sustainability

MDPI

Article

Low-Carbon Transition and Green Innovation: Evidence from Pilot Cities in China

Taohong Wang [1], Zhe Song [1], Jing Zhou [2], Huaping Sun [3,*] and Fengqin Liu [4,5,*]

[1] School of Business, Nanjing University, Nanjing 210093, China; dg20020062@smail.nju.edu.cn (T.W.); zsong1@nju.edu.cn (Z.S.)
[2] School of International Economics and Trade, Nanjing University of Finance and Economics, Nanjing 210023, China; zj173@163.com
[3] School of Finance and Economics, Jiangsu University, Zhenjiang 212013, China
[4] School of Law, Jiangsu University, Zhenjiang 212013, China
[5] Graduate School, Sehan University, Noksaek-ro 1113, Samho-eup, Yeongam-gun 58447, Korea
* Correspondence: shp797@163.com (H.S.); nbliufengqin617@163.com (F.L.)

Abstract: Officially launched in 2008, China's low-carbon city pilot project is aimed at creating green and low-carbon cities by restricting individual consumption and enterprise production behaviors as a means of controlling greenhouse gas emissions. Among other indicators, the impact of the pilot low-carbon initiative may be evaluated based on whether it induces enterprises to engage in green technology innovation. Using green patent application data from Chinese listed companies between 2009 and 2018, this paper applies a time-varying difference-in-difference (DID) model to conduct a multi-dimensional empirical test on the changes in listed companies' degrees of green innovation before and after the publication of the list of three batches of pilot cities. Our findings were as follows: first, as a means of environmental regulation, the pilot low-carbon city initiative's effect on enterprises' green technology innovation conforms to the Porter hypothesis—that is, it encourages enterprises to improve their production technology and enhances the green innovation levels of listed companies in pilot cities; second, in terms of regional differences, the low-carbon cities pilot initiative can significantly induce green innovation activities among enterprises in China's eastern region, but not in the central or western regions; third, from the perspective of enterprise ownership, the initiative promotes greater awareness of green innovation among non-state-owned enterprises than among state-owned enterprises. At the enterprise level, this paper provides theoretical support and empirical evidence for the success of the low-carbon city pilot initiative and highlights the implications for nationwide policy.

Keywords: low-carbon; pilot cities; green technology innovation; difference-in-difference model

Citation: Wang, T.; Song, Z.; Zhou, J.; Sun, H.; Liu, F. Low-Carbon Transition and Green Innovation: Evidence from Pilot Cities in China. *Sustainability* **2022**, *14*, 7264. https://doi.org/10.3390/su14127264

Academic Editor: João J. Ferreira

Received: 8 April 2022
Accepted: 1 June 2022
Published: 14 June 2022

1. Introduction

Among the gravest challenges facing mankind today is the unstable fluctuation of temperatures. Climate warming exposes millions of people to threats of flood, drought, and reduced availability of drinking water caused by melting glaciers, rising sea-levels, and frequent extreme weather events that endanger human life and property. Only when the trend of global warming is arrested will humans have a secure future.

The natural factors that contribute to global warming cannot be ignored, but the key role of anthropogenic contributors must be acknowledged. Over one million years have passed since our human ancestors abandoned their consumption of raw meat and blood. Over the intervening period, humans have continuously innovated new means of subsistence, from the earliest slash-and-burn agriculture to today's era of information and industrialization. The roar of machines has now replaced the cries of the hunt. The amounts of fossil fuel consumption required to run these machines is also increasing on a daily basis, and combustion-produced greenhouse gases have become one of the main drivers of the greenhouse effect. Moreover, numerous activities designed to meet the needs of human life and production, such as deforestation and land use changes, are also associated with large-scale greenhouse gas emissions. Scientists worldwide have reached the consensus that unchecked human behavior is the main cause of climate change. According to a report compiled by the humanitarian organization, Dara, without the implementation of effective measures to address the problem of climate change, more than 100 million people will lose their lives and economic growth will be reduced by 3.2% by 2030.

Countries have also recognized that climate warming will inflict irreversible harm to the earth on which humans depend. The Paris Agreement, jointly concluded by 196 parties in 2015, required all parties to submit their strategies for mitigating greenhouse gas emissions by 2020 and work together to limit average global temperature increases to below 2 °C above pre-industrial levels and, further, to aim toward an average temperature rise of below 1.5 °C compared to pre-industrial levels. To achieve this goal, parties to the agreement have taken measures to adapt to their national conditions and strengths and have enthusiastically entered a green and sustainable growth mode. China has also actively participated in international climate change issues and implemented a series of measures to deal with climate change. The low-carbon pilot city project is among the few projects in China to address simultaneously both residents' and enterprises' high carbon emissions. The project is aimed at restricting the behavior of residents and enterprises to promote low emissions and low pollution while maintaining high-speed development. This project thus plays a crucial role in reducing China's carbon emission levels.

The low-carbon city development project that China launched in 2008 lasted for 13 years. During this period, China announced three batches of low-carbon pilot cities in 2010, 2012, and 2017, respectively. With the goal of achieving peak carbon emissions, China has restricted the high-carbon-emission behaviors of enterprises and residents by imposing strict limits on enterprises' carbon emissions and vigorously supporting research and development relating to low-carbon products, thus fostering low carbon and environmentally friendly, green cities. This project restricts the high-carbon-emission behaviors of residents and enterprises at their source, and stimulates enterprises' and residents' eagerness to understand low-carbon initiatives and their willingness to apply this knowledge in practice, which has the effect of clarifying the source. Evaluation of the impact of the policy's implementation on enterprises' carbon emission levels is one of the methods available for evaluating the policy's effectiveness. In 2019, the United Nations Environment Programme projected that China's carbon dioxide emissions would continue to rise by 3%, and a total of 407 companies worldwide participated in the signing of the United Nations' 1.5 °C business target commitment. Chinese companies accounted for less than 2% of these 407 companies, and only three Chinese technological companies clearly indicated carbon neutrality. To realize the goal of controlling greenhouse gas emissions, more enterprises are required to participate in the measures targeting this goal. Investigation of the role and impact mechanisms of the low-carbon pilot policy at the enterprise level will not only provide guidelines for the respective pilot cities' governments' evaluations of the initiative's effects and implementation of the targeted policies, but will also provide a reference for cities subsequently included in the pilot.

The low-carbon city initiative is a crucial targeted policy adopted by China in a bid to reduce carbon emissions. The initiative tests an effective low-carbon city construction model in China by identifying pilot cities batch by batch. With the aim of reducing carbon consumption and production, low-carbon pilot cities' governments apply a suite of policy tools to restrict the carbon consumption and carbon production of both residents and enterprises. The governments of low-carbon pilot cities implement policies aimed at strictly regulating the emission of waste gas, wastewater, and waste from enterprises and stipulate production technology and pollutant emission concentration requirements to restrict carbon emissions during their production processes. For example, Zhenjiang city will include key enterprises with annual carbon emissions greater than 25,000 tons of carbon dioxide equivalent in the monitoring process and mete out penalization accordingly.

The low-carbon cities' governments' implementation of the corresponding policies will inevitably increase production costs for enterprises. Therefore, some enterprises will elect to reduce pollutant emissions by improving production technology used in the actual production process, which will offset or reduce environmental costs and enhance their innovation potential.

Low-carbon pilot city governments reduce green technology innovation costs using market-oriented policy tools—for example, by giving preferential treatment to green manufacturing enterprises as a means of encouraging other enterprises to engage in green production. For example, Beijing allocates a certain amount of incentive funds to enterprises selected for inclusion in the municipal and national green factory and green supply chain demonstration list. This policy can help alleviate the financial pressure associated with technological innovation, so that enterprises will have sufficient funds to invest in R&D and develop and use lower carbon and environmentally protective production technologies. Enterprises are required to disclose specific types of information to improve public awareness of environmental protection, foster enthusiasm for participation in environmental supervision, and compel other enterprises to transition to cleaner production and green manufacturing by resisting public pressures, such as those associated with high-carbon products and public opinion. The low-carbon pilot initiative can thus directly influence enterprises to engage in green technology innovation by increasing pollution control costs and subsidizing green production.

Most scholars' studies assume that environmental regulation is a mandatory measure or requirement taken by the government for enterprises, but some scholars propose that environmental regulation can be divided into official environmental regulation and voluntary regulation, and confirm that voluntary environmental regulation by enterprises has a significant incentive effect on the input and output of innovation [1,2]. The existing research on low-carbon pilot policies and enterprises' green technology innovation is extensive; however, studies of the ways in which low-carbon pilot policies affect enterprises' green technology innovation remain insufficient. The relevant articles include only the first or second two batches of low-carbon pilot provinces and cities using the traditional difference-in-difference (DID) model. We identify green patents using the international patent classification green list, and construct the indicators of the absolute and relative levels of the listed companies' green innovation, and analyze the impact of low-carbon pilot policies on enterprise green technology innovation by using the time-varying difference-in-difference model.

The remainder of the paper is arranged as follows: the second section summarizes the existing theories; the third section formulates the study's hypotheses; the fourth section tests the parallel trend and analyzes the empirical results; the fifth section tests the empirical results' robustness; the sixth section analyzes the heterogeneity from the two dimensions of enterprise ownership attributes and region; the seventh section includes mechanism research and analysis; and the final section presents the conclusions and policy implications.

2. Research Review

Few studies to date have examined the mechanisms by which low-carbon pilot policies impact green technology innovation at the enterprise level. However, several studies have investigated how environmental policies impact enterprises' green technology innovation efforts and the implementation effect of low-carbon city pilot policies.

2.1. Impact of Environmental Policies on Enterprises' Green Technology Innovation

Environmental policies aim to protect the environment, reduce pollutant emissions, and achieve sustainable economic development by restricting the behaviors of enterprises and individuals. The main mechanism by which environmental protection policies can restrict enterprises' behavior is the penalization of high-pollution activities. According to neoclassical economics, the charging system undoubtedly increases enterprises' production costs, resulting in the loss of cost advantage, sharp reductions in market competitiveness, negative effects on enterprises' development, and further financial constraints on enterprises' R&D investment. The capital and personnel investment of R&D are the key factors affecting the green technology innovation of enterprises and play a positive role in the green technology innovation [3]. Therefore, environmental protection policies will restrict enterprises from carrying out green technology innovation. However, Porter (1995) argued that a high-quality environment and economic development are not mutually exclusive: although environmental regulation increases enterprises' production costs, the maintenance of enterprise regulation within a reasonable range will compel enterprises to improve their production technology, production efficiency, and energy utilization efficiency to offset the cost of environmental pollution, enhance profitability, and reduce pollutant emissions [4]. In short, enterprises will take different actions when faced with environmental regulation. Enterprises' greater volition to manage regulation through green technology innovation aligns with the Porter hypothesis. Several studies have validated this hypothesis [5–7] with empirical findings indicating that environmental regulation can encourage enterprises to implement green technology innovation to a certain extent [8,9]. Studies have further explored the effects of different regulatory tools and found that various regulatory tools are used to restrict enterprise behavior and that enterprises' willingness to carry out green technology innovation also differs [10,11]. Most researchers have used listed companies' patent application data to measure enterprises' green technology innovation behavior. Findings demonstrate that the action form of environmental regulation on enterprise green technology innovation is not wholly consistent. The so-called reverse U-shape indicates that, in the early stage of the promulgation of environmental policies, enterprises' willingness to engage in green technology innovation will gradually increase, while after the policies have been implemented for some time, the enterprises are still willing to engage in green technology innovation, but that this willingness will gradually diminish [12]. The so-called inverted "n"-type indicates that, in the early stage of the promulgation of environmental policies, enterprises' willingness to engage in green technology innovation will gradually weaken, while after the policies have been implemented for some time, enterprises' willingness to engage in green technology innovation will undergo a process of initial reinforcement followed by weakening [13]. Scholars have also focused on particular regions and industries to explore the effects of regional and industrial differences on the impact of environmental regulations on enterprise green technology innovation [14,15].

2.2. Research on Environmental Policies for Low-Carbon Cities

Since low-carbon pilot city governments primarily reduce urban carbon emissions by regulating enterprises' production behavior and residents' consumption behavior, the literature on the policy effects of low-carbon city pilot policies has focused on two key aspects: some scholars have investigated the factors that affect residents' behavior, while others have started from the enterprise level and empirically analyzed enterprises' low-carbon emission behavior and the effectiveness of measures aimed at reducing carbon emissions. As the heart of any urban space, residents are undoubtedly essential stakeholders in the construction of low-carbon cities. Existing residents' consumption patterns primarily indicate high energy consumption, high carbon emissions, and high pollution. The promotion of low-carbon and low energy consumption, low emissions, and low pollution is thus a key approach to the construction of low-carbon cities. As such, the realization of this transformation should be at the heart of low-carbon city construction. In this regard, domestic and international research has formed a mature context system. Environmental psychology analyzes the factors that dominate consumer behavior. Consumer economics systematically analyzes consumption patterns from a disciplinary perspective, which is among the key approaches to the study of consumer behavior. It also discusses internal factors, such as consumer psychology and cognition, and external factors, such as policy, education, and economy, and comprehensively considers the interaction between the two [16–19].

As a major source of urban carbon emissions, enterprises should be a key target of green and low-carbon city construction supervision. What attitudes do enterprises exhibit in the face of environmental policies? Are the measures taken by the enterprise effective? Do enterprises adopt different measures for different policy tools? These issues require investigation to assess enterprises' attitudes toward low-carbon city construction and to evaluate enterprises' contribution to low-carbon city construction. Evidence suggests that the low-carbon pilot initiative can encourage enterprises to engage in technological innovation, upgrade industrial structure, and reduce urban carbon emissions [20–22]. Research on low-carbon pilot policies has also offered suggestions as to how consideration indicators can be reasonably and effectively determined and corresponding policies may be designed [23–25].

2.3. Impact of Low-Carbon Pilot Policy on Enterprise Green Technology Innovation

The term "low-carbon pilot policy" does not refer to a particular policy, but rather to a comprehensive policy aimed at regulating various behaviors associated with environmental pollution and encouraging behaviors that are beneficial to environmental construction. The policy proposes to use penalties and incentives to fully engage enterprises' and individuals' awareness of the need to conserve resources and reduce energy consumption and pollutant emissions. As one of the initiative's targets, low-carbon enterprises will inevitably be affected by the abovementioned policies. Urban panel data indicate that the low-carbon pilot policy has improved urban technological innovation [26]. As a key player in technological innovation, enterprises' innovation behavior should become the foundation of urban technological innovation. On this basis, further investigation of low-carbon pilot policies' effects on enterprises' technological innovation activities is warranted. Most scholars have measured the degree of enterprise green technology innovation based on enterprises' green patent data—a logical approach. As one of the methods used to evaluate the effect of policy implementation, the time-varying difference-in-difference (DID) model is often used to assess pilot policies in low-carbon cities. Scholars have used the above two methods to explore the impact mechanism of low-carbon pilot policies on enterprises' green technology innovation [27,28]. Studies have confirmed that the degree of enterprises' green innovation in low-carbon pilot cities has improved significantly compared with the situation before, and without the pilot city initiative. Moreover, compared with low-carbon industry enterprises and state-owned enterprises, medium- and high-carbon industry enterprises and non-state-owned enterprises in pilot cities exhibit stronger willingness to engage in green technology innovation.

In view of these limitations, this paper's marginal innovation is mainly reflected in the following aspects: first, we collect patent data from parent companies and their subsidiaries from a list of Chinese companies, from 2009 to 2018, identify green patents using the international patent classification green list, and construct the indicators of the absolute and relative levels of the listed companies' green innovation. Second, using the time-varying difference-in-difference model and taking the promulgation time of the three batches of pilot policies as the time node, this study analyzes the impact of low-carbon pilot policies on enterprise green technology innovation. Third, taking technological innovation and human capital accumulation as intermediary variables, this paper analyzes the mechanisms by which low-carbon pilot policy impacts enterprises' green technology innovation.

3. Theoretical Hypothesis, Model, and Data

3.1. Theoretical Hypothesis Setup

The Porter hypothesis holds that although environmental regulation will increase production costs and reduce enterprises' competitiveness by increasing pollution control fees, appropriate regulation will compel enterprises to invest in production and R&D for technological innovation to synchronize benefit increase and environmental optimization. According to neoclassical economic theory, the collection of pollution control fees will exert an irreversible negative impact on the development of enterprises, primarily because the charging system increases their production costs, placing enterprises at a competitive disadvantage, which reduces profitability, and makes it difficult to sustain the capital investment that can be used for R&D, thus hindering the reformation of production technology. Continued use of older technology can exacerbate pollution, increase production costs and cause costs to fluctuate, jeopardizing the survival of an enterprise. Enterprises that are cognizant of these risks are more willing to invest in areas that operate according to more tolerant environmental policies. It is also possible that for enterprises in areas with strict policies, technological innovation can decline and economic development and innovation ultimately stagnate. The above two theories exhibit polarization in their analysis of the impact of environmental regulation on enterprise technological innovation; as such, further theoretical exploration is warranted.

Studies have found that the low-carbon pilot city policy negatively impacts city trade dependence [29]. The economic development of almost all cities in China continues to be dominated by the export of medium- and low-end products and processing and manufacturing. This trade structure directly increases cities' trade-associated carbon emissions, which makes it difficult for China to consider simultaneous trade expansion and environmental optimization. This trade model cannot be easily changed within a short time frame, and hinders low-carbon trade that is driven by science and technology. Enterprises that opt to engage in green technology innovation and abandon the traditional trade model are bound to undergo difficult periods [30,31]. Moreover, the low-carbon pilot city policy's transition to the government's investment policy and the location choices of foreign-funded enterprises are not conducive to technological innovation [32]. The pollution shelter hypothesis concerns the role that environmental policy plays in foreign direct investment. The hypothesis holds that the enhancement of environmental regulation will increase enterprises' production costs, which is not conducive to increased foreign direct investment [33–35]. To sum up, this paper proposes the following:

Hypothesis 1. *Enterprises' green technology innovation in low-carbon pilot cities will be restrained.*

The implementation scope of the low-carbon cities pilot policy covers most parts of China, and the industrial model is closely related to economic level and carbon emissions. On the one hand, the industrial structures of central and southern Liaoning and Beijing-Tianjin-Tangshan regions, which are dominated by heavy industry, determine that the proportion of coal in the urban energy consumption structure of these regions is high, enterprise emission reduction costs are very high, and excessive coal use is often accompanied by high carbon emissions; on the other hand, the Pearl River Delta and Shanghai-Nanjing-Hangzhou regions, which are dominated by light industry, have higher economic development levels and more funds to invest in R&D for energy-saving and emission reduction technological transformation, making the decline in carbon emission intensity in these regions more possible [36]. Therefore, this paper proposes the following:

Hypothesis 2. *Compared with the central and western regions, the low-carbon city policy is more helpful in promoting green technology innovation among urban enterprises in China's eastern region.*

China's existing enterprises can be divided into state-owned and non-state-owned enterprises. When the state is the actual owner of the enterprise, all economic behaviors are determined by the government department. Since enterprises may have different owners, willingness to engage in green technology innovation in the context of environmental policies may also vary. While state-owned enterprises are natural practitioners of government policies, they also enjoy policy support in various aspects, including financial subsidies, tax relief, and financing facilities [37]. Therefore, it is difficult for external enterprises to pose a significant competitive threat to them, given that their environmental regulation is weak, and the degree to which green technology innovation is induced is limited. Non-state-owned enterprises' means of production are completely privately owned and exclusively for profit, and they are also responsible for their own profits and losses. The market competition is more intense, and willingness to improve production technology while reducing pollution costs in the production process under the action of environmental regulation is stronger [38]. Therefore, this paper proposes the following:

Hypothesis 3. *Compared with state-owned enterprises, non-state-owned enterprises are more willing to engage green technology innovation in the context of low-carbon pilot policies.*

The intention to construct low-carbon pilot cities is not a mere pipe dream. However, to make low-carbon cities a reality, not only are efforts required on the part of enterprises, but the government must also contribute to the green innovation process. Financial investment is undoubtedly one of the primary means by which the government may participate in social governance: the government provides enterprises with financial support with the aim of promoting R&D and innovation. Such investments are recorded as science and technology expenditure in the urban statistical yearbook. Can government expenditure of this nature motivate enterprises to engage in green technology innovation? According to the existing literature, enterprises' R&D and innovation activities are significantly constrained by capital. Where government capital investment is available, it can significantly encourage green technology innovation. Therefore, this paper proposes the following:

Hypothesis 4. *The governments of low-carbon pilot cities will motivate enterprises to engage in green technology innovation through increased science and technology expenditure.*

As a city's economy undergoes rapid development, its demand for talent increases accordingly. Under the banner of advocating for "green development," low-carbon pilot cities' governments will accomplish the construction of low-carbon cities through high-quality talent training. Talent is one of the most indispensable elements that enterprises require for technological innovation [39]. Low-carbon pilot cities can not only influence the innovation behavior of enterprises through financial investment, but can also cultivate high-quality R&D personnel, providing enterprises with a source of R&D and innovation manpower. Therefore, this paper proposes the following:

Hypothesis 5. *The governments of low-carbon pilot cities will motivate enterprises to engage in green technology innovation by promoting the accumulation of human capital.*

3.2. Model Design

This paper aimed to explore the mechanisms by which low-carbon pilot policy impacts enterprises' green technology innovation. As an effective tool in the policy effect evaluation method toolbox, the difference-in-difference method is undoubtedly the optimal choice for this study. In this paper, the investigation of low-carbon city pilot policies covers three batches of pilot provinces and cities. The publication time of the three batches of pilot cities is set as the policy impact point, and a time-varying difference-in-difference model is constructed. Since the list of the first batch of low-carbon pilot cities was published in July 2010 and the list of the second batch was published in November 2012, considering governments' and enterprises' response time lag, the policy impact points of the two batches were set as 2011 and 2013, respectively. In line with the difference-in-difference model's basic concept, from the perspective of enterprise green innovation, this paper compares the degrees of green innovation between pilot areas and non-pilot areas before and after the low-carbon pilot policy and eliminates the factors that remain fixed over time and cannot be observed to evaluate reasonably the implementation effect of the low-carbon pilot policy. When the individual policy impact time points in the treatment group are inconsistent, it is necessary to use the time-varying difference-in-difference model for processing. The general DID model is as follows:

$$y_{i,t} = \beta_0 + \beta_1 treat_i + \beta_2 post_t + \beta_3 treat_i \times post_t + \alpha x_{i,t} + \epsilon_{i,t} \tag{1}$$

where, $y_{i,t}$ is the dependent variable; i(i = 1, ... , N) represents an individual; t(t = 1, ... , T) represents time; $x_{i,t}$ represents the control variable, which varies over time and per individual; α is the coefficient of the control variable; $\epsilon_{i,t}$ is the model error term; $treat_i$ is a group virtual variable and individual i belongs to the treat group; then $treat_i = 1$, individual I belongs to the treat group, and $post_t$ is a virtual variable of time. After the policy is implemented, click $post_t = 1$, otherwise, $post_t = 0$; and its coefficient β_2 reflects the time effect. Meanwhile, $treat_i \times post_t$ is the cross-multiplication term of $treat_i$ and $post_t$, and its coefficient β_3 reflects the policy effect of DID.

Equation (1) can only represent the traditional DID model—that is, all individuals in the treatment group are impacted by the policy at the same time point. When the individual treatment group's policy impact time point is inconsistent, it must be handled using the time-varying DID model. Based on the relevant data, this paper constructs time-varying DID model as follows:

$$EP_{i,t} = \alpha + \theta D_{r,t} + \rho X_{i,t} + u_i + \lambda_i + \delta_t + \epsilon_{i,t,r} \tag{2}$$

where i, t, and r represent the enterprise, time, and city, respectively, and $EP_{i,t}$ represent the green patent applications of enterprise I in year t. $D_{r,t}$ is a fictitious variable of the treated period that varies by region, indicating whether the city r is impacted by the policy in year t. If the city r is impacted by the policy in year t, it means that the city r enters the treated period, and the value of all subsequent periods is 1; otherwise, the value is 0. $X_{i,t}$ is a series of control variables affecting enterprise green technology innovation. u_i, λ_i, and δ_t refer to the fixed effect of province, industry, and time; $\epsilon_{i,t,r}$ represents the random disturbance term. In Equation (2), only the total number of enterprises' green patent applications (EP) is regressed as a dependent variable. The subsequent empirical results will also reflect the incorporation of the number of green invention patent applications (EIP) and green utility model patent applications (EUP) into the regression as dependent variables. In the robustness test, the Equation (2) is also used for regression. The only difference being the replacement of the absolute value of green patent as the dependent variable with the corresponding relative value of green patent.

3.3. Data Source and Processing

3.3.1. Variable Description

Scholars often use green patent data to measure enterprises' green technology innovation. Therefore, this paper selects listed companies' green patent application volumes as the explanatory variable. The data are obtained by calculating the logarithm of the collected enterprise green patent application volume, which is replaced by EP below. Patents can be divided into invention patents and utility model patents. To determine further which patent application types are most significantly affected by low-carbon city pilot policies, we collected corresponding data and performed logarithmic processing to obtain the numbers of enterprise green invention patent applications (EIP) and green utility model patent applications (EUP). The robustness test is performed using data for the proportion of green patent applications in all patent applications of the listed company (REP), the proportion of green invention patent applications in all invention patent applications of the company (REIP), and the proportion of green utility model patent applications in all utility model patent applications of the company (REUP) to ensure the robustness of the benchmark analysis. The ratio of each city's scientific and technological R&D expenditure to regional financial expenditure is used to represent technological innovation, and the sum of the product of the number of students in primary schools, middle schools, and ordinary colleges and universities and their corresponding years of education is used to represent human capital accumulation.

To minimize the impact of inter-enterprise differences on the analysis results, this paper first used the common control variables at the enterprise level, including a series of variables, such as enterprise debt, Tobin Q value, and capital intensity. However, the estimation results indicate that including these variables will reduce the significance.

Therefore, this paper omits several control variables commonly used by enterprises and only controls the enterprise size (lnsize) measured by the logarithm of the total capital at the end of the year, the enterprise liabilities (lndebts), the return on total assets (ROA), the shareholding ratio of the largest shareholder (Top1), and the proportion of the number of independent directors in the total number of directors (independ). At the city level, the industrial structure is controlled by the output value of regional tertiary industry accounts for the proportion of regional GDP; for the sulfur dioxide emission per unit output value, the logarithm ($lnSO_2$) is taken for the emission. Considering that a change in enterprise scale mainly affects subsequent strategic decision-making, the enterprise's current liabilities will affect R&D investment of the company in the next phase in the long run, and so the enterprise's scale and liabilities are delayed by one phase, and are used by lnsize and lndebts, respectively. At the same time, industrial structure and sulfur dioxide emissions are significantly affected by the policy, and the policy's promulgation results in a lag to its effect. Therefore, these two variables also lag by one period, using industry and $lnSO_2$, respectively. The indicator measures and data sources mentioned above are shown in Table 1.

Table 1. Index measurement and data source.

Variable	Measures	Data Source
EP	Green patent application volume of listed companies	State Intellectual Property Office of the People's Republic of China
REP	Proportion of green patent applications in all patent applications of the listed company	
Te	Proportion of R&D expenditure of each city in regional financial expenditure	China Urban Statistical Yearbook
human	The sum of the product of the number of students in primary schools, middle schools and ordinary colleges and universities and their corresponding years of education	
lnsize	Proportion of the number of independent directors in the total number of directors	CSMAR database
lndebts	Logarithm of corporate liabilities	
Top1	Shareholding ratio of the largest shareholder	
independ	Proportion of the number of independent directors in the total number of directors	
ROA	The return on total assets	
industry	The proportion of regional tertiary industry output value in regional GDP lags behind by one period	China Urban Statistical Yearbook
$lnSO_2$	The logarithm of sulfur dioxide emission per unit output value lags by one period	

3.3.2. Data Source and Processing

This paper uses patent data from A-share listed companies in China's Shanghai and Shenzhen stock markets from 2009 to 2018 and the corresponding enterprise- and city-level data to conduct a descriptive statistical analysis (see Table 2). The patent data were obtained from the State Intellectual Property Office of the People's Republic of China, the economic data were obtained from the CSMAR database, and the urban-level data are from the 2010–2019 China Urban Statistical Yearbook. According to the regulations of the People's Republic of China on the administration of the registration of enterprise legal persons (hereinafter referred to as "the regulations"), state-owned enterprises are those registered in accordance with the regulations, and the investment subject of assets is the state-owned assets management department, while the remainder are non-state-owned enterprises.

Table 2. Descriptive statistical characteristic of main variables.

Variable	Index	Observations	Average	S.D	Min	Max
EP	Green patent applications	19,690	0.26	0.668	0	5.602
REP	Proportion of green patents	19,690	0.033	0.106	0	0.996
Te	Technological innovation	19,690	0.016	0.014	0.002	0.057
human	Human capital accumulation	18,050	1647.65	1944.572	35.69	15,000
lnsize	Logarithm of enterprise scale	19,689	22.134	1.512	15.418	30.952
lndebts	Logarithm of corporate liabilities	19,688	−0.958	0.659	−4.89	4.015
Top1	Ratio of the largest shareholder	19,690	34.998	15.212	3.003	100
independ	Independent director proportion	19,654	0.419	2.132	0.1	100
ROA	Return on total assets	19,689	0.041	0.806	−5.259	108.366
industry	Industrial structure	19,690	53.326	13.609	0	80.98
$lnSO_2$	Logarithm of sulfur dioxide emission per unit output value	19,690	−7.669	1.828	−14.514	−2.577

Data source: China Urban Statistical Yearbook (2010–2019), CSMAR database, State Intellectual Property Office of the People's Republic of China.

This paper studies the impact of low-carbon city pilot policies on enterprises' green technology innovation. Owing to the missing value in the collected data, this paper excludes samples with missing values in the listed companies' green patent data from 2009 to 2018. Samples from enterprises aged less than or equal to one year are eliminated. After screening, 19,690 cross-sectional data entries were obtained.

4. Parallel Trend Test and Empirical Result Analysis

4.1. Parallel Trend Test

To use the difference-in-difference method to evaluate the policy effect, the control group and the experimental group must show the same change trend prior to the policy's impact. Before the low-carbon pilot policy impact, enterprises' green innovation trends in low-carbon pilot cities and non-pilot cities should be consistent. Therefore, prior to using the difference-in-difference method for estimation, a parallel trend test must be conducted to determine whether the change trend of the number of green patent applications of enterprises in the experimental group is consistent with that of enterprises in the control group before the implementation of the low-carbon pilot policy. In this paper, the green patent application data are aggregated according to the pilot batches, and the average value at the enterprise level is taken to replace the average value of green patent applications in cities. The mean value is taken as the vertical axis and the year as the horizontal axis to obtain the parallel trend test chart (as shown in Figure 1).

The four broken lines in Figure 1 represent the green patent application values of unit enterprises in the first, second, and third batches of low-carbon pilot areas and non-pilot areas, respectively. The marked times in the figure are 2011, 2013, and 2017, respectively. Taking 2011 as the dividing line, no significant gap is evident in the number of green patent applications of unit enterprises in the first three batches of pilot areas and non-pilot areas in 2011; the four broken lines are essentially at the same level and overlap from time to time. From 2008 to 2013, the number of unit enterprises' green patent applications in the second batch of low-carbon pilot areas was essentially parallel to that in non-pilot areas. Before the promulgation of the pilot policy (2008–2017), no major gap was observed between the change trends of unit enterprises' green patent applications in the third batch of pilot regions and non-pilot regions. The above indicates that, before the implementation of the low-carbon pilot, the experimental and control groups' green innovation trends showed no systematic difference, which satisfies the parallel trend hypothesis.

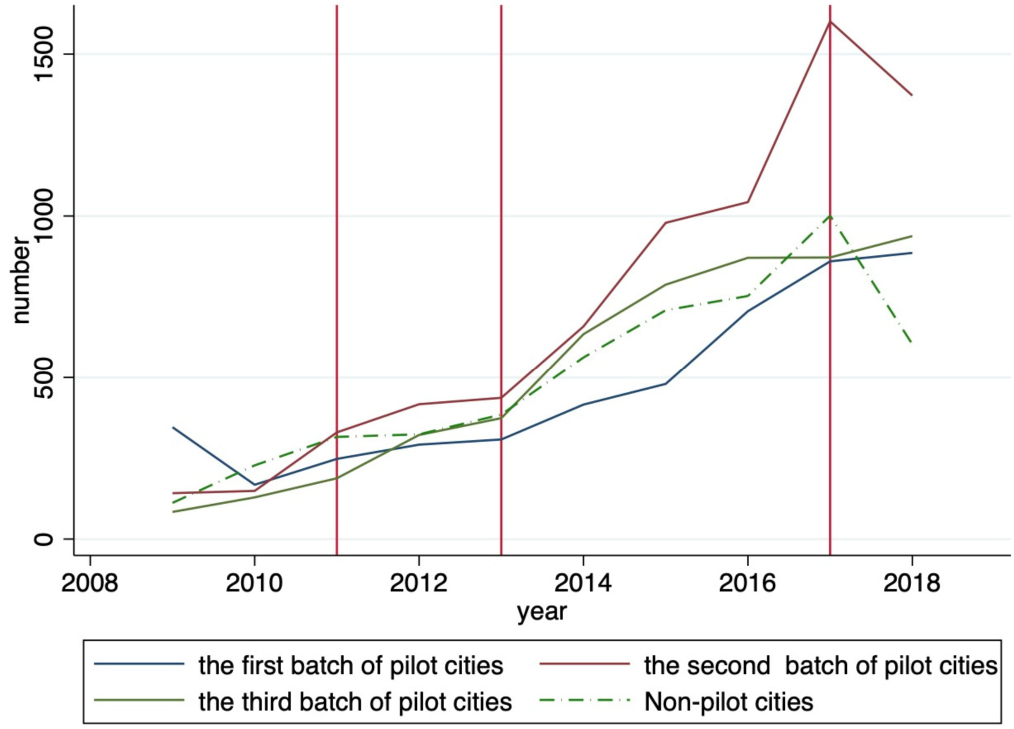

Figure 1. Comparison of patent applications of unit enterprises between pilot areas and non-pilot areas. Data source: State Intellectual Property Office of the People's Republic of China.

Further measurement tests will be conducted for the sample's parallel trend (see Table 3). This paper applies the parallel trend test method using the time-varying DID model, where D_ N (n = 0, 1, 2, 3, 4, 5) represents the corresponding interactive item of N years before policy implementation and D_2 refers to the interaction item between the dummy variable and the treated group variable in the two periods before the occurrence of the policy; DN represents the corresponding interaction item after the policy's implementation. For example, D2 represents the interaction item between the virtual variable and the treated group variable in phase 2 after the policy's implementation, while D0 represents the policy's current phase. Taking the period before the policy's implementation (i.e., D_phase 1) as the benchmark group, in accordance with the parallel trend test, the coefficient of DN and D_N can be used to evaluate whether it meets the assumption of parallel trend. Table 3 indicates that, prior to the low-carbon pilot policy's implementation; the virtual variable coefficient of D_N is not significant, regardless of the absolute level or relative level of green innovation. This indicates that prior to its inclusion in the construction of low-carbon pilot cities, the change in the degree of green innovation among enterprises in both pilot cities and non-pilot cities is consistent, and no difference emerges with respect to years—that is, it meets the requirements of the parallel trend hypothesis.

Table 3. Parallel trend test results.

	Absolute Value of Green Patent Applications			**Relative Value of Green Patent Applications**		
	EP	**EIP**	**EUP**	**REP**	**REIP**	**REUP**
	(1)	**(2)**	**(3)**	**(4)**	**(5)**	**(6)**
D_5	0.00494	−0.00881	0.0126	0.00124	0.00399	−0.000224
	(0.0264)	(0.0201)	(0.0164)	(0.00639)	(0.00556)	(0.00411)
D_4	0.0159	0.0158	0.000905	6.61×10^{-5}	0.00126	−0.00154
	(0.0222)	(0.0153)	(0.0169)	(0.00234)	(0.00246)	(0.00225)
D_3	0.00546	0.00934	−0.00437	−0.000667	-9.28×10^{-5}	−0.00288
	(0.0178)	(0.0144)	(0.0132)	(0.00242)	(0.00323)	(0.00207)
D_2	0.00673	0.0112	−0.00496	0.000607	0.00226	−0.00169
	(0.0202)	(0.0176)	(0.0124)	(0.00317)	(0.00352)	(0.00247)
D0	0.00291	0.00663	−0.0134	0.000287	0.00122	−0.000305
	(0.0214)	(0.0177)	(0.0134)	(0.00288)	(0.00294)	(0.00213)
D1	-6.40×10^{-5}	−0.00290	−0.00495	0.000190	0.00114	−0.000899
	(0.0182)	(0.0166)	(0.0119)	(0.00257)	(0.00301)	(0.00173)
D2	−0.00347	−0.000727	−0.0120	0.00127	0.00303	−0.00104
	(0.0243)	(0.0197)	(0.0168)	(0.00275)	(0.00365)	(0.00240)
D3	−0.0222	−0.0163	−0.0199	0.000528	0.00148	−0.00142
	(0.0210)	(0.0158)	(0.0138)	(0.00304)	(0.00336)	(0.00251)
D4	−0.0178	−0.0104	−0.0182	0.00105	0.00172	2.14×10^{-5}
	(0.0197)	(0.0134)	(0.0180)	(0.00214)	(0.00249)	(0.00214)
D5	−0.0228	−0.0162	−0.0106	−0.00164	−0.00129	−0.00115
	(0.0163)	(0.0120)	(0.0170)	(0.00292)	(0.00306)	(0.00259)
Control variable	Yes	Yes	Yes	Yes	Yes	Yes
Constant	1.255 ***	0.817 ***	0.916 ***	0.145 ***	0.143 ***	0.111 ***
	(0.0728)	(0.0489)	(0.0612)	(0.0102)	(0.0115)	(0.00538)
time fixed effect	Yes	Yes	Yes	Yes	Yes	Yes
industry fixed effect	Yes	Yes	Yes	Yes	Yes	Yes
province fixed effect	Yes	Yes	Yes	Yes	Yes	Yes
Observations	19,690	19,690	19,690	19,690	19,690	19,690

Note: The standard deviation of cluster adjustment at the city level is in parentheses; *** indicates 1% of significance level. The following tables are the same. Data source: China Urban Statistical Yearbook (2010–2019), CSMAR database, State Intellectual Property Office of the People's Republic of China. The following tables are the same.

4.2. Impact of Low-Carbon Pilot Policy on Enterprise Green Technology Innovation

According to the time-varying DID model constructed above, the total number of enterprise green patent applications, the number of enterprise green invention patent applications, and the number of enterprise green utility model patent applications are, respectively, brought into the model and estimated using STATA software (see Table 4). After controlling the fixed effects of time, province, and industry, the estimated results are shown in columns (1), (3), and (5). Meanwhile, the estimated results are presented in columns (2), (4), and (6) when we transform the fixed effects of province and industry into the fixed effects of corresponding province and industry over time. As long as the individual fixed effect is included in the model, factors that remain fixed at all times, such as industry, region, province, enterprise ownership, and enterprise scale, cannot be controlled in the model, and so this paper does not control the individual fixed effect. The results presented in Table 4 also use the cluster adjustment standard error at the city level when estimating, and the results are placed in parentheses in the table.

Table 4. Impact of low-carbon pilot on green technology innovation of enterprises.

	EP		EIP		EUP	
	(1)	(2)	(3)	(4)	(5)	(6)
Dr.t	0.0225	0.0468 ***	0.0142	0.0385 **	0.00697	0.0209 *
	(0.0153)	(0.0174)	(0.0144)	(0.0171)	(0.00986)	(0.0126)
lnsize_	0.0603 ***	0.0604 ***	0.0503 ***	0.0499 ***	0.0344 ***	0.0367 ***
	(0.00644)	(0.00678)	(0.00529)	(0.00500)	(0.00461)	(0.00524)
lndebts_	0.0254 ***	0.0220 ***	0.0180 **	0.0143 *	0.0175 ***	0.0170 ***
	(0.00820)	(0.00772)	(0.00777)	(0.00743)	(0.00519)	(0.00515)
independ	−0.000173	−0.000350	3.95×10^{-5}	−0.000496 **	−0.000355	-4.41×10^{-5}
	(0.000342)	(0.000331)	(0.000250)	(0.000237)	(0.000237)	(0.000236)
Top1	−0.000550	−0.000409	−0.000267	−0.000131	−0.000423	−0.000375
	(0.000575)	(0.000545)	(0.000456)	(0.000434)	(0.000369)	(0.000357)
ROA	−0.00110	0.00165	0.000188	0.00288 *	−0.00171 **	-4.35×10^{-5}
	(0.00144)	(0.00216)	(0.00133)	(0.00170)	(0.000832)	(0.00132)
industry	0.000551	0.00107	0.00108	0.00160	7.16×10^{-5}	0.000420
	(0.00167)	(0.00189)	(0.00120)	(0.00134)	(0.00118)	(0.00138)
$\ln SO_2$_	−0.000381	−0.0269 **	−0.000429	−0.0259 **	−0.00471	−0.0103
	(0.00540)	(0.0113)	(0.00439)	(0.0108)	(0.00350)	(0.00629)
Constant	−1.284 ***	−1.317 ***	−1.131 ***	−1.206 ***	−0.734 ***	−0.725 ***
	(0.204)	(0.229)	(0.158)	(0.172)	(0.140)	(0.162)
time fixed effect	Yes	Yes	Yes	Yes	Yes	Yes
province fixed effect	Yes	Yes	Yes	Yes	Yes	Yes
industry fixed effect	Yes	Yes	Yes	Yes	Yes	Yes
province × time fixed effect	No	Yes	No	Yes	No	Yes
industry × time fixed effect	No	Yes	No	Yes	No	Yes
Observations	16,690	16,690	16,690	16,690	16,690	16,690

Note: *, ** and *** indicate 10%, 5%, and 1% of significance levels, respectively.

According to columns (1), (3), and (5) of Table 4, the coefficient of the dummy variable Dr.t in the processing period of dual regression varies from region to region and is not significant on the basis of adding the fixed effects of industry, province, and time and controlling the relevant economic variables of enterprises and cities; that is, the low-carbon pilot policy has no significant impact on the number of green patent applications of enterprises. The results in columns (2), (4), and (6) demonstrate that the coefficients of Dr.t are significant at the levels of 1%, 5%, and 10%, respectively, indicating that after controlling the fixed effect of time, the fixed effect of provinces over time, and the fixed effect of industries over time, pilot city enterprises' willingness to engage in green technology innovation is significantly stronger than that of pre-pilot and non-pilot city enterprises, which is consistent with the research results of other scholars [40]. The results presented in column (4) demonstrate that the coefficient of Dr.t is significantly positive at the level of 5%, and the results presented in column (6) indicate that the value of the Dr. t coefficient is significantly positive at the level of 10%. This indicates that, compared with the creation of utility models, enterprises prefer to improve production technology and engage in green technological innovation through invention and creation.

The so-called utility model patent means that through technological transformation, the product's shape and structure is better suited to real-life use. Compared with the invention patent, it has outstanding practical value, but the requirements regarding the creativity and technical level of the product's structure and shape are fewer than those of the invention patent. Any technical improvement involving the product and its production process belongs to the invention patent's content. We speculate herein that among enterprises' main motivations for engaging in green innovation is to improve production levels and reduce energy consumption. Utility model patents exclusively target products' shapes or structures, and it is difficult to improve production levels by applying new technologies to these parts. Enterprises should seek to reduce carbon emissions mainly from the production process, and it is relatively easy to reduce carbon emissions and improve productivity by using new production processes. Therefore, enterprises will prioritize green inventions to reduce carbon emissions. At the same time, enterprises are constrained by the availability of funding, and the funds used to carry out R&D and the innovation of green utility models will be limited, resulting in a phenomenon whereby the low-carbon pilot policy plays only a minor role in promoting the patent application of green utility models.

The estimation results indicate that the low-carbon pilot policy has significantly increased the total number of green patent applications and green invention patent applications of listed companies in the pilot cities compared with those before the policy's implementation and those in non-pilot cities, indicating that the policy plays a significant role in promoting green innovation. The empirical results are wholly contrary to hypothesis 1, which indicates that the role played by the low-carbon city pilot policy in enterprises' green technology innovation is more in line with the Porter hypothesis. When faced with environmental regulation, enterprises exhibit strong intentions to improve production technology and engage in green production. Diminished foreign investment has had no decisive impact on R&D investment.

With respect to the control variables, enterprise scale and asset liability ratio play significant roles in promoting enterprises' green technology innovation, demonstrating that both larger and smaller enterprises are more keenly aware of the importance of green technology innovation. The proportion of independent directors and the shareholding proportion of the largest shareholder have a negative impact on enterprises' green technology innovation activities, indicating that major shareholders' innovation consciousness affects enterprises' innovation investment. The ROA has two effects on enterprises' green innovation behavior, which may be the result of external factors. The influence coefficient of the industrial structure variable is positive, which reflects that the increase in the tertiary industry's proportion is conducive to enterprise green technology innovation. The impact coefficient of sulfur dioxide emission is negative—that is, increased urban sulfur dioxide emissions will inhibit green technology innovation, and the effect of the government's policy to restrict enterprises' sulfur dioxide emissions has yet to be reported.

5. Robustness Test

As mentioned above, an important precondition for use of the difference-in-difference model is to ensure that the control group and the experimental group show no systematic difference prior to the policy's impact. On this basis, the difference-in-difference model can be used for analysis. However, whether changes in the trend of the experimental group after the policy impact are the result of the impact of the low-carbon pilot policy demonstrated in this paper requires further testing—that is, the robustness test. The robustness test includes, but is not limited to, changing variables, adjusting methods, eliminating special samples, and solving endogenous problems. In this paper, we use the proportion of green patent applications of listed enterprises in all enterprises' patent applications to replace the enterprises' green patent applications for the robustness test—that is, the explanatory variable in Equation (2) is replaced with the corresponding proportion of green patent applications. Table 5 shows that after controlling the control variables and fixed effects, the coefficient values shown in columns (1), (2), and (3) are significant at the 10% level. This demonstrates that no differences emerge whether the relative value of enterprise green patent is used as the dependent variable to measure the degree of enterprise green innovation or whether the absolute value of the enterprise green patent is used. The low-carbon pilot policy can still significantly motivate enterprises to engage in green technology innovation, which proves the robustness of the above analysis.

Table 5. Proportion of green patent applications of enterprises.

	REP	**REIP**	**REUP**
	(1)	**(2)**	**(3)**
Dr.t	0.00597 **	0.00631 *	0.00394 *
	(0.00245)	(0.00329)	(0.00233)
Control variable	Yes	Yes	Yes
Fixed effect	Yes	Yes	Yes
	v2	v3	v4
Constant	−0.109 ***	−0.128 ***	−0.0488 ***
	(0.0229)	(0.0259)	(0.0166)
Observations	16,690	16,690	16,690

Note: time fixed effect and province × time fixed effect and industry × time fixed effects are controlled in regression. The following tables are the same. *, ** and *** indicate 10%, 5%, and 1% of significance levels, respectively.

6. Heterogeneity Test

6.1. Regional Heterogeneity Test

High-quality environmental and economic developments are not mutually exclusive. The differences in the degree of green innovation undertaken by enterprises in the eastern, central, and western regions, which differ significantly with respect to economic development, exemplifies this point. In this paper, the dummy variables set in the east, central, and west regions are regressed (see Table 6). The size and positive and negative of the difference-in-difference partial coefficient reflect the low-carbon pilot policy's impact on enterprises' green technology innovation across the three regions. Columns (1), (4), and (7) in Table 6 present the results of regression with enterprise green patent applications; columns (2), (5), and (8) present the results of regression with enterprise green invention patent applications; and columns (3), (6), and (9) are the results of regression with enterprise green practical new patent applications. After controlling the control variables and fixed effects at the city and enterprise levels, only the difference-in-difference partial coefficient of regression using the total number of enterprise green patent applications in the eastern region is significant at the level of 10%. Meanwhile, the results of the regression using the green invention patent and green utility model patent applications in the eastern region show no significant impact. This may be an error caused by the interference of external factors. The role of green technology innovation in the central and western regions is not significant, and the coefficient value in the western region is negative, indicating that the low-carbon city pilot policy shows a negative inhibitory effect on the green technology innovation of enterprises in the western region. This may be because the western region is dominated by heavy industry, the proportion of coal in the energy consumption structure is high, the cost of enterprise emission reduction is high, and the region's economic development level is lower, which restricts the capital investment of enterprise green technology innovation and hinders the technological innovation of regional enterprises in line with neoclassical economic thought. In general, the low-carbon pilot policy has a stronger stimulating effect on the willingness of enterprises in the eastern region to engage in green innovation, the willingness of enterprises in the central region to carry out green innovation is not significantly stimulated by the low-carbon pilot policy, and the willingness of enterprises in the western region to engage in green innovation will be restrained by the low-carbon pilot policy. Differences are evident in the behavior of enterprises facing regulatory policies owing to different economic development levels. To sum up, hypothesis 2 aligns with the actual situation.

Table 6. Regional heterogeneity test.

	East			Central			West		
	EP	**EIP**	**EUP**	**EP**	**EIP**	**EUP**	**EP**	**EIP**	**EUP**
	(1)	**(2)**	**(3)**	**(4)**	**(5)**	**(6)**	**(7)**	**(8)**	**(9)**
Dr.t	0.041 **	0.037 **	0.0143	0.0665	0.0538	0.0187	0.0577	−0.00689	0.100 ***
	(0.019)	(0.019)	(0.0140)	(0.0567)	(0.0539)	(0.0365)	(0.073)	(0.0677)	(0.0331)
Control variable	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Fixed effect	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Observations	12,295	12,295	12,295	2879	2879	2879	1264	1264	1264

Note: ** and *** indicate 5% and 1% of significance levels, respectively.

6.2. Heterogeneity Test of Enterprise Ownership

Enterprise ownership is categorized according to the ownership of the enterprise's property. Enterprises whose entire property belongs to the state are state-owned enterprises, and non-state-owned enterprises correspond to state-owned enterprises. Because enterprises' ownership structures will affect their resources, institutions, and cognition as well as their responses to policies, enterprise ownership is also considered one of the most important institutional factors in emerging economies. In categorizing the enterprises into state-owned and non-state-owned enterprises and investigating the size and direction of the two samples' difference-in-difference coefficient values, we can grasp their response to the low-carbon city pilot policies. The coefficient values in columns (1), (3), and (5) of Table 7 reflect the green technology innovation effect of non-state-owned enterprises, and the coefficient values in columns (2), (4) and (6) reflect the green technology innovation effect of state-owned enterprises. Columns (1) and (2) present coefficient values that are significantly positive at the 5% level, and column (3)'s coefficient values are significantly positive at the 10% level, indicating that the low-carbon pilot policy can significantly promote the application of green patents and green invention patents of non-state-owned enterprises and enhance their awareness of their own degree of green innovation. For state-owned enterprises, only the coefficient value in column (4) is significantly positive at the 10% level, for the abovementioned potential reasons. Because state-owned enterprises' profits and losses are not borne by private individuals and often enjoy greater policy convenience, state-owned enterprises face less competitive pressure due to high costs and are less willing to engage in technological innovation. By contrast, non-state-owned enterprises do not enjoy the same policy convenience and must confront fiercer market competition. Enterprise owners' willingness to improve production technology as a means of reducing pollution costs in the production process under the aegis of environmental regulation is even stronger, demonstrating that hypothesis 3 is in line with reality. This is inconsistent with the conclusion that some scholars have arrived at that state-owned enterprises have a stronger political background than non-state-owned enterprises, so they can obtain more green technology innovation resources and are more inclined to carry out green technology innovation [41].

Table 7. Analysis of heterogeneity of enterprise ownership.

	EP		EIP		EUP	
	Non-State-Owned Enterprises (1)	**State-Owned Enterprises (2)**	**Non-State-Owned Enterprises (3)**	**State-Owned Enterprises (4)**	**Non-State-Owned Enterprises (5)**	**State-Owned Enterprises (6)**
Dr.t	0.0433 **	0.0635 **	0.0420 *	0.0475 *	0.0168	0.0311
Control variable	Yes	Yes	Yes	Yes	Yes	Yes
Fixed effect	Yes	Yes	Yes	Yes	Yes	Yes
Observations	9850	6840	9850	6840	9850	6840

Note: *, ** indicate 10%, 5% of significance levels, respectively.

7. Mechanism Research and Analysis

The benchmark regression results show that the low-carbon city pilot policy effectively motivates enterprises to engage in green technology innovation. Will low-carbon cities' governments thus encourage enterprises to undertake basic green innovation by increasing science and technology expenditure and promoting human capital accumulation? This paper constructs the following model to explore the mechanism by which the low-carbon city pilot policy impacts enterprise green technology innovation. Equation (3) examines the impact of low-carbon city pilot policies on technological innovation and human capital accumulation and constructs Equation (4) on this basis. Equation (4) adds the interaction items of virtual variables and intermediary variables, regardless of whether the low-carbon city pilot policy is implemented and investigates the impact of the interaction items on enterprises' green technology innovation behavior.

$$medi_{i,t} = \theta_1 + \theta_2 D_{r,t} + \theta_3 X_{i,t} + u_i + \lambda_i + \delta_i + \epsilon_{i,t,r} \tag{3}$$

$$EP_{i,t} = \eta_1 + \eta_2 medi_{i,t} * D_{r,t} + \eta_3 X_{i,t} + u_i + \lambda_i + \delta_i + \epsilon_{i,t,r} \tag{4}$$

The $medi_{i,t}$ in Equations (3) and (4) is the intermediary variable of technological innovation and human capital accumulation.

The mechanism test model constructed above uses STATA software for estimation (see Table 8), which controls the fixed effects of provinces over time and the fixed effects of industries over time. Columns (1) and (4) list the regression results of Equation (3) while (2) and (5) list the regression results of Equation (4). Columns (3) and (6) list the results obtained by changing the dependent variable of Equation (4) to the proportion of enterprise green patent applications. The results presented in column (2) are significantly positive, indicating that the low-carbon city pilot policy will promote green technology innovation by increasing technology R&D investment. The results presented in column (6) are also significantly positive, indicating that the low-carbon city pilot policy will encourage green technology innovation by promoting human capital accumulation.

Table 8. Mechanism Test.

	Technological Innovation			Human Capital		
	te	**EP**	**REP**	**Human**	**EP**	**REP**
Dr.t#te		1.111 **	0.14			
		−0.512	−0.0924			
Dr.t#human					1.33×10^{-5}	2.48×10^{-6} ***
					-9.35×10^{-6}	-9.59×10^{-7}
Control variable	Yes	Yes	Yes	Yes	Yes	Yes
Fixed effect	Yes	Yes	Yes	Yes	Yes	Yes
Observations	16,690	16,690	16,690	16,690	16,690	16,690

Note: ** and *** indicate 5%, and 1% of significance levels, respectively.

8. Conclusions and Recommendations

8.1. Main Conclusions

Based on data derived from the State Intellectual Property Office of the People's Republic of China, the CSMAR database, and the China Urban Statistical Yearbook from 2009 to 2019, this study used the absolute and relative values of listed companies' green patent applications to measure enterprises' green technology innovation and constructs a time-varying DID model to investigate the impact on the green innovation of listed companies in the pilot areas before and after the implementation of the three batches of low-carbon pilot city policies. In the estimation process, a series of variables at the enterprise and city levels are controlled to minimize errors caused by the external environment.

The heterogeneity of the regions in which the enterprises are located and the heterogeneity of the enterprise ownership attributes were investigated. The regional effect and the effect of enterprise ownership in terms of the low-carbon pilot policy were analyzed and the mechanism was tested. The estimation results indicate that, after controlling a series of control variables and fixed effects, the low-carbon pilot city policy has significantly motivated enterprises to engage in green innovation activities, and the overall promotion effect is significant; that said, while enterprises' green utility model innovation behavior is affected by the policy, the effect is not significant. Heterogeneity analysis of the effect of the low-carbon pilot policy between state-owned and non-state-owned enterprises revealed that the low-carbon pilot policy has a strong incentive effect on the willingness of non-state-owned enterprises to engage in green innovation while the incentive effect on state-owned enterprises' willingness to engage in green innovation is less obvious. The behavior of enterprises facing regulatory policies differs as a result of their different ownership attributes. Heterogeneity analysis of the low-carbon pilot policy's effect in different regions revealed that the low-carbon pilot policy plays a stronger role in stimulating the willingness of enterprises in the eastern region to engage in green innovation, while the willingness of enterprises in the central region to engage in green innovation is not significantly stimulated by the low-carbon pilot policy. The willingness of enterprises in the western region to engage in green innovation will be restrained by the low-carbon pilot policy, and the behavior of enterprises facing regulatory policies varies according to the region's economic development level. The mechanism test results show that the low-carbon city government will promote green technology innovation by increasing scientific R&D investment and promoting human capital accumulation.

Combined with the analysis, low-carbon pilot provinces and cities have taken many measures aimed at reducing carbon emissions. Among these measures is the strict control of enterprises' carbon emissions and the penalization of enterprises whose emissions exceed a specific amount so that enterprises must pay for the pollution they inflict. In addition to punitive measures, low-carbon pilot provinces and cities will also provide greater financial support to enterprises that actively engage in technological innovation and reduce carbon emissions, enabling enterprises to invest in energy-saving transformation to alleviate the pressure caused by the contradictory tension between economic growth, energy conservation, and emission reduction. In the 10 years since the first batch of pilot cities was published, the pilot regions have actively promoted the construction of low-carbon provinces and cities, accumulated extensive experience in practice, and explored a set of development models suitable for their regions. This has not only helped reduce their own regional carbon emissions, but has also provided reference materials for other regions. From this perspective, the low-carbon pilot policy has indeed played a key role in real life and contributed to the reduction in carbon emissions in China.

8.2. Policy Recommendations

Based on the above conclusions, this paper draws the following policy implications:

First, both practice and statistical analyses show that low-carbon city policy can influence enterprises' green technology innovation to a certain extent and thus promote the construction of low-carbon provinces and cities in China, which will contribute significantly to reducing China's carbon emissions and help form a society characterized by harmonious environmental and economic development. Therefore, the nationwide construction of low-carbon cities should be promoted. Policymakers should further expand the low-carbon city pilot initiative's scope to achieve the nationwide construction of low-carbon cities as soon as possible.

Second, the low-carbon city policy plays a significant role in promoting enterprises' green invention patent applications, but not in promoting enterprises' green utility model patent applications. This is to some extent due to the limited funding that is available for enterprises to use. Therefore, policy makers should formulate incentive or subsidy policies to distinguish patented technologies so that enterprises can create green inventions and green utility models simultaneously.

Third, the heterogeneity test of enterprise ownership and the regional heterogeneity test found that, under the low-carbon pilot policy, non-state-owned enterprises exhibit greater awareness of green innovation than state-owned enterprises and the degree of green innovation in the eastern region is higher than that in the central and western regions. On one hand, policy makers should implement policies that ensure state-owned and non-state-owned enterprises face the same constraints and apply the same strict environmental supervision mechanism to state-owned enterprises. On the other hand, policy makers should promote the optimization and transformation of industrial structure in the central and western regions, implement strict environmental supervision mechanisms, shift financial subsidies for energy conservation and emission reduction, and enhance the driving force of green innovation, so that the central and western regions can consider environmental protection alongside economic development.

Finally, when further promoting the construction of low-carbon cities nationwide, differences in economic development level, government management level, and geographical location in China's different regions should be fully considered alongside the actual situations of different regions. This will allow the formulation of policies that correspond to local conditions as well as individualized emission targets and indicators.

There are some differences in the impact of low-carbon pilot policies on green innovation in different provinces, and the impact of different ownership systems is also very different. The mechanism behind this deserves in-depth and systematic research. This paper conducts only a preliminary analysis from the two aspects of technology R&D investment effect and human capital accumulation effect, which can be analyzed from more dimensions in the future. In addition, the low-carbon pilot policy is still being promoted and improved. With the introduction of the latest policy, we can further use the latest data for comparative analysis, in order to obtain a more universal policy definition to guide the practical activities of green transformation.

Author Contributions: Data curation, J.Z.; Formal analysis, T.W.; Investigation, F.L.; Project administration, H.S.; Resources, Z.S. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Key Program of National Social Science Fund of China (21AZD067), the medium and long-term research project of Nanjing University's new era liberal arts excellence research program (0104-14914219).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: This study did not report any data.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Bu, M.; Qiao, Z.; Liu, B. Voluntary environmental regulation and firm innovation in China. *Econ. Model.* **2020**, *89*, 10–18. [CrossRef]
2. Jiang, Z.; Wang, Z.; Zeng, Y. Can voluntary environmental regulation promote corporate technological innovation? *Bus. Strategy Environ.* **2020**, *29*, 390–406. [CrossRef]
3. Huang, X.; Hu, Z.; Liu, C.; Yu, D.; Yu, L. The relationships between regulatory and customer pressure, green organizational responses, and green innovation performance. *J. Clean. Prod.* **2016**, *112*, 3423–3433. [CrossRef]
4. Porter, M.E.; van der Linde, C. Toward a new conception of the environment-competitiveness relationship. *J. Econ. Perspect.* **1995**, *9*, 97–118. [CrossRef]
5. Zhao, A.; Wang, J.; Sun, Z.; Guan, H. Environmental taxes, technology innovation quality and firm performance in China—A test of effects based on the Porter hypothesis. *Econ. Anal. Policy* **2022**, *74*, 309–325. [CrossRef]
6. Lee, M.; Park, H. The Impact of the Environmental Policy Stringency on Korean Exports of Environmental Goods. *J. Environ. Policy Adm.* **2020**, *28*, 1–22.
7. Petroni, G.; Bigliardi, B.; Galati, F. Rethinking the Porter Hypothesis: The Underappreciated Importance of Value Appropriation and Pollution Intensity. *Rev. Policy Res.* **2019**, *36*, 121–140. [CrossRef]
8. Fang, J.; Gao, C.; Lai, M. Environmental regulation and firm innovation: Evidence from National Specially Monitored Firms program in China. *J. Clean. Prod.* **2020**, *271*, 122599. [CrossRef]
9. Weiss, J.F.; Anisimova, T. The innovation and performance effects of well-designed environmental regulation: Evidence from Sweden. *Ind. Innov.* **2019**, *26*, 534–567. [CrossRef]
10. Guo, J. The effects of environmental regulation on green technology innovation—Evidence of the Porter effect in China. *Financ. Trade Econ.* **2019**, *40*, 147–160.
11. Wang, R. Dynamic correlation between environmental regulation and green technology innovation: Retesting based on Porter Hypothesis. *Sci. Technol. Manag. Res.* **2020**, *40*, 243–250.
12. Yu, K.; Hu, Y.; Song, Z. Environmental regulation, government support and green technological innovation: An empirical study based on resource-based enterprises. *J. Yunnan Univ. Financ. Econ.* **2019**, *35*, 100–112.
13. Yu, H.; Cui, Y. Dual Environmental Regulation, Technological Innovation and Manufacturing Transformation and Upgrading. *Financ. Trade Econ.* **2019**, *30*, 15–24.
14. Zhao, L.; Gao, H.; Xiao, Q. An empirical study on the impact of environmental regulation on the efficiency of green technology innovation. *Stat. Decis. Mak.* **2021**, *37*, 125–129.
15. Wang, C.; Li, Z.; Jiang, P. A study on the influence mechanism of environmental regulation on technological innovation in China's heavily-polluting industries. *Sci. Res. Manag.* **2021**, *42*, 88–99.
16. Shi, J. Study on low carbon consumption behavior and influencing factors of urban residents—A case study of Fuzhou City, Fujian Province. *Resour. Sci.* **2015**, *37*, 308–317.
17. Zhou, S.; Wang, D.; Qu, Z. Study on the influencing factors of rural residents' consumption behavior of low-carbon products—The intermediary role of consumption intention. *Enterp. Econ.* **2016**, *35*, 40–44.
18. Wei, J.; Chen, H.; Long, R. Ecological personality and its impact on low-carbon consumption behavior of urban residents. *J. Beijing Univ. Technol.* **2017**, *19*, 45–54.
19. Liu, W.; Ji, R. The impact of low-carbon awareness and low-carbon lifestyle on low-carbon consumption intention. *Ecol. Econ.* **2019**, *35*, 40–45; discussion 103.
20. Zhou, D.; Zhou, F.; Wang, X. Impact of low-carbon pilot policy on the performance of urban carbon emissions and its mechanism. *Resour. Sci.* **2019**, *41*, 546–556.
21. Lu, J.; Wang, X.; Liu, L. Industrial structure upgrading effect of low carbon city policy—Quasi natural experiment based on low-carbon city pilot. *J. Xi'an Jiaotong Univ.* **2020**, *40*, 104–115.
22. Zhang, H. Can low-carbon city construction reduce carbon emissions? Evidence from a quasi-natural experiment. *Econ. Manag. J.* **2020**, *42*, 25–41.
23. Huang, B. The Allocation of Experimental Points in Contemporary China. Ph.D. Thesis, Zhejiang University, Hangzhou, China, 2018.
24. Liu, T.; Wang, Y. Problems and countermeasures in the implementation of pilot policies for low-carbon cities. *Environ. Prot.* **2019**, *47*, 39–42.
25. Zhuang, G. Policy design logic of low-carbon city pilots in China. *China Popul. Resour. Environ.* **2020**, *30*, 19–28.
26. Lu, J.; Wang, X. The impact of low-carbon pilot policy on China's urban technological innovation—A quasi-natural experimental study based on low-carbon city pilot. *J. China Univ. Geosci.* **2019**, *19*, 128–141.
27. Xu, J.; Cui, J. Low-carbon cities and firms' green technological innovation. *China's Ind. Econ.* **2020**, *12*, 178–196.
28. Zhong, C.; Hu, D.; Huang, Y. Evaluation of green innovation effect of low carbon pilot policy—An empirical study from the data of Chinese Listed Companies. *Sci. Technol. Prog. Policy* **2020**, *37*, 113–122.
29. Zhang, Z.; Liu, M. The impact of low carbon pilot city policy on trade dependence—An empirical study based on DID model. *Ecol. Econ.* **2019**, *35*, 33–38.
30. Sun, H.; Edziah, B.K.; Sun, C.; Kporsu, A.K. Institutional quality and its spatial spillover effects on energy efficiency. *Socio-Econ. Plan. Sci.* **2021**, 101023. [CrossRef]

31. Sun, H.; Edziah, B.K.; Kporsu, A.K.; Sarkodie, S.A.; Taghizadeh-Hesary, F. Energy efficiency: The role of technological innovation and knowledge spillover. *Technol. Forecast. Soc. Chang.* **2021**, *167*, 120659. [CrossRef]
32. Li, L.; Wang, J.; Xu, Y. The impact of low carbon pilot city policy on enterprise technological innovation—An empirical study based on DID model. *Ecol. Econ.* **2019**, *35*, 48–54.
33. Jin, C.; Wang, W. Does Pollution Haven Hypothesis exist in China—An empirical test based on spatial VAR model? *J. Int. Trade* **2016**, *8*, 108–118.
34. Lin, L.; Sun, W. Location choice of FDI firms and environmental regulations reforms in China. *J. Regul. Econ.* **2016**, *50*, 207–232. [CrossRef]
35. Dean, J.; Lovely, M.; Wang, H. Are foreign investors attracted to weak environmental regulations? Evaluating the evidence from China. *J. Dev. Econ.* **2009**, *90*, 1–13. [CrossRef]
36. Dong, M.; Li, C. Net carbon emission reduction effect of the pilot policies in low-carbon provinces. *China Popul. Resour. Environ.* **2020**, *30*, 63–74.
37. Jiang, T.; Sun, K.; Nie, H. City level, total factor productivity and resource mismatch. *Manag. World* **2018**, *34*, 38–50; discussion 77, 183.
38. Acemoglu, D.; Aghion, P.; Bursztyn, L.; Hemous, D. The environment and directed technical change. *Am. Econ. Rev.* **2012**, *102*, 131–166. [CrossRef]
39. Hernandez-Sancho, F.; Picazo-Tadeo, A.; Reig-Martinez, E. Efficiency and environmental regulation. *Environ. Resour. Econ.* **2000**, *15*, 365–378. [CrossRef]
40. Shen, W.; Wang, Y.; Luo, W. Does the Porter hypothesis hold in China? Evidence from the low-carbon city pilot policy. *J. Appl. Econ.* **2021**, *24*, 246–269. [CrossRef]
41. Wang, R.; Wang, F.; Xu, L.; Yuan, C. R&D expenditures, ultimate ownership and future performance: Evidence from China. *J. Bus. Res.* **2017**, *71*, 47–54.