggesting that LCCP may inhibit the quality of green patents, leading to a "green innovation bubble". Motivated by the central

Table 1
The measurement and literature source of variable.

Variable Types	Variable Names	Variable Symbol	Variable Measurement	Literature Sources
Explained variable	Green technology innovation quantity	*GTI_qn*	Natural logarithm of the number of green invention patents granted plus one	[34]
	Green technology innovation quality	*GTI_ql*	Difference degree of IPC numbers in green patents at the large group level	[60,61]
	Embodied technology introduction	*ETI*	Cash paid for the purchase and construction of fixed assets, intangible assets, and other long-term assets/total assets	[51]
Explanatory variable	LCCP policy effect	*LCCP*	policy*post	[57]
Control Variable	Firm scale	*LnScale*	Natural logarithm of total enterprise assets	[41,58]
	Firm age	*LnAge*	Natural logarithm of the years of establishment up to sample year	[41,58]
	Firm revenue	*LnReven*	Natural logarithm of the total revenue	[41,58]
	The number of employees	*LnEmp*	Natural logarithm of the total number of employees	[41,58]
	Liquidity ratio	*Liqu*	Liquid assets/liquid liabilities	[41,58]
	Fixed assets ratio	*Fix_rate*	Fixed assets/total assets	[41,58]
	Return on assets	*ROA*	Net profit/average assets	[41,58]
	Capital structure	*Lev*	Total liabilities/total assets	[41,58]
	Cash flow ratio	*Cashflow*	Cash flow/total assets	[41,58]

Table 2
Variable description.

Variable	N	Mean	SD	Min	p50	Max
GTI_qn	9220	0.297	0.656	0	0	4.29
GTI_ql	9220	0.126	0.241	0	0	0.8
ETI	9289	0.055	0.047	0.002	0.041	0.226
LnScale	9291	21.85	1.194	19.59	21.702	25.426
LnAge	10010	2.671	0.481	0.693	2.773	3.434
LnReven	9291	21.343	1.392	18.56	21.207	25.089
LnEmp	9142	7.955	1.133	5.384	7.892	11.009
Liqu	10029	2.4	2.613	0.401	1.557	17.75
Fix_rate	10029	0.255	0.148	0.023	0.224	0.656
ROA	10029	0.048	0.064	−0.186	0.041	0.253
Lev	9291	0.422	0.202	0.048	0.421	0.897
Cashflow	9280	0.05	0.067	−0.143	0.047	0.249

Table 3
Baseline regression.

Variables	GTI_qn		GTI_ql		ETI	
	(1)	(2)	(3)	(4)	(5)	(6)
LCCP	0.0849***	0.0663***	−0.0113*	−0.0165**	0.0031**	0.0037***
	(0.0161)	(0.0176)	(0.0074)	(0.0079)	(0.0014)	(0.0014)
LnScale		0.1126***		0.0009		0.0094***
		(0.0223)		(0.0099)		(0.0017)
LnAge		−0.1089*		0.0563**		−0.0282***
		(0.0557)		(0.0246)		(0.0043)
LnReven		0.0343		0.0071		−0.0143***
		(0.0210)		(0.0093)		(0.0016)
LnEmp		0.0808***		0.0110		0.0093***
		(0.0181)		(0.0081)		(0.0014)
Liqu		−0.0007		0.0010		−0.0034***
		(0.0033)		(0.0015)		(0.0003)
Fix_rate		−0.0760		−0.0372		−0.0897***
		(0.0726)		(0.0326)		(0.0057)
ROA		0.2899**		0.0895		0.0864***
		(0.1347)		(0.0588)		(0.0103)
Lev		−0.0115		−0.0053		−0.0077
		(0.0605)		(0.0270)		(0.0047)
Cashflow		−0.0719		0.0175		0.0000
		(0.0921)		(0.0418)		(0.0073)
Firm FE	Yes	Yes	Yes	Yes	Yes	Yes
City FE	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
N	9220	8386	10029	9142	9289	9140
R2_Adj	0.6297	0.6527	0.3664	0.3680	0.4558	0.4938

Note: Standard errors in parentheses; significance level: ***P < 0.01, **P < 0.05, *P < 0.1.

government policy, the "race to the bottom" mode between local governments and enterprises mainly induces enterprises to "green-washing" and "seek subsidies" through low-quality green patents, which also aggravates the dilemma of enterprises' green innovation to a certain extent [62].

4.2. Parallel trend test

A key assumption in using the DID model is that there are no significant differences in green technology progress between the experimental group and control group before the implementation of the LCCP policy, i.e. the parallel trend assumption. Therefore, we use an event study, as in Beck et al. (2010) [63], to test whether the pre- and post-trend in green technology innovation and ETI satisfies the parallel trend assumption. The model can be expressed as equation (3):

$$GTP_{ict} = \alpha + \sum_{k=1}^{4} \beta_{-k} Pre_{ict}^{-k} + \beta_0 Current_{it} + \sum_{k=1}^{4} \beta_{+k} Post_{ict}^{+k} + \gamma \boldsymbol{X}_{ict} + \mu_i + \sigma_c + \lambda_t + \varepsilon_{ict} \tag{3}$$

Where, Pre_{ict}^{-k} represents the dummy variable of firm i in city c in year t before the implementation of the LCCP policy. It equals 1 if city c is selected as a pilot in year t and zero otherwise. Similarly, $Post_{ict}^{+k}$ equals 1 if city c becomes a pilot in year t and zero otherwise. β_{-4}-β_{-1}, the coefficients of Pre_{ict}^{+k}, signify the pre-LCCP trends in green technology innovation and ETI, and β_{+1}-β_{+4} measure the lagged effect of the LCCP policy on green technology progress. β_0 represents the current effect. If the estimates of β_{-4}-β_{-1} are insignificant and close to 0, while β_{+1}-β_{+4} are significantly different from 0, the parallel trend assumption is satisfied.

As shown in Table 4, all the estimated coefficients of β_{-4}-β_{-1} in column (1) are insignificant and close to 0, implying no significant differences between the experimental group and the control group. In contrast, β_0-β_{+4} are statistically significant and positive for *GTI_qn* and *GTI_ql*, while negative for *ETI* in most cases. Moreover, the overall increasing trends of these coefficients in absolute values indicate that the policy has profound effects on green technology innovation and ETI of manufacturing enterprises. Meanwhile, the stronger negative effect of the policy on the quantity of granted green patents suggests the larger innovation bubbles.

4.3. Placebo test

Construct a fictitious experimental group. To eliminate estimation bias caused by missing variables or other unobservable factors, following Ferrara et al. (2012) [64], we estimate equation (1) based on a random sample of manufacturing enterprises in a control group in batches, and repeat this process 500 times. As shown in Fig. 2, the coefficients of the random samples are insignificant and close to 0, implying that the LCCP policy has little effect on the green technology progress of enterprises in control groups.

We also randomly selected the year in which the cities were approved to be pilot cities. Given the short time interval between the first two batches and the limited implementation period of the third batch, we pay special attention to the second batch. The time of the LCCP policy is randomly shifted forward, taking 2010 as an example, and only examining the effect of the policy over the four years from 2008 to 2011. The estimated coefficients reported in columns (1)–(3) of Table 5 are found to be statistically insignificant.

To address the concern that the changes in green technology progress are induced by other exogenous shocks or environmental regulations instead of LCCP, we sort out the three most relevant policies implemented during the investigated period: the Carbon Emission Trading Scheme (CETS), the Air Pollution Prevention and Control Action Plan (Action Plan for short), and the Announcement on the Implementation of Special Emission Limits for Air Pollutants (Announcement for short). Specifically, for the CETS launched in 2011, the manufacturing enterprises in Beijing, Shanghai, Tianjin, Chongqing, Hubei, and other seven pilot provinces and cities are the experimental group; for the Action Plan implemented in 2013, enterprises in industries such as coal-fired power plants, steel enterprises, and other heavily polluting industries are the experimental group; for the Announcement issued at the end of 2013, enterprises in 47 key regions are the experimental group. After deleting the firms in all these experimental groups and re-running the estimation with equation (1), we obtain the results shown in column (4)–(6) of Table 5, whose coefficients are still significant, indicating that the effect of LCCP on green technology progress still holds.

4.4. Robustness checks

(1) Propensity Score Matching DID (PSM-DID). The pilot cities are selected non-randomly, as the central government prefers to select well-developed cities with green innovation capacity and sound economic foundations to explore and promote low-carbon development. Given the potential selection bias in the LCCP cities, we use the PSM-DID model to test robustness. Specifically, we treat the firm-level control variables in Table 1 as covariates and use the logit model to estimate the propensity score. We select cities in the control group based on the k-nearest neighbor method that has common characteristics with those in the experimental group. The estimated results are shown in columns (1)–(3) of Table 6. The positive effect of the LCCP policy on the quantity of green innovation and ETI still holds, as well as the negative effect on the quality of green innovation, which means that the policy does promote green technology progress and creates green innovation bubbles in the meantime.

(2) Two-stage DID. The third set of pilot cities may become the control group for the first and second sets of cities, because in a staggered DID model, different cities in the experimental group were selected as pilots in different years, leading to the negative weighting of the heterogeneous treatment effect and an estimate bias. Therefore, following Butts and Gardner (2022) [65], we re-estimate equation (1) using a two-stage DID. In the first stage, we identify the group and policy effects, and in the second stage, we identify the residuals after eliminating the group and policy effects jointly with the remaining variables. As reported in columns (4)–(6) of Table 6, the policy effect of LCCP is still statistically significant.

(3) Substituting the explained variable. If we replace the measure of *GTI_qn* with the logarithm of the total number of approved green invention patents and utility models (*Innovation*), substitute *GTI_ql* with the quality of approved patents calculated by the mean - value method (*Qua_mean*), *ETI* with the depreciation rate of fixed assets measured by the percentage of depreciation of fixed assets to net fixed assets (*Depre_rate*), and then estimate with equation (1), we obtain the results as shown in columns (7)–(9) of Table 5. In addition, we re-estimate the model without Beijing, Shanghai, Tianjin, and Chongqing because of the marked differences between municipalities and other cities. The results are shown in columns (11)–(12) of Table 6. As can be seen clearly, the point estimates of LCCP remain significant and the effects of the policy on green innovation progress still hold. By far, H1 and H2 are verified.

4.5. Heterogeneity tests

Firm scale. To investigate the heterogeneous effects of the LCCP policy on manufacturing enterprises of different scales, we include the standardized interactions of firm scale (*LnScale*) and LCCP in equation (1) for estimation. The results are presented in columns (1)–(3) of Table 7. The results of the intersection (*LCCP*LnScale*) are all statistically significant, positive in the case of *GTI_qn* and *GTI_ql*, but negative in *ETI*, suggesting that the impact of the policy on the quantity of granted green patents is stronger in large enterprises, for

Table 4
Dynamic effect of the LCCP policy.

Variables	*GTI_qn*		*GTI_ql*		*ETI*	
	Coeff.	S.E.	Coeff.	S.E.	Coeff.	S.E.
Pre4	0.0508	(0.0395)	−0.0199	(0.0166)	−0.0040	(0.0029)
Pre3	−0.0200	(0.0394)	−0.0155	(0.0143)	−0.0007	(0.0025)
Pre2	0.0082	(0.0396)	0.0031	(0.0142)	0.0019	(0.0025)
Pre1	0.0431	(0.0371)	−0.0006	(0.0146)	0.0024	(0.0026)
Current	0.0803**	(0.0350)	−0.0359**	(0.0149)	0.0054**	(0.0026)
Post1	0.0758*	(0.0426)	−0.0167	(0.0151)	0.0031	(0.0027)
Post2	0.1230***	(0.0410)	−0.0386**	(0.0178)	0.0035	(0.0031)
Post3	0.1061**	(0.0437)	−0.0217	(0.0180)	0.0067**	(0.0032)
Post4	0.1583***	(0.3589)	−0.0453***	(0.1587)	0.0057**	(0.0279)
Controls	Yes		Yes		Yes	
N	8386		9142		9140	
Firm FE	Yes		Yes		Yes	
City FE	Yes		Yes		Yes	
Year FE	Yes		Yes		Yes	
R2_Adj	0.6541		0.3694		0.4943	

Note: Standard errors in parentheses; significance level: ***P < 0.01, **P < 0.05, *P < 0.1.

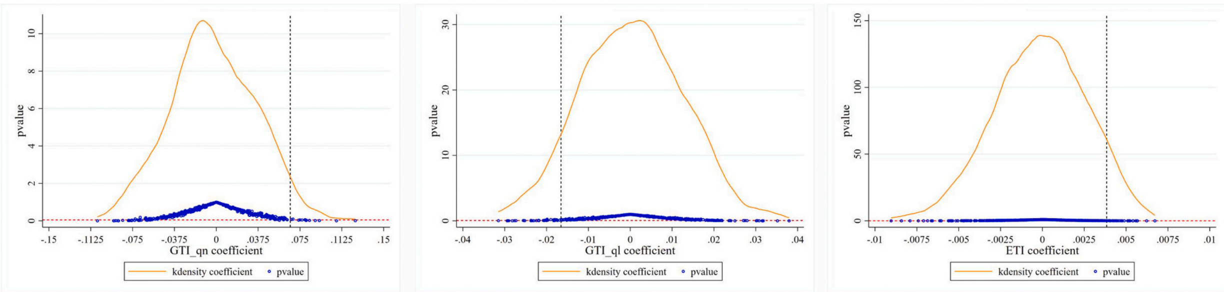

Fig. 2. Placebo tests of *GTI_qn*, *GTI_ql*, and *ETI*.

Table 5
Placebo tests with fictitious time and other environmental policies.

Variables	*Fictitious time*			*Exclude other environmental policies*		
	(1)	(2)	(3)	(4)	(5)	(6)
	GTI_qn	GTI_ql	ETI	GTI_qn	GTI_ql	ETI
*policy*2010*	*0.0014*	*0.0121*	*−0.0033*			
	(0.0324)	*(0.0211)*	*(0.0040)*			
LCCP				*0.0637****	*−0.0157**	*0.0034***
				(0.0177)	*(0.0080)*	*(0.0014)*
Controls	*Yes*	*Yes*	*Yes*	*Yes*	*Yes*	*Yes*
Firm FE	*Yes*	*Yes*	*Yes*	*Yes*	*Yes*	*Yes*
City FE	*Yes*	*Yes*	*Yes*	*Yes*	*Yes*	*Yes*
Year FE	*Yes*	*Yes*	*Yes*	*Yes*	*Yes*	*Yes*
N	*1552*	*1552*	*1552*	*8318*	*9069*	*9067*
R2_Adj	*0.7498*	*0.5241*	*0.7088*	*0.6533*	*0.3685*	*0.4802*

Note: Standard errors in parentheses; significance level: ***P < 0.01, **P < 0.05, *P < 0.1.

which the negative effects of the policy on the patent quality can be minimized, thus limiting the "green innovation bubble". Compared with small enterprises, large enterprises receive more attention, which can reduce the patent bubble to some extent [53]. Moreover, the positive effects of the introduction of advanced equipment in large enterprises are also weakened, as large enterprises are more inclined to achieve green and low-carbon transformation through independent innovation rather than the introduction of external technologies.

Carbon emission intensity. To examine the heterogeneous effects on manufacturing enterprises with different emission intensities, we divide these enterprises into two groups: high carbon intensity (*CI=1*) and low carbon intensity (*CI=0*) according to the China Emissions Trading Rights Report. Then, we include the standardized interactions of carbon emission intensity (*CI*) and LCCP in

Table 6
Robustness checks.

	PSM-DID			Two-stage DID			Substituting explained variables			Excluding municipalities		
	(1)	*(2)*	*(3)*	*(4)*	*(5)*	*(6)*	*(7)*	*(8)*	*(9)*	*(10)*	*(11)*	*(12)*
	GTI_qn	*GTI_ql*	*ETI*	*GTI*	*GTI_ql*	*ETI*	*Innovation*	*Qua_mean*	*Depre_rate*	*GTI_qn*	*GTI_ql*	*ETI*
LCCP	*0.0437**	*−0.0274***	*0.0037**	*0.0813****	*−0.0109**	*0.0164****	*0.0639****	*−0.0146**	*0.0026****	*0.0594****	*−0.0127*	*0.0028**
	(0.0262)	*(0.0125)*	*(0.0022)*	*(0.0233)*	*(0.0064)*	*(0.0046)*	*(0.0230)*	*(0.0076)*	*(0.0009)*	*(0.0195)*	*(0.0088)*	*(0.0016)*
Controls	*Yes*	*Yes*	*Yes*	*Yes*	*Yes*	*Yes*	*Yes*	*Yes*	*Yes*	*Yes*	*Yes*	*Yes*
Firm FE	*Yes*	*Yes*	*Yes*	*Yes*	*Yes*	*Yes*	*Yes*	*Yes*	*Yes*	*Yes*	*Yes*	*Yes*
City FE	*Yes*	*Yes*	*Yes*	*Yes*	*Yes*	*Yes*	*Yes*	*Yes*	*Yes*	*Yes*	*Yes*	*Yes*
Year FE	*Yes*	*Yes*	*Yes*	*Yes*	*Yes*	*Yes*	*Yes*	*Yes*	*Yes*	*Yes*	*Yes*	*Yes*
N	*4200*	*4570*	*4576*	*8386*	*9142*	*9140*	*8386*	*9142*	*9142*	*7296*	*7950*	*7948*
R2_Adj	*0.6616*	*0.4339*	*0.5446*	*0.0490*	*0.0034*	*0.0649*	*0.7116*	*0.3749*	*0.6076*	*0.6117*	*0.3674*	*0.4707*

Note: Standard errors in parentheses; significance level: ***P < 0.01, **P < 0.05, *P < 0.1.

Table 7
Heterogeneity tests.

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
	GTI_qn	*GTI_ql*	*ETI*	*GTI_qn*	*GTI_ql*	*ETI*	*GTI_qn*	*GTI_ql*	*ETI*
LCCP	2.7064***	−0.2324**	0.0687***	0.0774***	−0.0253***	0.0092***	0.0241	−0.0206**	0.0056***
	(0.2383)	(0.1075)	(0.0191)	(0.0199)	(0.0090)	(0.0016)	(0.0228)	(0.0103)	(0.0018)
*LCCP*LnScale*	0.1256***	0.0113**	−0.0029***						
	(0.0108)	(0.0049)	(0.0009)						
*LCCP*CI*				−0.0375	0.0297**	−0.0199***			
				(0.0311)	(0.0139)	(0.0025)			
*LCCP*SEO*							0.0843***	0.0079	−0.0042*
							(0.0285)	(0.0128)	(0.0023)
Controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Firm FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
City FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
N	8386	9142	9140	8318	9069	9067	8318	9069	9067
R2_Adj	0.6589	0.3684	0.4796	0.6528	0.3684	0.4842	0.6531	0.3681	0.4803

Note: Standard errors in parentheses; significance level: ***P < 0.01, **P < 0.05, *P < 0.1.

equation (1) for estimation. The results are shown in columns (4)–(6) of Table 7. The results of the intersection (*LCCP*CI*) are significant for *GTI_ql* and *ETI*, but not for *GTI_qn*, suggesting that the impact of the policy on the number of green patents does not show an obvious difference between high-carbon-intensity (HCI) and low-carbon-intensity (LCI) enterprises, while for the former the negative impact of the pilot policy on innovation quality can be offset. The possible reason for this is that high-carbon-intensity enterprises are the focus of the policy, so the regulatory measures and rules would be stricter for them [66]. This is conducive to avoiding speculative behavior such as "seeking subsidies" and "green-washing". In the case of ETI, for HCI firms, the positive influence of the policy on external technology introduction tends to be weakened due to the financing penalty effect induced by the increasingly stringent environmental regulatory measures. In contrast, LCI enterprises are more inclined to realize green transformation through technology introduction.

Enterprise ownership. To further explore the impact of the LCCP policy on state-owned and non-state-owned enterprises, we incorporate in the estimation of the standardized interactions of enterprise ownership (SOE, SOE equals 1 for state-owned, 0 for non-state-owned) and the LCCP policy for estimation. The results are reported in columns (7)–(9) of Table 7. The coefficient of the interaction term is significantly positive in *GTI_qn* while it is negative in *ETI*, and insignificant in *GTI_ql*, implying that for state-owned enterprises, the positive effect of the policy on the quantity of granted patents is proved to be strengthened, while it is weakened for technology introduction. Under the regulation of the policy, compared with SOEs, non-state enterprises are more inclined to realize green transformation through technology introduction rather than independent innovation.

5. Further analysis

5.1. Potential pathways

As mentioned above, we delve into two potential mechanisms: financing constraints and environmental concerns to reveal the mechanism by which the LCCP policy influences enterprises' green technology progress. Following Wang et al. (2023) [67], equations (4) and (5) are constructed based on equation (1) to test the influence mechanism of LCCP policy on the green technology progress of manufacturing enterprises.

$$\boldsymbol{M}\left\{\begin{array}{c} SA^1, SA^2 \\ Attention^{pub}, Attention^{gov} \\ Focus^1,\ Focus^2 \end{array}\right\}_{ict} = \alpha + \beta Lccp_{ict} + \gamma \boldsymbol{X}_{ict} + \mu_i + \sigma_c + \lambda_t + \varepsilon_{ict} \tag{4}$$

$$(GTI_{ict}, ETI_{ict}) = \beta_1 + \beta_2 Lccp_{it} + \beta_3 \boldsymbol{M}_{it} + \gamma \boldsymbol{X}_{ict} + \mu_i + \sigma_c + \lambda_t + \varepsilon_{ict} \tag{5}$$

Where, M_{ict} denotes the mechanism variables, mainly including financing constraints (SA^1 and SA^2), environmental concerns of the public ($Attention^{pub}$) and government ($Attention^{gov}$), and enterprises ($Focus^1$ and $Focus^2$). Other variables remain the same as in equation (1).

5.1.1. Financial constraint mechanism

Following Hadlock and Pierce (2010), we can figure out the SA^1 index of manufacturing enterprises.[3] The greater the SA^1, the

[3] Following Hadlock and Pierce (2010), we calculate $SA^1 = |-0.737 * LnScale + 0.043 * Ln\,Scale^2 - 0.04 * Age|$, where *LnScale* and *Age* denote the same with these in Table 1.

higher the financing constraints. The estimates are shown in Columns (1)–(4) in Table 8. The coefficient of *LCCP* in Column (1) is significantly negative at the level of 1%, indicating that the pilot policy can effectively alleviate the financing constraints of manufacturing enterprises, the coefficients of SA^1 in Column (2) and Column (4) are significantly negative at the levels of 1% and 10%, respectively, indicating that *LCCP* policy promotes the *GCI* quantity increase and the *ETI* of manufacturing enterprises by alleviating financial constraints. while Column (3) indicates that the mitigation of financing constraints has no significant impact on the *GCI* quality of manufacturing enterprises. Additionally, the commercial credit constraint (SA^2) of enterprises is also measured by the ratio of net accounts receivable to total assets. Contrarily, the higher value of SA^2 suggests a lower dependence on external financing.

The estimates are shown in Columns (5)–(8) in Table 8. The coefficient of *LCCP* in Column (1) is significantly positive at the level of 1%, indicating that the pilot policy can reduce the external financing dependence of enterprises, the coefficients of SA^2 in Column (6) and Column (8) are significantly positive at the level of 1%, indicating that *LCCP* policy promotes enterprises' green technology progress by reducing dependence on external financing, Hence, H3 holds.

5.1.2. Environmental concerns mechanism

The environmental concerns include external environmental concerns and internal environmental concerns, the former of which focus mainly on the public and the government. Specifically, the public environmental concern ($Attention^{pub}$) is evaluated by the logarithm of the average annual search times of prefecture-level cities on mobile and PC through a Baidu index search with the keywords "environmental pollution". a high value means that the public is also more concerned about the environment. The estimates are shown in Columns (1)–(4) in Table 9. The coefficient of *LCCP* in Column (1) is significantly positive at the 1% level, indicating that the pilot policy has enhanced the environmental concerns of the public, the coefficients of $Attention^{pub}$ in Column (2) and Column (4) are significantly positive at the 1% level, indicating that *LCCP* policy promotes the green technology progress of manufacturing enterprises by enhancing public environmental attention, while Column (3) indicates that public environmental attention has no significant impact on the quality of *GIT* of manufacturing enterprises.

For the measurement of government environmental concern ($Attention^{gov}$), we use the proportion of environment-related word frequency in the total word frequency in the Government Work Report. A high proportion means that the government pays more attention to the environment. The estimates are shown in Columns (5)–(8) in Table 9. The coefficient of *LCCP* in Column (5) is significantly positive at the 1% level, indicating that the pilot policy has motivated increasing environmental concerns from local government, the coefficients of $Attention^{gov}$ in Column (6) and Column (8) are significantly positive at the level of 10% and 1%, respectively, indicating that *LCCP* policy promotes enterprises' green technology progress by enhancing the government's environmental attention. H4 has been confirmed. H4 has been confirmed.

The internal environmental concern ($Focus^1$) is measured according to the proportion of the frequency of environmental awareness keywords in the total number of words in the annual reports of listed companies. Alternatively, we adopt $Focus^2$ measured according to the disclosure of environmental protection system concepts from the CSMAR database, which incorporates 8 items for each enterprise. The value of each item equals 1 when disclosed, and 0 otherwise. Sum up all 8 items and take the natural logarithm, we obtain *Focus.*[2] The regression coefficients of LCCP shown in Columns (9)–(10) in Table 9 are all positive, but not statistically significant.

5.2. Performance analysis of green technology progress

According to the systematic evidence of the LCCP policy effect, we can conclude that the policy motivates the green technology progress of manufacturing enterprises, but meanwhile, induces a significant green innovation bubble, thus weakening the positive effect of the policy. To find further evidence, we construct equation (6) to evaluate the environmental performance (Env_{Perf}), economic performance ($Econ_{Perf}$), and environmental, social, and governance performance (ESG_{Perf}) of green technology progress (*GTP*) under different paths.

$$\left(Env_{Perf\,ict}, Econ\_Perf_{ict}, ESG_{Perf\,ict}\right) = \alpha + \beta GTP_{ict} + \gamma X_{ict} + \mu_i + \sigma_c + \lambda_t + \varepsilon_{it} \tag{6}$$

Where GTP_{ict} of firm *i* in city *c* and year *t* includes the quantity (*GTI_qn*) and quality (*GTI_ql*) of *GTI* as well as *ETI*, other variables remain the same as equation (1). Following Klassen and McLaughlin (1996) [56], Env_{Perf} equals 1 when firm *i* gains environmental recognition, otherwise 0. The raw data for these variables is sourced from the CSMAR database. Similarly, as mainstream literature, we use Tobin's Q (the ratio of market value to total assets) to evaluate $Econ_{Perf}$. Following Zhang et al. (2023) [4], we evaluate firms' ESG performance using Bloomberg's ESG scores.

Table 10 shows that the estimated coefficients of *ETI* are significant and positive for all three firm performances. This is in line with the relevant literature [68]. In contrast, the coefficients of *GTI_qn* are significantly positive for $Econ_{Perf}$ and ESG_{Perf}, and those of *GTI_ql* are even negative for Env_{Perf} and ESG_{Perf}, but not always significant. These results imply that, due to the green innovation bubble caused by low-quality patents, the introduction of advanced equipment instead of green innovation proves to be an easier way to realize both environmental and economic performance.

6. Conclusions and implications

To evaluate the facilitating and distorting effects of policy intervention on different pathways toward green technology progress, this study utilizes the staggered DID model to examine the impact of the LCCP policy on both the quantity and quality of GTI and ETI, in A-share listed manufacturing enterprises. The results show that the policy increases the quantity of green-granted patents and ETI,

Table 8
Financial constraint mechanism.

Variables	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	SA^1	GTI_qn	GTI_ql	ETI	SA^2	GTI_qn	GTI_ql	ETI
LCCP	−0.0100***	0.0552***	−0.0154*	0.0040***	0.0044***	0.0651***	−0.0168**	0.0036***
	(0.0021)	(0.0177)	(0.0081)	(0.0014)	(0.0015)	(0.0177)	(0.0080)	(0.0014)
SA^1		−1.1269***	0.0585	−0.0141*				
		(0.0956)	(0.0422)	(0.0074)				
SA^2						0.4975***	−0.0101	0.0596***
						(0.1332)	(0.0583)	(0.0102)
Controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Firm FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
City FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
N	8984	8236	8984	8982	9048	8302	9048	9046
R2_Adj	0.9830	0.6608	0.3685	0.4926	0.8455	0.6529	0.3679	0.4970

Note: Standard errors in parentheses; significance level: ***$P < 0.01$, **$P < 0.05$, *$P < 0.1$.

while decreasing the patent quality, thus creating a “green innovation bubble”. These conclusions remain valid after a series of rigorous robustness tests. Furthermore, large enterprises, SOEs, and HCI enterprises are more likely to engage in GTI instead of ETI; however, small enterprises, non-SOEs, and LCI enterprises are more inclined to achieve a transition to green and low-carbon practices through ETI. The mechanism analysis shows that the LCCP policy facilitates the GTI and ETI in manufacturing enterprises mainly by easing financing constraints, reducing reliance on external funding sources, and increasing public and governmental environmental awareness. Consistent with existing literature, growing GTI and ETI contribute to enhancing both the economic and ESG performance. ETI also facilitates the improvement of environmental performance.

Accordingly, we can draw important lessons from these findings to optimize the LCCP policy. Most importantly, a policy-compatible evaluation system for green technology progress, in particular the quality of granted green patents, needs to be established. Government incentives for green and low-carbon technologies are still largely based on the quantity of patents, as there are no reasonable and effective methods for evaluating the quality of green patents, leading to speculation and the "green innovation bubble". Insignificant and uncertain benefits from high-quality patents would further discourage manufacturing enterprises from innovating on their own. Therefore, the involvement of a third party can help set up a scientific, reasonable, and operational evaluation system. Moreover, it is also worth noting the insignificant effect of the policy on the internal environmental focus, which is largely attributed to the “weak constraint and weak incentive” nature of the policy, as it did not impose sufficient binding constraints to enforce compliance. Therefore, the pilot cities could make full use of environmental regulations and local preferential policies to strengthen mandatory and incentive measures to enhance the management focus and concern for environmental protection.

Given the different route preferences of different enterprises, the way to achieve green technology progress is to cultivate the green innovation ecosystem in which large, state-owned, and HCI enterprises take the lead and small, non-state-owned, and LCI enterprises follow. In doing so, innovation policy support for the LCCP policy must focus on encouraging large, state-owned, and HCI enterprises to enter into key areas such as energy conservation and consumption reduction, carbon capture, utilization and storage, coordinated carbon reduction, and so on. At the same time, these small, non-state-owned, and LCI enterprises should be given access to low-carbon subsidies and loans to introduce and adopt advanced energy-saving equipment, thus accelerating the dissemination and application of green and low-carbon technologies.

To increase the awareness and concern for green and low-carbon production is to achieve higher environmental performance. In particular, more attention should be paid to improving the internal environmental awareness of enterprises. By integrating the innovation and introduction of green technologies, the internal unity of economic and environmental performance would be jointly promoted. In the process of further implementing the pilot policy, the green innovation performance and environmental performance of enterprises should be simultaneously included in the evaluation of these pilot cities. In this way, the awareness and concern of enterprises for green development in terms of energy conservation, emission reduction, and cleaner production would be continuously improved.

Our investigation of the effects of the LCCP policy also has some limitations: first, our calculation of the ETI takes into account the conditions for capital updating at the firm level. It would be useful for future studies to further investigate ETI from industry and regional dimensions to more accurately capture the greening effect of technology adoption. Second, our study only examines the impact of the LCCP policy on manufacturing firms, specifically on green technology progress. However, the implementation of the policy requires the coordination of all environmental regulations [69]. Thus, the cooperative effects of policy on the pathways of green technology progress need to be further investigated. Third, our study mainly considers the direct effects of the policy rather than the chain effects on both upstream and downstream enterprises along the pollution control industry chain, which in turn motivates more enterprises to participate in green technology innovation activities. This also needs to be investigated in further study.

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Table 9
Environmental concerns mechanism.

Variables	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
	Attention^{pub}	GTI_qn	GTI_ql	ETI	Attention^{gov}	GTI_qn	GTI_ql	ETI	Focus^{1}	Focus^{2}
LCCP	0.1122***	0.1015***	0.0020	0.0036*	0.0301***	0.0629***	−0.0122	0.0027*	0.0015	0.0034
	(0.0143)	(0.0215)	(0.0129)	(0.0020)	(0.0066)	(0.0194)	(0.0086)	(0.0015)	(0.0045)	(0.0202)
$Attention^{pub}$		0.0693***	−0.0051	0.0103***						
		(0.0122)	(0.0134)	(0.0028)						
$Attention^{gov}$						0.0609*	−0.0046	0.0035***		
						(0.0354)	(0.0154)	(0.0003)		
Controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Firm FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
City FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
N	5053	4495	5053	5051	7801	7156	7801	7799	7764	7240
R2_Adj	0.9469	0.6925	0.4145	0.5610	0.4428	0.6623	0.3752	0.4940	0.5667	0.6981

Note: Standard errors in parentheses; significance level: ***P < 0.01, **P < 0.05, *P < 0.1.

Table 10
Performance analysis.

Variables	(1)	(2)	(3)	(4)	(5)	(6)
	Env_{Perf}		$Econ_{Perf}$		ESG_{Perf}	
GTI_qn	0.0024	0.0015	0.0408	0.1020**	0.0785***	0.0452**
	(0.0087)	(0.0089)	(0.0473)	(0.0466)	(0.0216)	(0.0214)
GTI_ql	−0.0056	−0.0129	0.0115	0.0639	0.0164	−0.0051
	(0.0179)	(0.0181)	(0.0983)	(0.0958)	(0.0446)	(0.0438)
ETI	0.2304**	0.1963*	1.5252***	1.3989***	1.3647***	1.1710***
	(0.1108)	(0.1133)	(0.5438)	(0.5427)	(0.2668)	(0.2650)
Controls		Yes		Yes		Yes
Firm FE	Yes	Yes	Yes	Yes	Yes	Yes
City FE	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
N	6562	6482	8232	8109	7336	7333
R2_Adj	0.4816	0.4833	0.6619	0.6883	0.5044	0.5235

Note: Standard errors in parentheses; significance level: ***P < 0.01, **P < 0.05, *P < 0.1.

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Additional information

No additional information is available for this paper.

Data availability statement

The datasets used in this study are available from the corresponding author upon reasonable request.

CRediT authorship contribution statement

Yanfang Wang: Writing – review & editing, Writing – original draft, Project administration, Methodology, Data curation, Conceptualization. **Jingmin Yao:** Writing – review & editing, Writing – original draft, Validation, Supervision, Software, Conceptualization.

Declaration of competing interest

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

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