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The definitive publisher version is available online at [10.1016/j.eap.2024.06.014](https://doi.org/10.1016/j.eap.2024.06.014)

Low-Carbon City Pilot Policy and Enterprise Low-Carbon Innovation

– A Quasi-Natural Experiment from China

Abstract

This study investigates whether the implementation of this policy fosters low-carbon innovation among enterprises and identifies the mechanisms underpinning its effects. Utilising low-carbon patent authorisation data from A-share listed companies in the Shanghai and Shenzhen stock markets between 2008 and 2019, this study employs a difference-in-differences model to conduct a multi-dimensional empirical examination of these questions. The findings indicate that the low-carbon city pilot policy can stimulate low-carbon innovation at the enterprise level to a certain extent, and this conclusion remains robust after a series of rigorous tests. The impact of low-carbon innovation is more pronounced in the authorisation of invention patents, with the pilot policy exerting a more significant influence on state-owned enterprises and enterprises with strong political affiliations. Further analysis reveals that government subsidies constitute the primary mechanism through which the pilot policy takes effect, effectively promoting low-carbon innovation in enterprises. This paper offers theoretical and empirical support for evaluating the low-carbon city pilot policy at the enterprise level and advances policy implications in three areas: further policy development, enterprise characteristics, and the application of various policy instruments.

Keywords: Low-carbon city pilot policy; Low-carbon innovation; Difference-in-differences

1. Introduction

Over the past four decades, China's rapid economic growth has significantly increased fossil fuel consumption and associated carbon emissions (Stern and Xie, 2022; Xu et al., 2022). Urban areas, as centres of population, industrial activities, and infrastructure development, have been major contributors to this trend. As the challenges posed by climate change intensify, addressing anthropogenic greenhouse gas emissions has become a pressing concern for stakeholders worldwide. Consequently, transforming urban centres into sustainable, low-carbon cities has become a strategic priority for China, particularly in light of its international carbon commitments (Li et al., 2022; Liu and Xu, 2022; Yang et al., 2023). Within this context, enterprises assume a dual role as significant carbon emitters and potential innovators in low-carbon research and development.

Existing literature on low-carbon technological innovation often employs the 'double externality' framework (Xie et al., 2022), which emphasises the complex interplay between achieving economic and environmental objectives simultaneously. The Porter hypothesis has been a foundational concept in examining the influence of environmental policies on low-carbon innovation (Porter & Linde, 1995; Zhao et al., 2022; Yu et al., 2023). However, research gaps persist, particularly in the development of robust metrics that go beyond R&D expenditures and comprehensively capture innovation outcomes. Despite the increasing use of detailed patent data in scholarly studies (Calel & Dechezleprêtre, 2016), the academic literature presents a range of conclusions, with some studies highlighting the positive impact of environmental policies (Berrone, 2013; Bergek and Berggren, 2014) and others indicating potential limitations (Zhao & Sun, 2016).

Furthermore, the depth of academic investigation into low-carbon city pilot policies remains relatively limited. Conventional evaluation criteria, such as energy consumption and carbon intensity, provide a narrow perspective on the subject. While these metrics are crucial, they do not fully capture the catalytic role of pilot policies in promoting urban low-carbon development, especially from an innovation perspective (Cheng et al., 2015; Gehrsitz, 2017). The relationship between policy implementation and innovation, particularly at the enterprise level, warrants more comprehensive exploration.

This paper aims to address these research gaps and contribute to the academic discourse in several ways. First, our study departs from traditional macro-level approaches and adopts a micro-level enterprise perspective, employing a multi-period difference-in-differences (DID) methodology. This nuanced approach allows for a quantitative analysis of the impact of low-carbon city pilot policies on enterprise-driven low-carbon innovation.

Moreover, drawing upon the seminal Porter hypothesis, our research delves into the mechanisms through which low-carbon pilot policies, as crucial environmental regulations, shape the trajectory of enterprise low-carbon innovation. This investigation sheds light on the intricacies of these dynamics and expands the academic discussion on the factors influencing enterprise low-carbon innovation (Porter & Linde, 1995).

In addition to these contributions, our study offers a granular analysis by distinguishing between different forms of enterprise ownership and examining the role of political affiliations. This examination is essential for understanding the heterogeneous effects of low-carbon pilot policies. Finally, by presenting a rigorous quantitative evaluation of these pilot policies, we

aim to provide actionable insights for policymakers. These recommendations can inform the refinement of policy mechanisms and drive the momentum for future low-carbon urban development.

By situating our research at the intersection of policy, innovation, and enterprise dynamics, we endeavour to bridge existing research gaps and contribute to the current knowledge base. We offer a comprehensive perspective on low-carbon city development and its implications.

Our paper continues as follows. Section 2 reviews the literature and develops the hypothesis, Section 3 describes our research design, Section 4 presents our empirical findings, Section 5 provides further analysis, and Section 6 concludes.

2. Background and hypotheses development

2.1 Background

The increasing concentration of greenhouse gases in the atmosphere, primarily attributed to anthropogenic activities, has led to global warming and its associated risks, including economic disruption, health impacts, food and water insecurity, more frequent and intense extreme weather events, and sea-level rise. Over the past four decades, China has experienced rapid economic development, accompanied by a significant increase in fossil fuel consumption and carbon emissions. This has resulted in severe environmental degradation and mounting pressure on the sustainability of ecosystems and the economy. In response to these challenges, the Chinese government has introduced a series of environmental regulatory measures to reduce greenhouse gas emissions.

As centres of population, industry, transportation, and infrastructure, cities account for over 80% of China's energy consumption and carbon emissions, making them critical focal points for mitigating climate change. As urbanisation and industrialisation continue to accelerate, the issues of energy consumption and carbon emissions in Chinese cities have become increasingly pressing.

China has 337 cities, comprising 293 prefecture-level cities, four municipalities, and 30 autonomous prefectures. To ensure that China meets its greenhouse gas emission reduction targets for 2030 under the Paris Agreement, the National Development and Reform Commission (NDRC) has implemented a series of low-carbon pilot programs. The first batch of low-carbon pilot projects was launched on July 19, 2010, covering five provinces and eight cities. The second batch, initiated on November 26, 2012, included three provinces and municipalities and 26 prefecture-level cities. The third batch, announced on January 7, 2017, added 45 cities, districts, and counties to the program (see Figure 1, Figure 2, and Table 1 for details on the pilot cities and the timeline of policy implementation). By 2022, China had designated six low-carbon pilot provinces and regions, four municipalities, and 142 low-carbon pilot cities, representing approximately 42.14% of all cities in the country. With the exception of Tibet and Qinghai, at least one low-carbon pilot city has been established in every province, municipality, and autonomous region in mainland China.

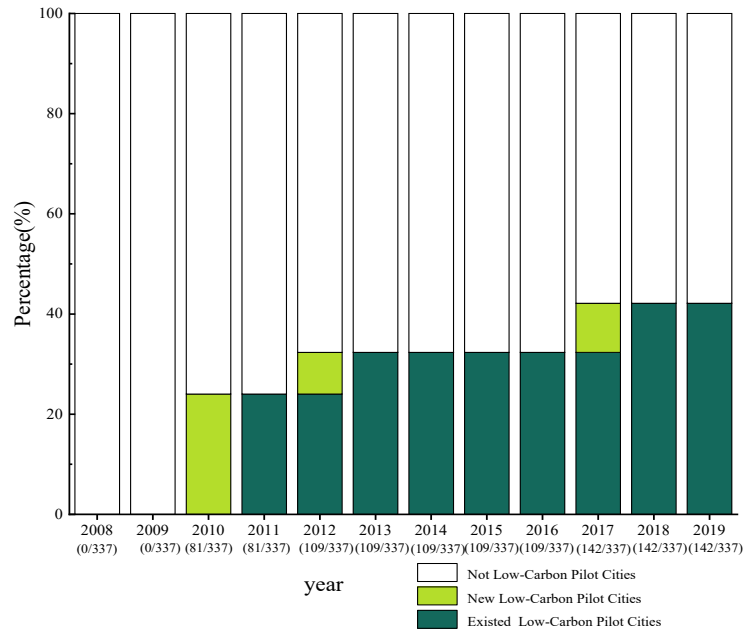


Fig. 1. Annual changes in the number of low-carbon pilot cities

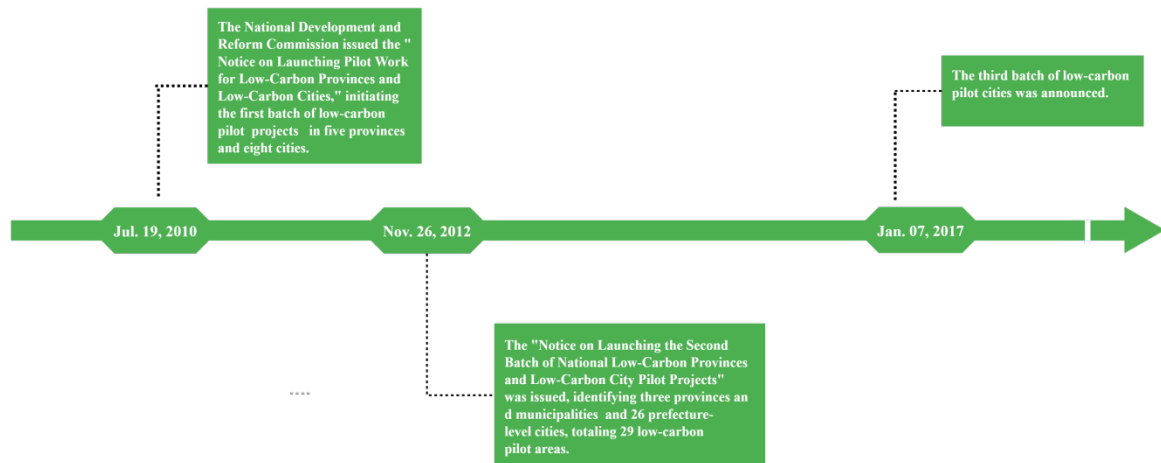


Fig. 2. : Timeline of policy implementation

Table 1: List of Low-Carbon Pilot Cities

First Batch of Pilot Provinces and Cities	Guangdong, Hubei, Liaoning, Shaanxi, Yunnan, Tianjin, Chongqing, Shenzhen, Xiamen, Hangzhou, Nanchang, Guiyang, and Baoding
Second Batch of Pilot Provinces and Cities	Beijing, Shanghai, Hainan, Shijiazhuang, Qinhuangdao, Jincheng, Hulunbuir, Jilin, Daxing'anling, Suzhou, Huaian, Zhenjiang, Ningbo, Wenzhou, Chizhou, Nanping, Jingdezhen, Ganzhou, Qingdao, Jiyan, Wuhan, Guangzhou, Guilin, Guangyuan, Zunyi, Kunming, Yan'an, Jinchang, and Urumqi
Third Batch of Pilot Provinces and Cities	Wuhai, Shenyang, Dalian, Chaoyang, Xunke, Nanjing, Changzhou, Jiaxing, Jinhua, Quzhou, Hefei, Huaibei, Huangshan, Lu'an, Xuancheng, Sanming, Gongqingcheng, Ji'an, Fuzhou, Jinan, Yantai, Weifang, Changyang Tujia Autonomous County, Changsha, Zhuzhou, Xiangtan, Chenzhou, Zhongshan, Liuzhou, Sanya, Qiongzong Li and Miao Autonomous County, Chengdu, Yuxi, Simao District of Pu'er City, Lhasa, Ankang,

	Lanzhou, Dunhuang, Xining, Yinchuan, Wuzhong, Changji, Yining, Hetian, and the First Division Alsaer
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Developing low-carbon cities is crucial for China to reverse its carbon emission growth trend and fulfil its low-carbon commitments under international agreements. The low-carbon pilot projects have been comprehensively implemented across the country, focusing on various aspects of urban development, such as industrial structure adjustment, energy structure optimisation, low-carbon transportation, low-carbon buildings, and low-carbon lifestyles. These efforts include reducing carbon dioxide emissions in the production sector by restructuring industries and promoting the development of emerging low-carbon industries through formal and informal environmental regulatory systems and incentive policies, such as carbon emission trading schemes.

While the low-carbon pilot policies have achieved significant results in reducing carbon emissions, the NDRC requires pilot areas to further clarify low-carbon development principles, accelerate research and development of low-carbon technologies, establish low-carbon industrial systems, implement greenhouse gas emission target responsibility systems, foster green and low-carbon lifestyles and consumption patterns, encourage low-carbon innovation, optimise urban industrial structures, and promote clean energy consumption. Ultimately, the goal is to achieve high-quality economic development in cities while reducing their carbon footprint.

Low-carbon city pilot policies serve as urban-level environmental regulations designed to help China achieve its climate action goals. These regulations are characterised by weak constraints, industry-specific targeting, and policy combinations. The effectiveness of such weak constraint environmental policies in inducing low-carbon innovation in enterprises remains to be examined. Low-carbon city pilot policies aim to reduce energy consumption and emissions during production processes, improve energy efficiency, and promote low-carbon industrial transformation (Zhu and Lee, 2022; Hou et al., 2022). In this context, enterprises play a critical role as primary innovation participants, and the development of low-carbon innovation technologies through scientific research and innovation is vital for the successful implementation of related policies.

2.2 Hypotheses development

The "Porter Hypothesis" suggests that environmental regulations affect enterprises' production decisions in two ways. On the one hand, environmental regulations generate compliance cost effects, increasing enterprises' emission reduction and pollution control costs. This may lead to reduced research and development (R&D) investment in the short term or redirect investments to other types (Jaffe & Stavins, 1995). On the other hand, well-designed environmental policies can generate innovation compensation effects, as stringent environmental regulations provide significant economic incentives for enterprises (Porter & Linde, 1995). Under appropriate regulatory pressure, enterprises are motivated to engage in technological innovation, enhancing energy efficiency and reducing pollution emissions in the production process to meet required

emission levels, ultimately achieving both environmental and economic benefits. Based on this theoretical foundation, the following hypotheses are proposed:

Hypothesis 1a: The implementation of low-carbon city pilot policies may promote green technological innovation in enterprises.

Hypothesis 1b: The implementation of low-carbon city pilot policies may inhibit green technological innovation in enterprises.

The Resource-Based View (RBV) suggests that policies have heterogeneous effects when applied to different entities. In emerging economies, enterprise ownership is considered a crucial institutional factor, as companies with diverse ownership structures may exhibit substantial differences in cognitive logic, institutional logic, and resource endowments, potentially leading to varied policy responses. Due to the unique position of state-owned enterprises (SOEs) within China's economic system, SOEs face greater political constraints and are major contributors to local economies and tax revenues. The government tends to provide policy support and financial subsidies to SOEs, incorporating public service objectives into their business operations.

As a result, SOEs pursue profit maximisation like other enterprises while also undertaking numerous political and social functions assigned by the government. They are responsible for fulfilling social obligations, participating in environmental management, and achieving regulatory requirements. Moreover, SOEs are subject to heightened public scrutiny, necessitating the maintenance of a positive corporate image. The government and various social sectors exert intangible pressure on SOEs regarding environmental protection (Kumar, 2006). In contrast, non-SOEs primarily focus on maximising shareholder value, concentrating more on profit generation and potentially neglecting environmental management concerns.

As central and local governments promote development concepts such as 'green innovation' and 'carbon peaking, carbon neutrality', SOEs are more likely to become the primary platform for implementing economic development strategies and promoting economic structural transformation and upgrading than non-SOEs. Consequently, under the impetus of low-carbon city pilot policies, SOEs possess greater capacity, pressure, and motivation to engage in low-carbon innovation and upgrading. Based on this reasoning, the following hypothesis is proposed:

Hypothesis 2: The promotional effect of low-carbon city pilot policies on low-carbon innovation is more pronounced for state-owned enterprises.

Political connections are considered valuable and scarce resources, functioning as informal institutional arrangements influencing resource allocation (Faccio, 2006). Enterprises invest time and money in cultivating relationships with government officials, including businesspeople participating in politics (e.g., enterprise controllers serving as representatives of people's congresses and members of political consultative committees) and officials entering the private sector (e.g., enterprises hiring government officials or government officials starting their own businesses). These connections provide enterprises with advantages in understanding government policy trends, obtaining tax incentives and government subsidies, and improving resource allocation, ultimately bringing significant benefits to their development.

Governments implementing low-carbon city pilot policies support enterprises' low-carbon efforts and adopt a series of incentive policies. Political connections help enterprises secure more government-supported resources and enable them to access government innovation industry policies and strategic innovation initiatives earlier, enhancing their competitive position in the market. Politically connected enterprises are more likely to collaborate with universities and research institutions, promote the accumulation of internal research resources, and possess robust R&D institutions and industry-university-research platforms. This is conducive to transforming innovation resources and significantly promoting the conversion of authorised patents.

Furthermore, politically connected enterprises are more likely to gain financing approval from domestic banks, thus obtaining more credit preferences. The strategic decisions of politically connected enterprises are often constrained by government officials' preferences. Generally, politically connected enterprises bear heavy policy burdens in addition to achieving their own objectives. Based on this logic, the following hypothesis is proposed:

Hypothesis 3: The promotional effect of low-carbon city pilot policies on low-carbon innovation is more pronounced for politically connected enterprises.

3. Research Design

3.1 Modelling design

This study utilises the low-carbon pilot policy as a quasi-natural experiment and employs a difference-in-difference (DID) model to investigate the policy impact on firms' low-carbon innovation. The DID method has been extensively used to evaluate economic policies; however, its effectiveness is contingent upon meeting the parallel trends assumption. In this study, the selection of pilot cities initially relies on self-declaration from various regions. Pilot cities may inherently emphasise low-carbon innovation in firms, causing the treatment and control groups to exhibit dissimilar initial characteristics.

To examine the impact of the low-carbon pilot policy on firms' low-carbon transformation and upgrading, this study adopts a multi-time point DID model, as shown in Equation (1), to test the policy's effect on low-carbon transformation in both pilot and non-pilot cities:

$$Innovation_{it} = \alpha + \beta Policy_{it} + \gamma Control_{it} + \lambda_i + \mu_t + \varepsilon_{it} \quad (1)$$

In this equation, $Innovation_{it}$ represents the low-carbon innovation situation of firm i in year t . For firms located in low-carbon pilot cities, $Policy_{it}$ denotes whether the city where firm i is situated is included in the list of low-carbon pilot cities in year t . The coefficient β is the primary focus of this study, measuring the policy's treatment effect. A significantly positive β indicates that low-carbon pilot cities can promote firms' low-carbon innovation, whereas a negative sign suggests a suppressive effect. $Control_{it}$ encompasses a series of control variables at both firm and city levels, with the selection of control variables consistent with the baseline regression. λ_i and μ_t represent the fixed effects of firms and years, respectively, while ε_{it} serves as the random error term, adhering to an independent and identically distributed assumption.

3.2 Data Selection

Considering the availability, accuracy, and relative completeness of listed company data, we conduct an empirical analysis using Chinese A-share listed companies from 2008 to 2019 as our sample. We manually collected city and annual data on pilot low-carbon policies. At the firm level, patent data are obtained from the WinGo financial text data platform, while other data are sourced from the CNRDS database. At the city level, data are derived from the China City Statistical Yearbook. In the process of sample selection, to ensure the validity and rationality of the research sample, the original data are processed in the following steps: (1) firms in the ST and PT categories are excluded; (2) financial industry companies are removed; (3) observations with missing dependent variables, independent variables, control variables, and industry classifications are eliminated. All continuous variables undergo 1% Winsorize treatment at both ends. Ultimately, we obtain 15,134 sample observations.

3.3 Variable Definition

3.3.1 Independent Variable: Low Carbon Pilot City Policy Variable

Our analysis of the low-carbon pilot policy covers three batches of low-carbon pilot provinces and cities. Given this, the specific pilot work is primarily promoted in urban areas. Accordingly, we divide the low-carbon pilot provinces into prefecture-level cities and examine overlapping areas between batches. For instance, Shenyang, Zhongshan, and other cities are included in the third batch of pilot cities, but their provinces are incorporated in the first batch of pilot provinces. Thus, these cities are considered part of the first batch rather than the third batch. The first batch of low-carbon pilot cities was launched on July 19, 2010, the second batch began on November 26, 2012, and the third batch started at the end of February 2017. Taking into account the time lag of low-carbon pilot city policy implementation, this study sets the implementation time points for the three batches of low-carbon pilot city policies as 2010, 2013, and 2017, respectively.

3.3.2 Dependent Variable

Corporate Low-Carbon Innovation: The United Nations Framework Convention on Climate Change (UNFCCC) has developed a list of Environmentally Sound Technologies (ESTs), and the IPC Expert Committee has established the IPC Green Patent Database, creating a correspondence between green low-carbon technologies and the IPC. This study refers to the International Patent Classification (IPC) Green List published by WIPO GREEN, which divides green low-carbon technologies into seven categories: alternative energy production, transportation, energy conservation, waste treatment, agriculture and forestry, administrative management and design, and nuclear energy. We manually organise the IPC codes for green low-carbon technologies and analyse and retrieve the basic patent information downloaded from the WinGo platform, obtaining panel data on corporate low-carbon innovation. Since the number of granted patents better reflects a company's current innovation capabilities, we calculate the number of granted low-carbon innovation patents (Grant) to measure corporate low-carbon innovation. To further reflect the varying levels of innovation and value of low-carbon patents, we differentiate low-carbon invention patents (Igrant) and low-carbon utility model patents (Igrant1). Generally, the former is considered to have higher innovation than the latter. Considering the temporal nature of granted low-carbon innovation patents, we also use lagged corporate low-carbon patent grant data for measurement.

3.3.3 Control Variables

A series of indicators are selected as control variables at both the corporate and city levels. First, basic corporate characteristics include: ROA and LEV, which represent a company's return on net assets and the asset-liability ratio, respectively. AGE represents the company's age; according to the life cycle theory, the level of innovation may vary at different stages of development. SIZE indicates the company's size, and it is generally believed that larger companies have a higher success rate in innovation. Secondly, corporate governance characteristics include: property rights (SOE), the proportion of shares held by the largest shareholder (Top1), and board independence (Indep). Thirdly, city-level control variables include: labour force size (PRA), represented by the number of employees; fiscal expenditure scale (FEXP), represented by local fiscal budget expenditures. Additionally, all the aforementioned variables are logarithmically transformed in this study.

Table 2: Variable Definition

Variable	Definition
Grant	The sum of low-carbon invention patents and utility model patent grants, plus 1, then taking the natural logarithm.
Igrant	Low-carbon invention patents plus 1, then taking the natural logarithm.
Igrantl	Utility model patents plus 1, then taking the natural logarithm.
Policy	Whether the company's city is listed as a low-carbon city pilot in the given year; if yes, then 1 for all subsequent years. Otherwise, 0.
Top1	The ratio of the largest shareholder's holdings to the total share capital.
SOE	Whether the ultimate controller is a state-owned holding company; if yes, then 1, otherwise 0.
Indep	The number of independent directors is divided by the total number of board members.
Size	The natural logarithm of total assets at the end of the year.
Lev	Total liabilities are divided by total assets at the end of the year.
ROA	Net profit is divided by total assets.
AGE	The natural logarithm of the company's age since its establishment.
CFO	Operating net cash flow is divided by total assets.
PRA	The natural logarithm of the number of employees (in tens of thousands) in the company's city.
FEXP	The natural logarithm of local fiscal budget expenditures in the company's city.

4. Results

4.1 Descriptive Statistics

The descriptive statistics of the main variables are shown in Table 3. As seen from Table 3, during the sample period, the low-carbon patent grants of Chinese listed companies are slightly right-skewed, indicating that fewer companies are obtaining low-carbon patent grants, and a small number of companies provide the majority of low-carbon patents. Moreover, the right-skewness of the data distribution for low-carbon invention patent grants and utility model patent grants is even greater, suggesting that only a few companies are able to gain approval for invention patents and utility model patents with higher value in terms of low-carbon technology improvements and research and development.

Table 3: Descriptive Statistics

Variable	N	Mean	SD	Min	p25	p50	p75	Max
Grant	15134	0.338	0.672	0	0	0	0.693	3.045
Igrant	15134	0.150	0.424	0	0	0	0	2.197
Igrantl	15134	0.237	0.550	0	0	0	0	2.565

Policy	15134	0.578	0.494	0	0	1	1	1
Indep	15134	0.385	0.106	0	0.333	0.375	0.444	0.667
SOE	15134	0.300	0.458	0	0	0	1	1
Top1	15134	0.350	0.146	0.0850	0.235	0.333	0.450	0.742
Size	15134	22.09	1.466	16.70	21.11	21.81	22.71	31.04
Lev	15134	0.394	0.202	0.0480	0.232	0.381	0.536	0.922
ROA	15134	0.0470	0.0520	-0.165	0.0180	0.0440	0.0740	0.196
CFO	15134	0.0500	0.0640	-0.132	0.0110	0.0480	0.0880	0.228
AGE	15134	2.772	0.333	1.792	2.565	2.773	2.996	3.497
FEXP	15134	16.08	1.157	13.71	15.22	15.93	16.89	18.22
PRA	15134	5.052	1.043	2.763	4.320	4.981	5.928	6.710

4.2 Regression Results

This study employs a triple difference-in-differences (DID) approach to evaluate the impact of low-carbon pilot policies on corporate low-carbon technology innovation, with the estimation results presented in Table 4. Columns (4), (5), and (6) add control variables based on columns (1), (2), and (3), respectively. The results show that, first, regardless of whether control variables are included, the regression coefficients of low-carbon pilot policies in columns (1) and (4) are significant at the 5% level, indicating that the pilot policy of low-carbon cities effectively promotes the innovation of enterprises in low-carbon technology. Second, in terms of patent heterogeneity, after including control variables, the regression coefficient of low-carbon pilot policies in column (5) is 0.0382 and significant at the 1% level, while the regression coefficient of low-carbon pilot policies in column (6) is not significant. This suggests that low-carbon pilot policies have a more pronounced promoting effect on invention patents with higher innovativeness. The conclusions of this study are consistent with the views of scholars such as Berrone (2013) and Bergek & Berggren (2014), confirming the Porter hypothesis based on China's low-carbon pilot policies.

Table 4: Regression Results

	(1) Grant	(2) Igrant	(3) Igrant1	(4) Grant	(5) Igrant	(6) Igrant1
Policy	0.0379** (2.2256)	0.0397*** (3.2083)	0.0035 (0.2403)	0.0356** (2.1060)	0.0382*** (3.0988)	0.0025 (0.1688)
Indep				0.0608 (1.3546)	0.0353 (1.0802)	0.0384 (0.9689)
SOE				-0.0117 (-0.2661)	-0.0403 (-1.1325)	0.0312 (0.8376)
Top1				0.0208 (0.2320)	0.1153* (1.8175)	-0.0604 (-0.7783)
Size				0.1297*** (9.2160)	0.0661*** (6.7200)	0.0901*** (7.3606)
Lev				-0.0508 (-1.0478)	-0.0596* (-1.7256)	-0.0204 (-0.4871)
ROA				-0.2320** (-2.1511)	-0.1597** (-2.0733)	-0.1079 (-1.1540)
AGE				0.1718* (1.8101)	0.0676 (0.9574)	0.1714** (2.1430)
CFO				-0.0449 (-0.5523)	-0.0392 (-0.6898)	-0.0431 (-0.6187)
FEXP				-0.0036 (-0.0828)	0.0041 (0.1291)	-0.0076 (-0.2049)
PRA				-0.0012	0.0237	-0.0181

_cons	0.3157*** (30.2525)	0.1272*** (16.8503)	0.2348*** (26.1673)	(-0.0423) -2.9546*** (-3.8017)	(1.2547) -1.7140*** (-3.0310)	(-0.7475) -2.0035*** (-2.9963)
Control Variables	N	N	N	Y	Y	Y
Firm effects	Y	Y	Y	Y	Y	Y
Year effects	Y	Y	Y	Y	Y	Y
N	15134	15134	15134	15134	15134	15134
adj. R^2	0.591	0.474	0.528	0.601	0.474	0.539

Note: In the regression, all control variables, independent variables, and dependent variables are current period data. ***, **, and * represent significance at the 1%, 5%, and 10% levels, respectively.

4.3 Robustness Tests

4.3.1 Parallel Trend Test

In the aforementioned empirical analysis, we preliminarily evaluated the promoting effect of the low-carbon city pilot policy on corporate low-carbon innovation. The parallel trend assumption implies that before the implementation of the low-carbon pilot policy, the time trends of low-carbon patent authorisations in pilot and non-pilot cities are as consistent as possible. Given that satisfying the parallel trend assumption is an important prerequisite for using multi-period DID, we followed the practice of Zhu and Lee (2022) and constructed our model as:

$$Innovation_{it} = \alpha_0 + \sum_{k=5}^5 \beta_k \times Z_{rt} + \alpha_1 \sum Control_{it} + \lambda_i + \mu_t + \varepsilon_{it} \quad (2)$$

Where t_0 represents the time after the introduction of the low-carbon pilot policy, k represents the k year after the policy's introduction, and Z_{rt} represents the k year after city r is included in the scope of the low-carbon city pilot scope (the value of k ranges from $[-5, 5]$, including 5 years before and after the policy's introduction. If the time exceeds 9 years, it is still set as 5 years in the model). Meanwhile, the estimated coefficient β_k reflects the difference in the number of low-carbon patent applications between the treatment and control groups after k years of pilot policy implementation. Figure 3 reports the results of the parallel trend test, with the first period after the pilot policy as the base period (Year of adoption), where Pre5—Pre1 represents 5 to 1 years before policy implementation, and Post1—Post5 represents 1 to 5 years after policy implementation. It can be observed that the coefficient estimates in each period before the implementation of the low-carbon city pilot policy are not statistically significant, indicating that the research sample passes the parallel trend test. Moreover, after the implementation of the policy, the coefficient values are all positive, maintaining positivity and significance, and the overall trend continues to rise, suggesting that the low-carbon city pilot policy has a significant positive effect on low-carbon innovation of enterprises.

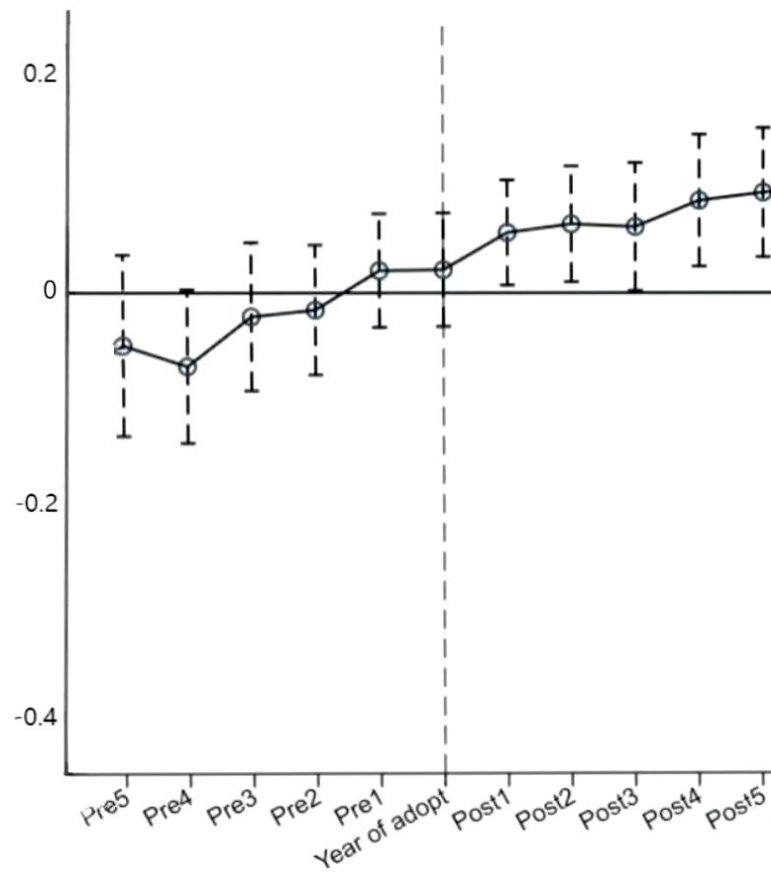


Fig. 3. Results of Parallel Trend Test

4.3.2 Placebo Test

To further verify that the low-carbon innovation of enterprises is affected by the pilot policy rather than other unobservable factors, we identify the randomness of the demonstration city pilot policy effects in this study. Following the distribution of the policy variable (Policy) in the baseline regression, we employ a placebo test with 500 random samples to construct a "pseudo-policy dummy variable" and re-estimate using Model (1) to test the coefficients and P-value distribution. Figure 3 shows the distribution of the estimated coefficients and P-values of the "pseudo-policy dummy variable." The mean value of the estimated coefficients is close to 0 and far smaller than the baseline regression coefficient. Moreover, the distribution of the estimated coefficients is relatively close to a normal distribution, with most P-values greater than 0.10, not significant at the 10% level. This indicates that the conclusion that the low-carbon city pilot policy promotes enterprise low-carbon innovation is not accidental and has passed the placebo test, further demonstrating the robustness of the estimation results in this study.

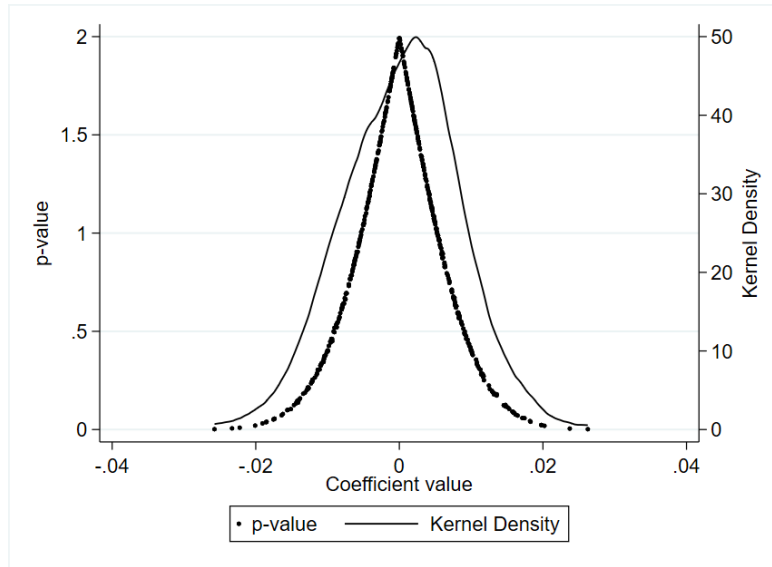


Fig. 4. Placebo Test

4.3.3 Lagged Effect Analysis

Considering the time-lagged nature of innovation, as suggested by existing literature, this study also employs a one-period lag of Low Carbon Polit City Policy as a measurement. The estimation results are presented in Table 5. Examining the regression outcomes, first and foremost, irrespective of the inclusion of control variables, the regression coefficients of the low-carbon pilot policy in columns (1) and (4) are statistically significant at the 10% level, indicating that the low-carbon pilot policy continues to have a significant influence on promoting low-carbon innovation in enterprises within pilot areas, even with a one-period lag. Secondly, regarding the heterogeneity of patent categories, the regression coefficients of the low-carbon pilot policy in columns (2) and (5) are both positive and significant at the 5% level, while the regression coefficients of the low-carbon pilot policy in columns (3) and (6) are not statistically significant. This finding further substantiates that the low-carbon pilot policy exerts a more pronounced promotional effect on invention patents characterised by higher levels of innovation. The results align with those presented in Table 5, demonstrating that the regression outcomes remain robust following a one-period lag.

Table 5: Results of Lagged Effect Analysis

	(1) Grant	(2) Igrant	(3) Igrant1	(4) Grant	(5) Igrant	(6) Igrant1
L.Policy	0.0258* (1.8529)	0.0355** (2.5298)	-0.0053 (-0.3184)	0.0234* (1.8292)	0.0338** (2.4089)	-0.0062 (-0.3700)
Indep				0.0465 (0.8755)	0.0284 (0.7155)	0.0291 (0.6153)
SOE				0.0241 (0.5042)	-0.0146 (-0.3836)	0.0470 (1.0943)
Top1				0.0328 (0.3082)	0.1348* (1.7796)	-0.0589 (-0.6234)
Size				0.1340*** (8.0020)	0.0646*** (5.3828)	0.0965*** (6.4746)
Lev				-0.0888 (-1.5161)	-0.0666 (-1.5574)	-0.0505 (-0.9838)
ROA				-0.2683** (-2.1563)	-0.1994** (-2.2027)	-0.1185 (-1.0938)

AGE				0.1602 (1.3028)	0.0778 (0.7898)	0.1662 (1.5916)
CFO				-0.0605 (-0.6231)	-0.0260 (-0.3706)	-0.0781 (-0.9375)
FEXP				0.0396 (0.7867)	0.0282 (0.7320)	0.0203 (0.4606)
PRA				-0.0189 (-0.5596)	0.0145 (0.6016)	-0.0347 (-1.1422)
_cons				-3.5742*** (-3.9245)	-2.0361*** (-2.9773)	-2.4585*** (-3.0495)
Firm fixed effect	N	N	N	Y	Y	Y
Year fixed effect	N	N	N	Y	Y	Y
N	12057	12057	12057	12057	12057	12057
adj. R^2	0.625	0.507	0.557	0.629	0.508	0.560

Note: In the regression, all control variables, independent variables, and dependent variables are current period data. ***, **, and * represent significance at the 1%, 5%, and 10% levels, respectively.

4.3.4 Eliminating the Impact of Other Policies

During the sample period, there were several pilot policies implemented, such as the National Intellectual Property Rights (IPR) Demonstration Cities, Smart City Pilot Policy, and the Broadband China Pilot Policy, which might also influence the low-carbon innovation of companies. To mitigate the potential biases caused by overlooking these policies, we introduced dummy variables into our model: IPR, SM, and KD. These variables respectively represent the National Intellectual Property Rights Demonstration Cities, Smart City Pilot Policy, and Broadband China Pilot Policy. We included these variables in model (1) and conducted regression analysis. The results can be found in Table 6. As observed from the table, the regression outcomes are largely consistent with our primary findings, indicating that even after excluding the interference from the aforementioned policies, the results remain significant.

Table 6: Robustness Test – Eliminating the Impact of Other Policies

	(1) Grant	(2) Igrant	(3) Igrant1
Policy	0.0404** (2.3517)	0.0351*** (2.8234)	0.0083 (0.5590)
Indep	0.0605 (1.3486)	0.0343 (1.0476)	0.0384 (0.9711)
SOE	-0.0129 (-0.2913)	-0.0383 (-1.0735)	0.0287 (0.7687)
Top1	0.0279 (0.3118)	0.1136* (1.7921)	-0.0534 (-0.6897)
Size	0.1314*** (9.3299)	0.0664*** (6.7309)	0.0916*** (7.4651)
Lev	-0.0517 (-1.0656)	-0.0594* (-1.7193)	-0.0214 (-0.5111)
ROA	-0.2348** (-2.1759)	-0.1590** (-2.0640)	-0.1110 (-1.1859)
AGE	0.1670* (1.7557)	0.0714 (1.0099)	0.1659** (2.0699)
CFO	-0.0451 (-0.5545)	-0.0382 (-0.6728)	-0.0442 (-0.6342)
FEXP	0.0038 (0.0881)	0.0094 (0.2940)	-0.0031 (-0.0838)

PRA	-0.0017 (-0.0637)	0.0259 (1.3764)	-0.0194 (-0.7964)
SM	-0.0158 (-0.7363)	0.0224 (1.5263)	-0.0224 (-1.2048)
KD	-0.0481*** (-2.7044)	-0.0121 (-0.9314)	-0.0387** (-2.5108)
IPR	-0.0056 (-0.2817)	-0.0170 (-1.2710)	0.0099 (0.5720)
_cons	-3.0603*** (-3.9245)	-1.8202*** (-3.2192)	-2.0616*** (-3.0650)
Firm fixed effect	Y	Y	Y
Year fixed effect	Y	Y	Y
N	15134	15134	15134
adj. R ²	0.595	0.476	0.531

Note: In the regression, all control variables, independent variables, and dependent variables are current period data. ***, **, and * represent significance at the 1%, 5%, and 10% levels, respectively.

4.3.5 Incorporating Macro-level Control Variables

Taking into account the potential influence of the macroeconomic environment, this study further integrates macro-level control variables, building upon the existing enterprise and city-level controls. Regression analyses, after this incorporation, indicate that the results remain statistically significant. Consequently, the robustness of our findings is upheld even after adjusting for macro-level determinants.

Table 7: Robustness Test - Incorporating Macro-level Control Variables

	(1) Grant	(2) Igrant	(3) Igrant1
Policy	0.0400** (2.3244)	0.0348*** (2.7736)	0.0095 (0.6415)
Indep	0.0488 (1.0855)	0.0206 (0.6280)	0.0396 (0.9948)
SOE	0.0110 (0.2349)	-0.0202 (-0.5407)	0.0403 (0.9963)
Top1	0.0334 (0.3655)	0.1053 (1.6221)	-0.0334 (-0.4203)
Size	0.1374*** (9.1469)	0.0720*** (6.7504)	0.0939*** (7.1560)
Lev	-0.0675 (-1.3497)	-0.0791** (-2.2011)	-0.0268 (-0.6157)
ROA	-0.2811** (-2.5501)	-0.1928** (-2.4598)	-0.1247 (-1.2851)
AGE	0.1574* (1.6479)	0.0627 (0.8924)	0.1688** (2.0596)
CFO	-0.0119 (-0.1445)	-0.0068 (-0.1186)	-0.0429 (-0.6044)
FEXP	-0.0064 (-0.1380)	0.0014 (0.0413)	-0.0068 (-0.1722)
PRA	-0.0000 (-0.0015)	0.0232 (1.2078)	-0.0177 (-0.7180)
GDPGR	0.0516 (0.3964)	0.1826** (1.9612)	0.0031 (0.0280)
GDP	-0.0137 (-0.1751)	-0.0475 (-0.8349)	-0.0106 (-0.1615)
_cons	-2.8994*** (-2.9175)	-1.2896* (-1.7740)	-1.9900** (-2.3481)

Firm fixed effect	Y	Y	Y
Year fixed effect	Y	Y	Y
<i>N</i>	14871	14871	14871
adj. <i>R</i> ²	0.597	0.474	0.532

Note: In the regression, all control variables, independent variables, and dependent variables are current period data. ***, **, and * represent significance at the 1%, 5%, and 10% levels, respectively.

4.3.6 Robustness Test of Multi-period DID

Goodman-Bacon (2021) indicated that DID designs involving multiple time periods and treatment time variations could result in negative weights for treatment effect parameters. Even in situations with mixed ownership, regression results might still be biased even if the parallel trend assumption holds. This study, therefore, employs the DID estimator with multiple periods proposed by Callaway and Sant'Anna (2021) (hereafter, CS), termed "csdid" (DD with multiple periods estimator), to gauge effects. This estimation method is particularly robust for multi-period DID when heterogeneous treatment effects are present. The specific results are presented in Table 8. The findings reveal that, under this estimation technique, both the coefficients of Grant and Igrant are significantly positive, consistent with the primary regression results, suggesting that the conclusions of this study are robust.

Table 8: Robustness Test of Multi-period DID

	Grant	Igrant	Igrant1
Coefficient	0.0510**	0.0415**	0.0215
Standard Errir	0.02097	0.02083	0.02526

4.4 Mechanism Analysis

The empirical test results presented earlier demonstrate that the low-carbon city pilot policy fosters low-carbon innovation in enterprises, particularly in state-owned enterprises and those with political connections. To delve into the policy's effectiveness, we further analyse its mechanism for alleviating financing constraints. Schumpeter's innovation theory posits that the accessibility of funds plays a vital role in technological innovation. Innovation activities often confront severe external financing constraints due to uncertain returns, information asymmetry in the innovation process, and elevated monitoring costs, which subsequently suppress firms' innovation endeavours (Aghion et al., 2012). Under the pressure of profit generation, enterprises with stringent financing constraints are more likely to concentrate on short-term gains, current financial statements, and exhibit a lack of enthusiasm for long-term investments. This tendency hinders the development of independent R&D and collaborative innovation.

In contrast to traditional technological innovation, low-carbon technological innovation is characterised by substantial upfront capital investment, extended profit cycles, and unpredictable risks. This situation implies a greater need for capital investment in transformative innovations within the low-carbon technology sector (Johnstone et al., 2010; Huang et al., 2019). However, low-carbon technology R&D exhibits increased uncertainty and positive externalities, which leads to relatively low enthusiasm among enterprises and significant limitations on R&D funding accumulation. Implementing low-carbon pilot initiatives necessitates government financial support. Full government subsidies are employed

to denote the amount of subsidies received by companies, with the government subsidy expressed as $sub = \ln(sub + 1)$. Since China's current tax incentive policies are mainly aimed at corporate income tax benefits, including preferential tax rates, preferential tax bases, and preferential tax amounts, income tax incentives are primarily considered, excluding other items such as value-added tax refunds and tax and fee rebates. Empirical analysis of tax incentive policies predominantly employs the effective tax rate variable (Stickney & McGee, 1982; Porcano, 1986; Shevlin, 1987). This study follows Porcano (1986) and uses the effective corporate income tax rate (income tax expense/pre-tax profit) as a proxy for tax incentives (Tax), with a smaller Tax indicating a higher degree of tax incentives. This paper analyses the mechanism of the low-carbon city pilot policy from the perspective of alleviating financing constraints based on models (3) and (4), and tests whether the policy can promote corporate low-carbon innovation through government subsidies and tax incentives. Mediator refers to government subsidies (Sub) and tax incentives (Tax).

$$Mediator_{it} = \alpha + \beta Policy_{it} + \gamma Control_{it} + \lambda_i + \mu_t + \varepsilon_{it} \quad (3)$$

$$Innovation_{it} = \alpha + \beta_1 Policy_{it} + \beta_2 Mediator_{it} + \gamma Control_{it} + \lambda_i + \mu_t + \varepsilon_{it} \quad (4)$$

As shown in Table 9, the regression results indicate that the low-carbon city pilot can significantly enhance corporate low-carbon innovation based on the previous analysis. Columns (1) to (4) present the analysis results when $Mediator = sub$. When the dependent variable is government subsidy (Sub), the regression coefficients of the low-carbon city pilot (Policy) are all significantly positive, suggesting that the policy increases government subsidies for regional enterprises. In columns (2) to (4), with the dependent variable being corporate low-carbon innovation, the focus is on the regression coefficients of the mediator variable government subsidy (Sub) and low-carbon city pilot (Policy). Both are found to be significantly positive, indicating that higher government subsidies lead to more corporate low-carbon innovation output, with a more pronounced promotional effect on highly innovative low-carbon invention patents. Furthermore, government subsidies partially mediate the relationship between the low-carbon city pilot and corporate low-carbon innovation.

Columns (5) to (8) present the analysis results when $Mediator = Tax$. When the dependent variable is tax incentives (Tax), the regression coefficients of the low-carbon city pilot (Policy) are all significantly negative, indicating that the policy reduces the actual income tax rate for regional enterprises, allowing them to enjoy more significant tax incentives. In columns (6) to (8), with the dependent variable being corporate low-carbon innovation, the focus is on the regression coefficients of the mediator variable tax incentives (Tax) and low-carbon city pilot (Policy). Both are found to be significantly negative, indicating that lower actual income tax rates and greater tax incentives lead to more corporate low-carbon innovation output. This may be due to the implementation of tax incentive policies reducing the cost of corporate R&D activities, alleviating financing constraints, and stimulating companies to increase R&D investment and actively engage in R&D activities. The innovation outcomes generated by R&D activities can further enhance corporate tax incentives, forming a virtuous cycle conducive to increasing innovation output (Feldman & Kelley, 2006). On the other hand, tax incentives alleviate financing constraints and guide enterprises to continuously engage in innovative activities by reducing tax obligations.

Table 9: Mechanism analysis of the low-carbon city pilot policy

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	Mediator=Sub				Mediator=Tax			
	Mediator	Grant	Igrant	Igrant1	Mediator	Grant	Igrant	Igrant1
Policy	0.2874* (1.7864)	0.0350** (2.0672)	0.0377*** (3.0613)	0.0020 (0.1393)	-0.0079** (-2.2219)	0.0348** (2.0627)	0.0377*** (3.0603)	0.0020 (0.1400)
Mediator		0.0022** (2.1870)	0.0015** (1.9757)	0.0015* (1.7198)		-0.0977** (-2.3526)	-0.0660** (-2.1280)	-0.0530 (-1.4645)
Indep	-0.4097 (-0.8375)	0.0617 (1.3756)	0.0359 (1.0993)	0.0390 (0.9848)	0.0072 (0.7265)	0.0615 (1.3709)	0.0358 (1.0952)	0.0387 (0.9787)
Soe	0.9004** (1.9658)	-0.0137 (-0.3114)	-0.0417 (-1.1708)	0.0299 (0.8030)	0.0158* (1.7560)	-0.0102 (-0.2317)	-0.0393 (-1.1028)	0.0321 (0.8609)
Top1	1.0735 (1.1585)	0.0185 (0.2059)	0.1137* (1.7919)	-0.0620 (-0.7992)	0.0403* (1.7942)	0.0247 (0.2760)	0.1180* (1.8586)	-0.0583 (-0.7509)
Size	0.9141*** (6.2080)	0.1277*** (9.0272)	0.0647*** (6.5391)	0.0887*** (7.2193)	0.0065* (1.8603)	0.1303*** (9.2538)	0.0665*** (6.7534)	0.0904*** (7.3824)
Lev	-0.3121 (-0.6376)	-0.0501 (-1.0331)	-0.0592* (-1.7119)	-0.0199 (-0.4757)	-0.0790*** (-6.6018)	-0.0585 (-1.2052)	-0.0648* (-1.8723)	-0.0246 (-0.5859)
ROA	-0.0775 (-0.0662)	-0.2318** (-2.1512)	-0.1596** (-2.0719)	-0.1078 (-1.1535)	0.3974*** (13.1790)	-0.1931* (-1.7629)	-0.1335* (-1.7079)	-0.0868 (-0.9132)
AGE	-1.9907** (-2.1824)	0.1761* (1.8593)	0.0706 (1.0017)	0.1743** (2.1817)	0.0007 (0.0389)	0.1719* (1.8114)	0.0677 (0.9583)	0.1714** (2.1431)
CFO	-0.5617 (-0.7392)	-0.0437 (-0.5374)	-0.0384 (-0.6754)	-0.0422 (-0.6067)	-0.0169 (-0.8763)	-0.0465 (-0.5726)	-0.0404 (-0.7095)	-0.0439 (-0.6314)
FEXP	-0.2296 (-0.5828)	-0.0031 (-0.0712)	0.0045 (0.1399)	-0.0072 (-0.1956)	-0.0021 (-0.2146)	-0.0038 (-0.0874)	0.0040 (0.1246)	-0.0077 (-0.2077)
PRA	0.1537 (0.6046)	-0.0015 (-0.0545)	0.0235 (1.2423)	-0.0184 (-0.7567)	-0.0015 (-0.2287)	-0.0013 (-0.0474)	0.0236 (1.2500)	-0.0182 (-0.7508)
_cons	-0.1275 (-0.0177)	-2.9543*** (-3.8035)	-1.7138*** (-3.0329)	-2.0034*** (-2.9965)	0.0190 (0.1106)	-2.9527*** (-3.7937)	-1.7128*** (-3.0249)	-2.0025*** (-2.9934)
Firm	Y	Y	Y	Y	Y	Y	Y	Y
Year	Y	Y	Y	Y	Y	Y	Y	Y
N	15134	15134	15134	15134	15134	15134	15134	15134
adj. R ²	0.621	0.595	0.476	0.531	0.234	0.595	0.476	0.531

Note: In the regression, all control variables, independent variables, and dependent variables are current period data. ***, **, and * represent significance at the 1%, 5%, and 10% levels, respectively.

5. Further Analysis

5.1 Heterogeneity Analysis

5.1.1 Ownership of Enterprises

In China, the nature of ownership has always been a significant factor leading to heterogeneity among enterprises. Therefore, based on the benchmark model, the overall sample is divided into state-owned enterprises and non-state-owned enterprises to further investigate whether the low-carbon city pilot policy would generate heterogeneous low-carbon innovation effects on different types of enterprise entities. The estimation results are shown in Table 10. The coefficients of the low-carbon city pilot policy (Policy) are significantly positive in the state-owned enterprise sub-sample corresponding to columns (1) and (3); moreover, the regression coefficients of the low-carbon city pilot policy (Policy) are not significant in the non-state-owned enterprise sub-sample. This indicates that there is indeed heterogeneity in the low-carbon innovation of enterprises due to ownership attributes, and the low-carbon city pilot policy can more significantly promote the low-carbon innovation of state-owned enterprises, with the direction of impact being low-carbon invention patents. For non-state-owned enterprises, the pilot policy's low-carbon innovation is insignificant overall. The possible reason, as mentioned earlier, is that state-owned enterprises are more likely to receive policy support and financial subsidies. They not only pursue profit maximisation goals like general enterprises but also shoulder the heavy burden of participating in environmental management

assigned by the government. Moreover, the government and all sectors of society will exert intangible pressure on state-owned enterprises in environmental protection (Kumar, 2006). Therefore, state-owned enterprises have more strength, pressure, and motivation to engage in low-carbon innovation and upgrading under the promotion of low-carbon city pilot policies. Thus, hypothesis H2 is verified.

Table 10: Heterogeneity analysis of enterprises' ownership

	(1) SOE=1 Grant	(2) SOE=0 Grant	(3) SOE=1 Igrant	(4) SOE=0 Igrant	(5) SOE=1 Igrant1	(6) SOE=0 Igrant1
Policy	0.0504* (1.7065)	0.0282 (1.3727)	0.0812*** (3.6403)	0.0124 (0.8659)	-0.0074 (-0.2835)	0.0113 (0.6505)
Indep	0.2192** (2.0323)	0.0018 (0.0376)	0.2633*** (3.0338)	-0.0401 (-1.2167)	0.0541 (0.5672)	0.0273 (0.6376)
Top1	-0.2495 (-1.5315)	0.0550 (0.5004)	-0.0494 (-0.4036)	0.0949 (1.3741)	-0.2158 (-1.5251)	-0.0411 (-0.4279)
Size	0.1464*** (4.7330)	0.1563*** (9.4138)	0.1127*** (4.8421)	0.0737*** (6.8216)	0.0721*** (2.6851)	0.1173*** (7.9708)
Lev	-0.0296 (-0.2825)	-0.0602 (-1.0809)	-0.0790 (-1.0512)	-0.0366 (-0.9435)	0.0104 (0.1172)	-0.0426 (-0.8645)
ROA	-0.3102 (-1.4039)	-0.2193* (-1.8438)	-0.2290 (-1.4245)	-0.1499* (-1.8013)	-0.0719 (-0.3769)	-0.1304 (-1.2447)
AGE	0.1927 (1.0359)	0.1230 (1.1446)	0.1336 (0.9328)	0.0382 (0.5187)	0.1879 (1.2150)	0.1280 (1.3667)
CFO	0.0660 (0.4219)	-0.0735 (-0.7792)	0.1653 (1.4502)	-0.1011 (-1.5930)	-0.0996 (-0.7459)	-0.0148 (-0.1813)
FEXP	-0.0871 (-1.0775)	0.0329 (0.6502)	-0.1025* (-1.6610)	0.0463 (1.2708)	-0.0307 (-0.4362)	0.0050 (0.1146)
PRA	-0.0349 (-0.5809)	0.0233 (0.7494)	0.0067 (0.1460)	0.0444** (2.1843)	-0.0560 (-1.0731)	-0.0005 (-0.0181)
_cons	-1.8937 (-1.3099)	-4.0838*** (-4.4419)	-1.2307 (-1.1049)	-2.5518*** (-4.0171)	-1.0377 (-0.8251)	-2.7516*** (-3.4521)
Firm fixed effect	Y	Y	Y	Y	Y	Y
Year fixed effect	Y	Y	Y	Y	Y	Y
Test Difference (P-Value)	0.0000***		0.0000***		0.0000***	
N	4494	10590	4494	10590	4494	10590
adj. R ²	0.648	0.564	0.529	0.454	0.599	0.488

Note: In the regression, all control variables, independent variables, and dependent variables are current period data. ***, **, and * represent significance at the 1%, 5%, and 10% levels, respectively.

5.1.2 Political Connections

The phenomenon of political connections in enterprises is a pervasive occurrence worldwide. In fact, political connections can be regarded as a type of political capital established by organisations in economies with inadequate formal systems to secure essential resources for survival. This study adopts the approach of Fan et al.(2007) to define a company's political connections (PC) as 1 when the company's executives have previously or currently held positions in party committees (including disciplinary committees), government, standing institutions of the People's Congress and the Chinese People's Political Consultative Conference, courts, and procuratorates, or have previously or currently served as party representatives, People's Congress representatives, and CPPCC members. If none of these conditions apply, the value is set to 0. The data source for the executives' résumés is derived from the CSMAR database, and the scope of executives defined in this article encompasses all

disclosed executives of the company, excluding independent directors (including directors, supervisors, and other executives). Based on this definition, a grouped regression analysis is conducted, with specific regression results presented in Table 11. The analysis further investigates whether the low-carbon city pilot policy yields heterogeneous low-carbon innovation effects on different politically connected enterprise subjects.

The regression results indicate that the coefficients of the low-carbon city pilot policy (Policy) in the first and third columns corresponding to the politically connected enterprise sub-samples are 0.0398 and 0.0452, respectively, and are significant at the 10% and 1% levels. However, in enterprises without political connections, the promotional effect of the low-carbon city pilot policy (Policy) on low-carbon innovation is not statistically significant. Several reasons may account for this observation. Firstly, politically connected enterprises may bear substantial policy burdens in addition to striving to achieve their organisational objectives. Secondly, it is plausible that politically connected enterprises are more likely to receive tax preferences, fiscal subsidies, and domestic bank financing approvals, thereby alleviating financing constraints and providing funds for low-carbon innovation initiatives. Lastly, politically connected enterprises may be more capable of forging cooperative relationships with universities and research institutions through government channels, which could facilitate the transformation of innovative resources and bolster the number of authorised patents. These findings lend support to Hypothesis H3.

Table 11: Heterogeneity analysis of political connection

	(1) PC=1 Grant	(2) PC=0 Grant	(3) PC=1 Igrant	(4) PC=0 Igrant	(5) PC=1 Igrant1	(6) PC=0 Igrant1
Policy	0.0398* (1.8052)	0.0368 (1.2280)	0.0452*** (2.8099)	0.0182 (0.8650)	0.0039 (0.1986)	0.0153 (0.6142)
Indep	0.0900 (1.3430)	0.0066 (0.1026)	0.1525*** (2.9973)	-0.0839* (-1.8808)	-0.0117 (-0.1969)	0.0621 (1.1065)
SOE	0.0128 (0.2285)	0.0342 (0.3429)	-0.0171 (-0.3848)	-0.0058 (-0.0755)	0.0553 (1.1276)	0.0419 (0.4974)
Top1	-0.0246 (-0.1979)	0.1595 (1.0760)	0.0657 (0.7395)	0.1870* (1.8298)	-0.0587 (-0.5444)	-0.0330 (-0.2579)
Size	0.1334*** (6.3150)	0.1760*** (7.1669)	0.0833*** (5.4542)	0.0709*** (4.3920)	0.0908*** (4.9727)	0.1295*** (5.9675)
Lev	-0.0197 (-0.2882)	-0.1344 (-1.6371)	-0.0750 (-1.5226)	-0.0845 (-1.4664)	0.0192 (0.3333)	-0.0713 (-0.9673)
ROA	-0.2482 (-1.6030)	-0.1459 (-0.8412)	-0.1870 (-1.6177)	-0.0445 (-0.3978)	-0.0870 (-0.6378)	-0.1137 (-0.7489)
AGE	0.0804 (0.5805)	0.3739** (2.4386)	0.0139 (0.1282)	0.2401** (2.3402)	0.1145 (1.0012)	0.2600* (1.9347)
CFO	-0.0053 (-0.0464)	-0.0275 (-0.2232)	0.0231 (0.2867)	-0.0727 (-0.8884)	-0.0463 (-0.4680)	0.0128 (0.1221)
FEXP	0.0193 (0.3226)	-0.0222 (-0.3215)	-0.0073 (-0.1597)	0.0465 (0.9516)	0.0316 (0.6242)	-0.0537 (-0.8758)
PRA	0.0205 (0.4973)	-0.0194 (-0.4900)	0.0348 (1.2456)	0.0005 (0.0200)	-0.0029 (-0.0788)	-0.0190 (-0.5424)
_cons	-3.3070*** (-3.0500)	-4.0731*** (-3.1912)	-1.8608** (-2.2737)	-2.8184*** (-3.2860)	-2.6013*** (-2.8368)	-2.3118** (-2.0070)
Firm fixed effect	Y	Y	Y	Y	Y	Y
Year fixed effect	Y	Y	Y	Y	Y	Y
Test Difference (P-Value)	0.0000***		0.0000***		0.0014***	

N	8319	6455	8319	6455	8319	6455
adj. R ²	0.615	0.588	0.478	0.510	0.559	0.502

Note: In the regression, all control variables, independent variables, and dependent variables are current period data. ***, **, and * represent significance at the 1%, 5%, and 10% levels, respectively.

5.1.3 Intensity of Environmental Regulation

Environmental regulation, as a critical component of societal regulation, refers to the government's efforts to modulate corporate economic activities by establishing relevant policies and measures. The goal is to mitigate the negative externalities of environmental pollution caused by business operations, achieving a harmonious development between the environment and the economy. The "Porter Hypothesis" posits that increasing the intensity of environmental regulations can stimulate companies to pursue technological advancements and product innovations, thereby enhancing product competitiveness. In this study, the ratio of total investment in industrial pollution control to the added value of the industry is adopted as an indicator for the intensity of environmental regulation (Er). Regression is performed based on the sample mean; when the environmental regulation intensity indicator (Er) exceeds the sample mean, Er is set to 1; otherwise, it's 0. The specific regression results can be seen in Table 12. We further explore whether the low-carbon urban pilot policy would generate heterogeneous low-carbon innovative effects for corporate entities located in regions with varying intensities of environmental regulation.

Table 12: Heterogeneity Test - Intensity of Environmental Regulation

	(1) ER=1 Grant	(2) ER=0 Grant	(3) ER=1 Igrant	(4) ER=0 Igrant	(5) ER=1 Igrant1	(6) ER=0 Igrant1
Policy	0.0829** (2.3190)	-0.0122 (-0.5199)	0.1044*** (4.1622)	-0.0037 (-0.2114)	0.0157 (0.5074)	-0.0149 (-0.7431)
Indep	0.1822** (1.9682)	0.0082 (0.1389)	0.1683*** (2.5819)	-0.0451 (-1.0365)	0.1128 (1.3695)	0.0195 (0.3776)
SOE	-0.1024 (-1.2595)	0.0243 (0.4227)	-0.0360 (-0.6075)	-0.0455 (-0.9546)	-0.0982 (-1.3562)	0.0951** (2.0560)
Top1	0.1517 (0.9416)	-0.0541 (-0.4189)	0.2603** (2.5349)	0.1128 (1.1719)	-0.0480 (-0.3446)	-0.1165 (-1.0176)
Size	0.1499*** (5.6853)	0.1383*** (6.8219)	0.0840*** (4.4837)	0.0613*** (4.3319)	0.0930*** (3.8772)	0.1056*** (5.9037)
Lev	-0.0711 (-0.8331)	-0.0781 (-1.1052)	-0.0452 (-0.7398)	-0.0618 (-1.2496)	-0.0753 (-1.0302)	-0.0328 (-0.5274)
ROA	-0.2144 (-1.1933)	-0.3119** (-2.0596)	-0.0673 (-0.4985)	-0.2230** (-2.0953)	-0.1854 (-1.1442)	-0.1549 (-1.1790)
AGE	0.6650*** (3.4148)	0.0074 (0.0597)	0.4740*** (3.5592)	-0.1079 (-1.1511)	0.4265** (2.5234)	0.1262 (1.2346)
CFO	-0.0373 (-0.2744)	-0.0137 (-0.1204)	-0.0113 (-0.1212)	-0.0291 (-0.3592)	-0.0677 (-0.5623)	-0.0102 (-0.1064)
FEXP	-0.0710 (-0.9061)	0.0355 (0.6306)	-0.1146** (-2.0857)	0.0627 (1.4665)	0.0114 (0.1586)	-0.0174 (-0.3594)
PRA	0.0197 (0.2507)	-0.0234 (-0.7232)	0.0647 (1.1830)	-0.0038 (-0.1682)	-0.0296 (-0.4485)	-0.0210 (-0.7224)
_cons	-3.9117*** (-2.7768)	-3.0962*** (-3.0313)	-1.7064* (-1.7802)	-1.8545** (-2.4388)	-3.0216** (-2.3503)	-1.9938** (-2.2456)
Firm fixed effect	Y	Y	Y	Y	Y	Y
Year fixed effect	Y	Y	Y	Y	Y	Y
Test Difference (P-Value)	0.0002***		0.0055***		0.0008***	
N	5645	8945	5645	8945	5645	8945

adj. R ²	0.570	0.614	0.461	0.506	0.498	0.551
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Note: In the regression, all control variables, independent variables, and dependent variables are current period data. ***, **, and * represent significance at the 1%, 5%, and 10% levels, respectively.

Based on the regression results, the coefficient of the Low-Carbon Urban Pilot Policy (Policy) in corporate sub-samples from regions with stronger government environmental regulations, as evident in columns (1) and (3), has regression coefficients of 0.0829 and 0.1044, respectively, which are significant at the 5% and 1% levels. In contrast, for enterprises in areas with weaker government environmental regulation, the Low-Carbon Urban Pilot Policy (Policy) does not show a significant impact on promoting low-carbon innovation within businesses.

A possible explanation for this might be that, after the implementation of the Low-Carbon Urban Pilot Policy, environmental regulatory policies become the primary driver for enterprises to invest in environmental management. The "Porter Hypothesis" posits that intensifying environmental regulations can stimulate companies to embark on technological advancements and product innovations, thus enhancing product competitiveness (Porter and Van, 1995). The stronger the environmental regulation, the lower the pollution level of enterprises. Consequently, the costs associated with pollution control increase, necessitating higher standards of pollution control technology. This can, in turn, compel enterprises to enhance their research and development efforts, leading to innovations in low-carbon technology.

5.1.4 Regional Industrial Structure

The transformation of the industrial structure is a central variable for understanding the differences in economic development between developing and developed nations. It is also intrinsically required for latecomer countries to expedite their economic growth (Chenery et al., 1989). Currently, the consensus in numerous literatures is that the upgrade and transition of the industrial structure play a pivotal role in regional economic development. The evolution of the industrial structure is a process where economic growth absorbs technological innovations and leading economic sectors replace one another in succession. This study, drawing inspiration from the research approach of Lan Qingxin et al. (2013), sequentially assigns weights to the three sectors of the industry. By doing so, we obtain an index representing the upgrade of the industrial structure (Structure), which approximates the overall qualitative enhancement of the industry. The calculation formula is as follows:

Structure = $\sum_{n=1}^3 S_n \times n$, $1 \leq \text{Structure} \leq 3$, Wherein, S_n represents the proportion of the value added by the n th sector. Regression is grouped based on the sample mean. When the index of industrial structure upgrade (Structure) exceeds the sample mean, SR is set to 1; otherwise, it's 0. Specific regression results can be found in Table 13. We further investigate whether the Low-Carbon Urban Pilot Policy has a heterogeneous effect on low-carbon innovation for corporate entities located in regions with different industrial structures.

Table 13: Heterogeneity Test - Regional Industrial Structure

	(1) SR=1 Grant	(2) SR=0 Grant	(3) SR=1 Igrant	(4) SR=0 Igrant	(5) SR=1 Igrant1	(6) SR=0 Igrant1
Policy	0.0141 (0.4187)	0.0481** (2.0182)	0.0307 (1.1927)	0.0469*** (2.8187)	-0.0159 (-0.5379)	0.0104 (0.5209)
Indep	0.0212 (0.3086)	0.0955 (1.5741)	0.0333 (0.6397)	0.0360 (0.8489)	-0.0034 (-0.0554)	0.0693 (1.3182)
SOE	0.0080 (0.1048)	0.0071 (0.1361)	-0.0529 (-0.8007)	0.0096 (0.2425)	0.0638 (1.1202)	0.0026 (0.0547)
Top1	0.2683	-0.0081	0.1939	0.1303*	0.1882	-0.1267

	(1.5307)	(-0.0727)	(1.4879)	(1.6832)	(1.2413)	(-1.3366)
Size	0.1156***	0.1198***	0.0523***	0.0557***	0.0868***	0.0805***
	(4.5650)	(6.3292)	(2.7783)	(4.3909)	(3.8557)	(5.1137)
Lev	-0.0738	-0.0176	-0.1250*	0.0006	-0.0007	-0.0156
	(-0.8410)	(-0.2829)	(-1.9497)	(0.0133)	(-0.0086)	(-0.3005)
ROA	-0.3193*	-0.1991	-0.1954	-0.1367	-0.2012	-0.0659
	(-1.8973)	(-1.3941)	(-1.5617)	(-1.3549)	(-1.3731)	(-0.5425)
AGE	0.3945**	-0.1491	0.2481*	-0.0618	0.3406**	-0.0804
	(2.2752)	(-1.1715)	(1.8681)	(-0.6688)	(2.3764)	(-0.7393)
CFO	0.0722	-0.1005	0.0196	-0.0466	0.0479	-0.0904
	(0.5407)	(-0.9818)	(0.2002)	(-0.6740)	(0.4234)	(-1.0297)
FEXP	0.1212	-0.1416**	0.0546	-0.1460***	0.0590	-0.0461
	(1.2601)	(-2.4531)	(0.8153)	(-3.4995)	(0.7099)	(-0.9618)
PRA	-0.0533	0.0152	-0.0667	0.0316	-0.0440	-0.0034
	(-0.6070)	(0.4965)	(-1.0173)	(1.5170)	(-0.6068)	(-0.1239)
_cons	-5.0839***	0.1259	-2.2323*	1.0852	-3.4119**	-0.5978
	(-2.7138)	(0.1244)	(-1.7375)	(1.4256)	(-2.0932)	(-0.7139)
Firm fixed effect	Y	Y	Y	Y	Y	Y
Year fixed effect	Y	Y	Y	Y	Y	Y
Test Difference (P-Value)	0.0007***		0.0000***		0.0000***	
N	6980	7970	6980	7970	6980	7970
adj. R ²	0.647	0.561	0.539	0.423	0.574	0.517

Note: In the regression, all control variables, independent variables, and dependent variables are current period data. ***, **, and * represent significance at the 1%, 5%, and 10% levels, respectively.

From the regression results, the coefficient of the Low-Carbon Urban Pilot Policy (Policy) for corporate sub-samples in regions with a lower proportion of tertiary industry, as evidenced in columns (2) and (4), shows regression coefficients of 0.0481 and 0.0469, respectively, which are significant at the 5% and 1% levels. However, for enterprises in regions with a higher proportion of the tertiary industry, the policy does not significantly promote low-carbon innovation.

This observation could be attributed to the fact that low-carbon pilot cities aim to develop and nurture emerging industries characterised by low energy consumption and pollution. Through appropriate industry policies and fiscal and tax support, these cities are guided to focus on energy-saving and environmentally friendly industries. This, to an extent, can optimise the traditionally extensive industrial structure of the city and achieve industrial upgrading. Hence, in regions where the index for industrial structure upgrading (Structure) is generally lower, the Low-Carbon Urban Pilot Policy has a more pronounced effect on promoting low-carbon innovation within businesses.

5.2 Economic Outcomes Examination

The above analysis indicates that the Low-Carbon Urban Pilot Policy can effectively stimulate low-carbon innovation in enterprises. However, patent applications or authorisations by enterprises only transform R&D investments into knowledge outputs, which still constitute an intermediate outcome. Thus, this paper further discusses whether the implementation of the Low-Carbon Urban Pilot Policy can enhance the green total factor productivity (GTFP) of enterprises and reduce carbon emissions through the channel of low-carbon innovation.

5.2.1 Green Total Factor Productivity (GTFP)

This study incorporates corporate environmental pollution into the evaluation system and employs the non-radial SBM-ML index (hereinafter referred to as the "ML index") to measure

the green total factor productivity (GTFP) of enterprises. The input and output indicators for GTFP are as follows:

1. **Input factors:**

- Labor input: represented by the number of employees in the enterprise.
- Capital input: represented by the net amount of fixed assets of the enterprise.
- Energy input: calculated based on the industrial electricity consumption of the city where the enterprise is located, converted based on the proportion of employees in the enterprise to the urban employment in the city.

2. **Expected output:** This is represented by the business revenue of the enterprise.

3. **Unexpected output:** Calculated based on the proportion of employees in the enterprise to the urban employment in the city for the "Three Industrial Wastes," namely industrial sulfur dioxide, industrial wastewater, and industrial flue dust emissions. This serves as the proxy variable for the unexpected output of the enterprise.

This study observes the impact of the Low-Carbon Urban Pilot Policy on the total factor productivity of enterprises by constructing an interaction term between corporate low-carbon innovation and the policy. Regression results can be found in Table 14.

Table 14: Economic Outcomes Examination - Green TFP

	(1) GTFP	(2) GTFP	(3) GTFP
Policy×Grant	0.0321*** (8.5967)		
Policy×Igrant		0.0344*** (6.4073)	
Policy×Igrant1			0.0319*** (7.5637)
Indep	-0.0097 (-1.5682)	-0.0093 (-1.5023)	-0.0085 (-1.3471)
SOE	-0.0129 (-1.2390)	-0.0122 (-1.1520)	-0.0145 (-1.3718)
Top1	-0.0345*** (-2.7646)	-0.0354*** (-2.8241)	-0.0340*** (-2.6625)
Size	0.0022 (1.0015)	0.0034 (1.5291)	0.0031 (1.3684)
Lev	-0.0024 (-0.3477)	-0.0021 (-0.2944)	-0.0038 (-0.5357)
ROA	0.0010 (0.0610)	-0.0004 (-0.0244)	-0.0013 (-0.0820)
AGE	-0.0467** (-2.3718)	-0.0410** (-2.0560)	-0.0470** (-2.3409)
CFO	0.0061 (0.5295)	0.0061 (0.5210)	0.0063 (0.5489)
FEXP	0.0044 (0.5375)	0.0042 (0.5120)	0.0070 (0.8521)
PRA	-0.0013 (-0.2896)	-0.0005 (-0.1220)	-0.0006 (-0.1428)
_cons	0.9992*** (7.9848)	0.9597*** (7.5525)	0.9366*** (7.4028)
Firm fixed effect	Y	Y	Y
Year fixed effect	Y	Y	Y
N	13695	13695	13695
adj. R ²	0.756	0.751	0.752

Note: In the regression, all control variables, independent variables, and dependent variables are current period data. ***, **, and * represent significance at the 1%, 5%, and 10% levels, respectively.

The results indicate that the coefficients of each interaction term are significantly positive at the 1% level. These findings consistently show that the low-carbon pilot city policy can promote enterprise low-carbon innovation, further enhancing the green total factor productivity (TFP) of enterprises. This may be due, on the one hand, to the fact that government support is crucial for a comprehensive improvement in green TFP. Obtaining the honorific title of a low-carbon pilot city and the series of related policy supports from the central government will motivate local governments to implement low-carbon pilot projects. As a result, local governments will increase their efforts to achieve carbon emission reduction targets and spare no effort to promote the development of the low-carbon industry, enhancing the green TFP. On the other hand, during the construction of low-carbon cities, technological innovation is a significant mechanism influencing urban economic development. By channels like technological innovation, local governments aim to cultivate sustainable economic development's endogenous growth momentum. As the driving force for economic growth under the new normal, the positive promotion of the low-carbon pilot policy on low-carbon innovation will boost the green TFP of enterprises.

5.2.2 Carbon Emissions

In the process of building a low-carbon city, achieving carbon reduction is the direct objective of local governments. This study collects data on carbon emissions, fossil energy consumption, and electricity and heat usage from annual corporate social responsibility reports, sustainability reports, environmental reports, listed company websites, and environmental department websites. The variable for listed company carbon emissions (GHC) (in millions of tons) is formulated as: Listed Company Carbon Emissions (GHC) = Emissions from Combustion and Leakage + Emissions from Production Processes + Waste Emissions + Emissions resulting from Land Use Changes (Forests converted to industrial land). By constructing an interaction term between enterprise low-carbon innovation and the low-carbon pilot city policy, this study examines the impact of the low-carbon pilot city policy on corporate carbon emissions. The regression results are presented in Table 15.

Table 15: Economic Consequence Test - Carbon Emissions

	(1) GHC	(2) GHC	(3) GHC
Policy×Grant	-2.2194*** (-5.3172)		
Policy×Igrant		-1.9530*** (-2.6879)	
Policy×Igrant1			-2.1257*** (-4.3456)
Indep	0.1592 (1.5667)	0.0927 (0.7214)	0.0882 (0.7401)
SOE	-0.2290** (-2.0121)	-0.2499* (-1.8861)	-0.1623 (-1.3119)
Top1	0.5254** (2.3493)	0.6509** (2.4261)	0.5916** (2.3546)
Size	0.6897*** (15.5122)	0.5787*** (11.6803)	0.6327*** (13.3409)
Lev	-0.0912 (-0.7578)	-0.0918 (-0.6306)	-0.0815 (-0.6070)
ROA	0.7922*** (2.9354)	0.9237*** (2.6993)	0.8095** (2.5624)

AGE	-0.5512*** (-2.6153)	-0.8397*** (-3.3087)	-0.5483** (-2.3639)
CFO	0.4515** (2.4398)	0.4315* (1.8803)	0.3953* (1.8886)
FEXP	0.0568 (0.4999)	0.0301 (0.2230)	-0.1254 (-1.0205)
PRA	-0.1736*** (-2.9022)	-0.2036** (-2.5580)	-0.2202*** (-3.2959)
_cons	-9.5090*** (-4.4896)	-6.0111** (-2.4081)	-5.2938** (-2.3392)
Firm fixed effect	Y	Y	Y
Year fixed effect	Y	Y	Y
N	12770	12770	12770
adj. R ²	0.881	0.811	0.844

Note: In the regression, all control variables, independent variables, and dependent variables are current period data. ***, **, and * represent significance at the 1%, 5%, and 10% levels, respectively.

The regression analysis indicates that all interaction term coefficients are significant at a 1% level and are notably negative. Such results suggest that the low-carbon city pilot policy can promote corporate low-carbon innovation, thereby reducing carbon emissions through technological effects. This aligns with the Porter Hypothesis, which posits that appropriate environmental regulatory intensity can not only offset companies' 'environmental compliance costs' but also enhance their productivity and competitiveness (Porter and Van, 1995). This results in advancements in production technology and upgrades in low-carbon environmental technologies, facilitating carbon emission reduction. It further underscores that the low-carbon city pilot policy has realised its anticipated carbon reduction effects, attesting to the effectiveness of low-carbon urban development. This offers empirical evidence for the potential expansion of the low-carbon city pilot scope, contributing valuable insights for national policy refinement concerning carbon reduction.

6. Conclusion and Implications

This study investigates the impact of the low-carbon city pilot policy, a crucial policy measure adopted by the Chinese government to achieve the 2030 carbon peak target, on enterprise low-carbon innovation. Employing a sample of A-share listed companies from 2008 to 2019 and utilising a difference-in-differences model, the findings suggest that the policy promotes innovation in the low-carbon technology domain, particularly for state-owned enterprises and enterprises with political connections. Government subsidies and tax incentives are identified as essential fiscal instruments for achieving the policy's objectives.

The empirical results demonstrate that the low-carbon city pilot policy effectively stimulates low-carbon innovation at the enterprise level, and this conclusion remains robust after a series of rigorous tests. The impact of the policy is more pronounced in the authorisation of invention patents, indicating its role in promoting high-value, innovative low-carbon technologies. Furthermore, the heterogeneity analysis reveals that state-owned and politically connected enterprises respond more strongly to the policy, engaging in more low-carbon innovation activities than their counterparts.

The mechanism analysis sheds light on the underlying channels through which the low-carbon city pilot policy influences enterprise low-carbon innovation. Government subsidies and tax incentives emerge as critical policy tools that alleviate financing constraints faced by enterprises, enabling them to allocate more resources towards low-carbon innovation. By

providing financial support and reducing the cost of research and development, these policy instruments create a favourable environment for enterprises to pursue low-carbon technological advancements.

The findings of this study contribute to the existing literature on environmental regulation and enterprise innovation, providing empirical support for the Porter Hypothesis in the context of China's low-carbon pilot policy. The results highlight the effectiveness of well-designed environmental policies in stimulating innovation and achieving both environmental and economic benefits. Moreover, the study extends the understanding of the heterogeneous effects of the policy across different types of enterprises, emphasising the importance of considering firm characteristics and institutional factors when evaluating policy outcomes.

Based on the conclusions, several policy implications can be derived. First, policymakers should consider incorporating enterprise low-carbon technology innovation as a key performance indicator in the planning and evaluation of low-carbon city pilot programs. By setting clear innovation targets and providing corresponding support, governments can effectively guide enterprises towards low-carbon development and accelerate the transition to a more sustainable economy.

Second, policymakers should adopt a differentiated approach when designing and implementing low-carbon innovation policies, considering enterprises' heterogeneous characteristics. While leveraging the leading role of state-owned enterprises, governments should also provide targeted support to non-state-owned enterprises, particularly those with strong innovation potential but limited resources. This can be achieved through a combination of policy concessions, fiscal subsidies, and other incentive mechanisms, fostering a more inclusive and balanced low-carbon innovation ecosystem.

Third, governments should continue to optimise the mix of policy instruments to maximise the impact of low-carbon city pilot policies on enterprise innovation. The findings suggest that government subsidies and tax incentives are effective in promoting low-carbon innovation. However, policymakers should also explore other complementary measures, such as green finance, technology transfer, and public-private partnerships, to create a comprehensive and sustainable policy framework.

In conclusion, this study provides valuable insights into the relationship between the low-carbon city pilot policy and enterprise low-carbon innovation in China. The findings contribute to the academic discourse on environmental regulation and innovation and offer practical recommendations for policymakers seeking to foster low-carbon development and achieve carbon emission reduction targets. As China continues to pursue its ambitious climate goals, understanding the mechanisms and heterogeneous effects of low-carbon policies on enterprise innovation will be crucial for designing effective and efficient policy interventions.

Future research could extend this study by examining the long-term impact of the low-carbon city pilot policy on enterprise innovation and economic performance and exploring the potential spillover effects of the policy across regions and industries. Additionally, comparative studies with other countries implementing similar low-carbon policies could provide valuable insights into the generalizability of the findings and identify best practices for promoting low-carbon innovation globally.

Reference

- Aghion P., P.Askenazy, N.Berman, G.Cette and L. Eymard.,2012. Credit Constraints and the Cyclicity of R&D Investment: Evidence from France[J]. *Journal of the European Economic Association*,10(5):1001-1024.
- Bergek A, Berggren C., 2014. The impact of environmental policy instruments on innovation: A review of energy and automotive industry studies[J]. *Ecological Economics*, 106(10): 112-123.
- Berrone P, Fosfuri A, Gelabert L, et al., 2013. Necessity as the mother of green inventions: Institutional pressures and environmental innovations[J]. *Strategic Management Journal*, 34(8):891-909.
- Calel R. and A.Dechedepretre., 2016. Environmental Policy and Directed Technological Change: Evidence from the European Carbon Market[J]. *Review of Economics and Statistics*, 98(1):173-191.
- Cheng J., J.H.Yi, S.Dai and Y.Xiong., 2019. Can Low-carbon City Construction Facilitate Green Growth? Evidence from China's Pilot Low-carbon City Initiative[J]. *Journal of Cleaner Production*, 231:1158-1170
- Clyde P. Stickney, Victor E. McGee., 1982. Effective Corporate Tax Rates the Effect of Size, Capital Intensity, Leverage and Other Factors[J], *Journal of Accounting and Public Policy*, 125-152.
- Cui J., J. Zhang and Y.Zheng., 2018. Carbon Pricing Irduces Innovation: Evidence from China's Regional Carbon Market Pilots[J]. *AEA Papers and Proceedings*, 108:453-457
- Fan, J. P., Wong, T. J., & Zhang, T., 2007. Politically connected CEOs, corporate governance, and Post-IPO performance of China's newly partially privatised firms[J]. *Journal of Financial Economics*, 84(2):330-357.
- Feldman, M. P., Kelley, M. R., 2006. The Exante, Assessment of Knowledge Spillovers: Government R&D Policy, Economic Incentives and Private Firm Behavior[J]. *Research Policy*, 35(10): 1509-1521.
- Gehrsitz M., 2017. The Effect of Low EmissionZones on Air Pollution and Infant Health[J]. *Journal of Environmental Economics and Management*, 83(5):121-144.
- Huang Z., G.Liao and Z.Li., 2019. Loaning Scale ard Government Subsidy for Promoting Green Innovation[J]. *Technological Forecasting and Social Change*, 144:148-156.
- Jaffe A B, Stavins R N., 1995. Dynamic Incentives of Environmental Regulations: The Effects of Alternative Policy Instruments on Technology Diffusion-Science Direct [J]. *Journal of Environmental Economics and Management*, 29(3):43-63.
- Jefferson G H, Tanaka S, Yin W., 2013. Environmental regulation and industrial performance: Evidence from unexpected externalities in China [D]. *Social Ence Electronic Publishing*, 111(12):108-142.
- Johnstone, N., I. Hascic and D. Popp., 2010. Renewable Energy Policies and Technological Innovation: Evidence Based on Patent Counts[J]. *Environmental and Resource Economics*, 45(1):133-155.
- Kumar S., 2006. Environmentally sensitive productivity growth: A global analysis using Malmquist-Luenberger index [J]. *Ecological Economics*, 56(2):280-293.
- Levinson A, Taylor M S., 2008. Unmasking the pollution haven effect [J]. *International Economic Review*, 49(1): 223-254.

- Milani, S., 2017. The Impact of Environmental Policy Stringency on Industrial R&D Conditional on Pollution Intensity and Relocation Costs [J]. *Environmental and Resource Economics*, 68(3): 595-620.
- Popp D., 2006. International Innovation and Diffusion of Air Pollution Control Technologies: The Effects of NO_x and Regulation in the U.S., Japan, and Germany [J]. *Journal of Environmental Economics and Management*, 51(1):46-71.
- Porcano, T.M., 1986. Corporate Tax Rates: Progressive, Proportional or Regressive[J].*Journal of the American Taxation Association*, 7: 7-31.
- Porter, M.E.and C.van der Linde., 1995. Toward a New Concept of the Environment-Competitiveness Relationship[J]. *Journal of Economic Perspectives*, 9(4): 97-118.
- Shevlin, T., 1987. Taxes and Off balance- sheet Financing: Research and Development Limited Partnerships[J]. *Accounting Review*, 480-509.
- Stern, N., & Xie, C., 2022. China's new growth story: Linking the 14th Five-Year Plan with the 2060 carbon neutrality pledge.[J] *Journal of Chinese Economic and Business Studies*, 1-21.
- Zhu, C., & Lee, C. C. 2022. The effects of low-carbon pilot policy on technological innovation: Evidence from prefecture-level data in China. *Technological Forecasting and Social Change*, 183, 121955.
- Wu J., 2011. Asymmetric roles of business ties and political ties in product innovation[J]. *Journal of Business Research*, 64(11): 1151-1156.
- Zhao X, Sun B., 2016. The influence of Chinese environmental regulation on corporation innovation and competitiveness [J]. *Journal of Cleaner Production*, 112(4): 1528-1536.
- Huo, W., Qi, J., Yang, T., Liu, J., Liu, M., & Zhou, Z. (2022). Effects of China's pilot low-carbon city policy on carbon emission reduction: a quasi-natural experiment based on satellite data. *Technological Forecasting and Social Change*, 175, 121422.
- Gao, D., Li, Y., & Li, G. (2022). Boosting the green total factor energy efficiency in urban China: Does low-carbon city policy matter?. *Environmental Science and Pollution Research*, 29(37), 56341-56356.
- Li, J., Fang, L., Chen, S., & Mao, H. (2022). Can low-carbon pilot policy improve atmospheric environmental performance in China? A quasi-natural experiment approach. *Environmental Impact Assessment Review*, 96, 106807.
- Liu, X., & Xu, H. (2022). Does low-carbon pilot city policy induce low-carbon choices in residents' living: holistic and single dual perspective. *Journal of Environmental Management*, 324, 116353.
- Yang, S., Jahanger, A., & Hossain, M. R. (2023). How effective has the low-carbon city pilot policy been as an environmental intervention in curbing pollution? Evidence from Chinese industrial enterprises. *Energy Economics*, 118, 106523.
- Xie, R., & Teo, T. S. (2022). Green technology innovation, environmental externality, and the cleaner upgrading of industrial structure in China—Considering the moderating effect of environmental regulation. *Technological Forecasting and Social Change*, 184, 122020.

- Yu, H., Peng, F., Yuan, T., Li, D., & Shi, D. (2023). The effect of low-carbon pilot policy on low-carbon technological innovation in China: Reexamining the porter hypothesis using difference-in-difference-in-differences strategy. *Journal of Innovation & Knowledge*, 8(3), 100392.
- Zhao, A., Wang, J., Sun, Z., & Guan, H. (2022). Environmental taxes, technology innovation quality and firm performance in China—A test of effects based on the Porter hypothesis. *Economic Analysis and Policy*, 74, 309-325.