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RESEARCH ARTICLE

Has the Low-Carbon City Pilot Policy Reduced Urban Carbon Emissions in China?

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Abstract: The promotion of low-carbon and ecologically friendly economic growth is widely accepted worldwide. The low-carbon city pilot policy was introduced by the Chinese government in three batches between 2010 and 2017 to address climate change. We use panel data from 277 Chinese cities from 2009 to 2019 to investigate the link between urban carbon emissions and the low-carbon city pilot policy. To alleviate the endogeneity brought on by sample selection bias, we utilize a combination of propensity score matching and the difference-in-difference model in our causal inference technique. The results demonstrate a noteworthy decrease in urban carbon emissions subsequent to the implementation of the policy. Through optimizing industrial structure, substituting clean energy, and innovating green technologies, this approach lowers urban carbon emissions. In addition, heterogeneity analysis results indicate that the carbon reduction effects in eastern and central cities are more significant than those in western cities. Finally, we provide policy recommendations on how to reduce urban carbon emissions.

Keywords: low-carbon city pilot policy, carbon emissions, DID model, industrial structure, green technology innovation

1. Introduction

The Chinese economy has grown remarkably since reform and opening-up measures were put into place. China now boasts the second-largest economy thanks to a more than 30-fold increase in GDP, according to the National Bureau of Statistics. But at the same time, it has also paid a huge environmental cost. As shown in Figure 1, China's GDP and carbon emissions have undergone significant changes in recent years. The World Bank estimates that ecological damage in China costs as much as 10 percent of GDP every year, which has become an urgent mission that needs to be solved. Between 1990 and 2020, China's proportion of CO_2 emissions in the world rose from 10 to 30.7%, ranking first in global carbon emissions.[1] The current annual carbon dioxide emissions in China are about 10 billion tons,[2] which is about a quarter of the global total emissions. The Chinese government has set carbon peak and carbon neutrality as key targets for the 75th United Nations General Assembly in 2020 and has actively promoted carbon emissions reduction programs within this framework. China initiated the low-carbon city pilot policy in 2010 following the State Council's 2009 proposal of China's 2020 action plan to decrease greenhouse gas emissions. Subsequently, in 2012 and 2017, the policy was carried out in multiple provinces and cities to explore low-carbon development patterns with Chinese characteristics. The development status of different cities leads to regional discrepancies in carbon emissions, and a "one-size-fits-all" approach cannot be adopted in carbon reduction policies. Can the low-carbon city pilot policy, then, successfully reduce urban carbon emissions within the context of China's dual carbon strategy and aid in meeting the country's carbon reduction targets? What are the specific impact mechanisms? Is there heterogeneity in the impact at the urban level? In addition to helping China reach its carbon peak and carbon neutrality, studying these challenges will help the world achieve its objective of green and environmentally conscious growth.

Over the past few decades, China's low-carbon city development has garnered increasing attention. Firstly, most of studies hold that this policy reduced carbon emissions [1–3] and improved urban carbon efficiency [4]. Secondly, some studies suggest that this policy may not effectively decrease carbon emissions. Fu et al. [5] argue this policy has a time lag and a short duration of effectiveness [6]. Yang et al. [7] posit that in situations where a city's economic development is comparatively lacking, the impact of policies manifests as a green paradox effect. Thirdly, a few studies have examined the impact mechanisms of policies, including green technology advancement [1, 8], reducing energy consumption, optimizing factor endowment structure, upgrading industrial structure [9], environmental information disclosure, and so on. Research space for this paper is provided by the ongoing discussions and disagreements over the studies on the impact of carrying out the policy on carbon reduction and the inadequate mechanism testing results that require more thorough and in-depth examination.

[1]Source: China Carbon Neutral Industry Panorama 2021 and World Energy Statistical Yearbook (70th edition) released by BP.
[2]2020 China Ecological Environment Statistical Annual Report.

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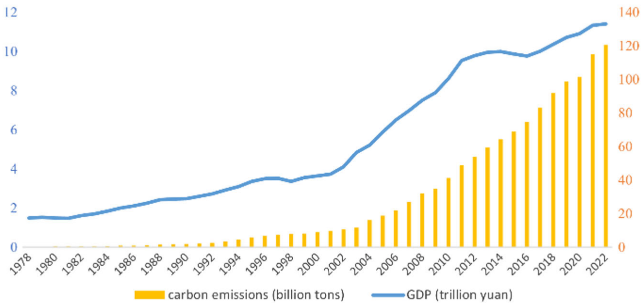
Figure 1
Carbon emissions and GDP in China



The marginal contributions are as follows: firstly, we assessed the study subjects' policy implications for each of the three low-carbon pilot city batches. Our objective is to provide a more thorough assessment of the implementation effect of low-carbon city pilot policy, since the policy for the third batch of pilot cities began in 2017 and some previous studies did not include the third batch of cities; this will serve as data support and an experience reference for the low-carbon pilot policy's subsequent sinking advancement.; secondly, from a methodological perspective, we employ a causal inference method combining propensity matching scores and difference-in-difference (PSM-DID). It uses PSM to match the entire sample and then performs difference-in-difference model on the remaining sample data, effectively alleviating the endogeneity. Moreover, we use various robustness testing methods, including parallel trend analysis, placebo test, and so on; thirdly, from a theoretical perspective, we proposed and examined three impact mechanisms: industrial structure optimization, clean energy substitution, and green technology advancement. We have developed a comprehensive theoretical framework to explain how policy actions affect the reduction of carbon emissions, thereby expanding the theoretical research on this topic.

2. Policy Background, Literature Review, and Hypothesis Development

2.1. Policy background

From a global perspective, low-carbon city pilot policy is a common means adopted by many countries to improve air quality. In recent years, countries such as Germany and Pakistan have adopted this policy to preserve the environment. Similarly, in order to improve environmental quality, China has actively explored low-carbon city pilot policy and implemented three phases of the policy. Local governments are allowed to implement low-carbon city construction based on their own actual situation and advantages. Central government only provides guidance from the strategic planning level. Local governments have the authority to develop specific solutions.

2.2. Literature review

2.2.1. Urban carbon emissions

Province capital cities saw a considerable growth in per capita energy consumption and carbon dioxide greenhouse gases, with the 35 largest Chinese cities accounting for 40% of the nation's total energy consumption and emissions in 2009 [10]. Meng et al. [11] found that the share of urban carbon emissions continued to increase between 1995 and 2010, especially in the eastern coastal areas. With the rapid development of the economy, population growth, urbanization expansion, and the increase in per capita income of residents have significantly increased carbon emissions [12–14], causing environmental degradation. Urban carbon emissions are mostly caused by industry and the burning of fossil fuels; therefore, material conservation and the repurposing of waste paper and slag are important [15]. The policy is one of the tools for environmental governance, but there is still a trend of increasing carbon emissions [16]. As a result, it is essential to extend the reach of policy execution and modify the intensity of particular policies' execution [17].

2.2.2. Low-carbon city pilot policy

In order to reduce greenhouse gas emissions and promote the development of an ecological society, the National Development and Reform Commission announced three batches of low-carbon pilot cities in 2010, 2012, and 2017. Putting into effect a carbon emission statistics system, exploring new policies in legislation, regulation, and other areas are some of the evaluation indicators for the low-carbon city pilot policy, which acts as a comprehensive environmental supervision tool [18]. This policy is explored by local governments based on the development stages, types, and resource endowments [19]. However, Song et al. [8] found that only one-third of policy innovation in each city is implemented, and policy implementation needs to be strengthened. Simultaneously, the implementation effect of this policy exhibits substantial regional variability owing to variations in population, financial status, development stage, and other traits across various areas [20].

2.2.3. Effects of low-carbon city pilot policy

As a measure of environmental regulation, the policy has been rapidly promoted in China. At present, the extant studies have been conducted on the regional effect and temporal effect of it. Due to the high levels of human and material resources in eastern and western cities, the policy has a more effective synergistic governance effect on carbon and haze [21]. In the opinion of Yang et al. [7], this policy exhibits a green paradox effect in the western area. Gao et al. [22] also indicated that cities with higher green economy construction in the eastern region have more significant policy implementation effects [23]. When Huang and Yi [24] compared the carbon emission trading rights policy and the low-carbon city pilot policy, they found that while both are capable of lowering carbon emissions, the low-carbon city pilot policy has a greater effect on reducing emissions in the western and central parts of the country. According to Jiang et al. [23], the policy is not keeping up with the times. Low-carbon city pilot policy, according to Huo et al. [2], may only effectively lower carbon emissions in the short term; they have minimal long-term impact and may even have the unintended consequence of increasing carbon emissions [6].

2.3. Hypothesis development

Since 2010, three batches of pilot cities have been consistently recognized under the policy as a tool for regulating the environment. The impact of the policy on reducing carbon emissions has also been continually investigated. The execution of the policy in China exhibits considerable variety when seen through the lens of regional policy implementation. Implementing this policy in the eastern part of China can significantly reduce emissions [25]; nonetheless, the impact is not favorable in the central and western areas due to the financial capacity and policy barriers of local governments [1, 5]. Additionally, some studies distinguish between resource-based and non-resource-based cities that have low-carbon construction. Resource-based cities had a significantly higher decrease in emissions than non-resource-based cities after putting this method into practice [4, 26]. Liu [3] found that when taking economic development level into consideration, the policy may significantly cut carbon emissions and have a beneficial geographical spillover effect in resource-based cities and eastern cities [27]. From the perspective of the temporal effect of policy implementation, Fu et al. [5] found the policy was significantly effective for the first four years after implementation and should continue to be implemented. Before 2016, the low-carbon level in Guiyang City had been consistently low, but there has been continuous improvement in its subsequent development [28]. Ren et al. [27] also found that the implementation of this policy had a lag. Drawing on the theoretical analysis presented above, we posit the following hypothesis:

H1: Putting low-carbon city pilot policy into action can encourage a decrease in carbon emissions.

A key element influencing energy use and carbon dioxide emissions is industrial structure [29]. Confronting the increasingly severe global environmental problems, lots of studies investigated the relationship between industrial structure and carbon emissions. According to Zhang et al. [30], the percentage of producer services in metropolitan areas has been positively influenced by pilot low-carbon cities. Uchiyama [31] demonstrated that when heavy industry gave way to the service sector in the industrial framework, energy demand growth in Japan became more stable, and urban carbon emissions significantly decreased. Zhao et al. [32] proved that industrial structure optimization had a positive impact on CO_2 emissions. At present, China is in a period of rapid urbanization and industrialization, and heavy industry still holds a significant share in the industrial structure [33]. Zheng and Shi [34] found the unbalanced and inadequate economic development among regions has led to the phenomenon of "pollution haven" that highly polluting sectors are moving from regions with established economies to those with developing economies. The policy is a command and control environmental regulation implemented from top to bottom. Its relevant documents clearly require local governments to establish a carbon emissions reduction target responsibility assessment system and carry out strict policy pilot supervision. On the one hand, the low-carbon policy guides traditional enterprises to apply low-carbon technology for production transition. By promoting the transition of polluting and energy-consuming enterprises to clean and low-carbon, it is possible to fully convert both the old and new driving factors. Finally, carbon emissions can be cut in the control process. In order to completely exploit the contribution of industrial structure optimization to carbon reduction and attain source control of carbon emissions, policy requires pilot cities to actively create new distinctive low-carbon industries from the perspectives of agriculture, industry, and service industries based on the actual situation of local resources and environment. Thus, we propose the following hypothesis:

H2: Low-carbon city pilot reduces carbon emissions by optimizing industrial structure.

One of the main causes of carbon emissions is the use of fossil fuels [35]. One of the main strategies for lowering carbon dioxide emissions is the switch from fossil fuels to clean energy [36, 37]. According to Saidi and Omri [38], achieving the "dual control" target of a total and intensity decrease in carbon emissions will be greatly aided by the development of renewable energy. Lin and Li [39] also found that clean energy consumption can make a regulating effect, so they suggested more support should be given to clean energy. The substitution effect of clean energy has also been confirmed in other countries and regions. For example, Mallah and Bansal [40] took regions of India as the research object and proposed that when clean technology is combined with energy conservation, carbon emissions can be reduced economically. Yi [41] demonstrated how the nation's clean energy program may successfully limit the carbon emissions of the US power industry. Focusing on China's energy consumption, coal makes up 56.2%[3] of total energy used in 2022. This shows that China still has a lot of room to grow in terms of energy conservation and utilizing the clean energy substitution impact [42]. The Chinese government has been vigorously advocating the pilot program, mandating the creation of low-carbon development plans for pilot provinces and cities, in line with the "dual carbon" target. The policy combines energy conservation and efficiency, increases carbon sinks, and explores promotion and utilization of clean energy. In combination with other market-oriented environmental regulations, enterprises are encouraged to invest in clean energy technology development and adopt clean energy sources [43, 44]. Thus, we propose the following hypothesis:

H3: Low-carbon city pilot decreases carbon emissions by making use of clean energy substitution.

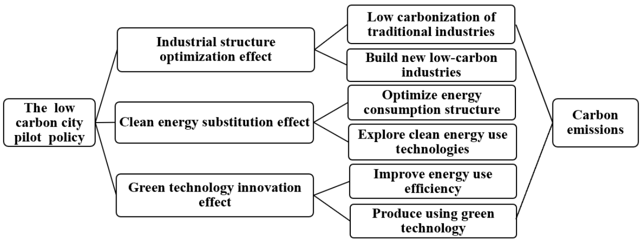
Xu et al. [45] proposed green technology innovation is essential for achieving a green and low-carbon economy. The application of green technology improves energy efficiency and makes it possible to replace conventional petroleum and coal with renewable energy [46]. Long-term carbon emissions were shown to be decreased by environment-related innovation, according to Mongo et al. [47]. According to Zeraibi et al. [48], Thailand considerably improved the quality of the environment and cut greenhouse gas pollution when it developed innovations that were environmentally friendly. However, according to Palmer's compliance cost theory [49], the implementation of environmental regulation would impose an extra cost on economic entities, leading to their lack of green innovation motivation. At present, there is still a lot of room for progress in China's green technological innovation. Many economic entities give up technological innovation mainly because of the high cost and risk of R&D [46]. In this way, the government alleviates the financial constraints of enterprises and concerns about the risks of technology innovation through subsidies, taxation, and other means. Businesses may more effectively create and employ green technology with government assistance, which will help to lower local emissions of carbon dioxide. Consequently, we put up the following theory:

H4: low-carbon environmental pilot reduces carbon emissions through green technology innovation.

We present a conceptual basis for the influence of the policy on urban carbon emissions, as seen in Figure 2, based on the earlier theoretical research. As shown in the figure, mechanism path 1: by encouraging the low-carbon transition of established businesses and creating new low-carbon ones, the policy lowers carbon emissions and maximizes the impact of industrial structure. Mechanism path 2: encouragement to use clean energy in production and daily life is part of the policy. Other initiatives include investigating clean energy technology, controlling carbon emissions at the source, and contributing to the reduction of carbon emissions by substituting clean energy. Mechanism path 3: low-carbon pilot cities emphasize improving environmental quality with technology, supporting enterprises' green technology innovation and green production through preferential policies,

[3] Source "Statistical Bulletin of the People's Republic of China on National Economic and Social Development in 2022".

Figure 2
Theoretical framework



improving energy efficiency with green technology, strictly controlling enterprises' carbon emissions standards, and giving full play to the role of green technology innovation in promoting carbon emissions reduction.

3. Research Design

3.1. Variable description

3.1.1. Explained variable

Urban carbon emissions. They include both carbon emissions generated by traditional energy sources primarily based on fossil fuels and carbon emissions generated by electricity and thermal energy consumption. Based on Li et al. [50], Gehrsitz and Kellerer [51], and Liu [3], we adopt the top-down accounting method of IPCC 2006.[4] It covers direct energy consumption, social electricity consumption, and urban heating consumption. The specific calculation equation is as follows:

$$Carbon = Cs + Cp + Cv + Cr = kEs + bEp + xEv + zEr \quad (1)$$

where Es, Ep, Ev, and Er represent the annual natural gas consumption, liquefied petroleum gas consumption, annual electricity consumption, and raw coal consumption required for urban heating, respectively. By multiplying them by the corresponding carbon emissions coefficients (k, b, x, z) of each energy source, the carbon emissions (Cs, Cp, Cv, Cr) generated by this energy can be obtained. According to the IPCC 2006 and energy consumption data, the k value is 2.1622 $kgCO_2/m^3$ and the b value is 3.1013 $kgCO_2/m^3$. In 2011, China's power grid was separated into six key regional grids: North, East, Northeast, Northwest, Central, and South China. Over the years, benchmark emissions factors x have been published for each of these regional power grids. The carbon emissions factor for raw coal is 2.53 kg CO_2 per kg of coal.

3.1.2. Explanatory variable

There are three groups of low-carbon cities, which are taken as explanatory variables in this paper. The first batch of pilot cities are five provinces and eight cities, and the regional scope of these five provinces intersects significantly with the last two batches. Therefore, we refer to Liu [3] and select eight cities including Tianjin as the first batch of pilot cities. There are 60 low-carbon pilot cities and 217 non-pilot cities, excluding cities with missing data. The pilot projects commenced in July 2010, followed by subsequent rounds in November 2012 and January 2017. Taking into account the policy's delayed impact, this study sets the launch years of the three batches of pilot initiatives as 2012, 2014, and 2018, respectively, following the approach used by Ren et al. [27].

[4] Intergovernmental Panel on Climate Change National Greenhouse Gas Inventory Guidelines.

3.1.3. Control variable

Based on Chen et al. [52] and Yang et al. [53], control variables include the following: (1) Level of economic development; (2) Population density; (3) FDI ratio. (4) Expenditure on science and technology; and (5) Financial development.

3.2. Model construction

We use a quasi-natural experiment technique to evaluate the impacts of the low-carbon city pilot program. Because conventional difference-in-difference models are endogenous, we use a causal inference technique called PSM-DID, which is derived from Gehrsitz [54]. The PSM is used to choose adequate oversight group for the treatment group, and DID is then used to look at the changes that the policy's implementation has brought about. The specific model is as follows:

$$Carbon_{i,t} = \alpha_0 + \alpha_1.(time_i \times treat_t) + \sum Controls_{i,t} + \lambda_t + \gamma_i + \varepsilon_{i,t} \quad (2)$$

where the explained variable, $Carbon_{i,t}$, represents the carbon emissions of the i-th city in year t, where i stands for the city, t for the period, and so on. The dummy variables for the year the policy is put into effect are indicated by the letters time and treat, respectively, for the pilot regions. The explanatory variable is treat × time (the following text is abbreviated as ttreat). When treat × time is equal to 1, it signifies that the policy has been put into effect and this is a pilot area. A highly negative estimated value of α_1 means the strategy has successfully cut emissions of carbon to a considerable degree. $\Sigma\ Controls_{it}$ is an array of control variables represented. The year-level fixed effect is represented by λ_t, whereas the city-level fixed effect is denoted by γ_i. Ultimately, the error term is ε_{it}.

To delve deeper into the impact channels of policies, we build the following mediating effect models according to Baron and Kenny [55].

$$M_{i,t} = \beta_0 + \beta_1 ttreated_{i,t} + \sum Controls_{i,t} + \mu_i + \lambda_t + \varepsilon_{i,t} \quad (3)$$

$$Carbon_{it} = \alpha_0 + \alpha_0 ttreated_{it} + \alpha_1 M_{it} + \sum Controls_{i,t} + \mu_i + \lambda_t + \varepsilon_{i,t} \quad (4)$$

In this framework, the mediating variables, denoted as M, encompass three key components: industrial structure optimization (M_1), clean energy substitution (M_2), and green technology innovation (M_3). To evaluate the industrial structure optimization, we consider the proportion of the GDP generated by the secondary and tertiary industries in the overall annual GDP, as proposed by Sun et al. [56]. Clean energy substitution is assessed using the natural logarithm of urban electricity consumption, as suggested by Song et al. [57]. Lastly, green technology innovation is represented by the urban comprehensive innovation index, as recommended by Li et al. [58].

Should β_1 in Equation (3) and α_1 in Equation (4) both exhibit statistical significance, it implies that the process of green technology innovation plays a pivotal role in mediating the decrease in carbon emissions. For the other two mediating variables, this also holds true.

3.3. Sample and data

The balanced panel data from 277 Chinese prefecture-level cities, covering 11 years from 2009 to 2019, were used in this

Table 1
Variable declaration

Variable type	Variable name	Variable code	Variable definition	Variable data source
Explained variable	Carbon emissions	Carbon	$Cs + Cp + Cv + Cr = kEs + bEp + xEv + zEr$	China Urban Statistical Yearbook, Intergovernmental Panel on Climate Change Guidelines for National Greenhouse Gas Inventories, baseline emission factors for regional power grids in China
Explanatory variable	Pilot low-carbon cities	ttreat	1 for the pilot, 0 otherwise	China Urban Statistical Yearbook
Control variable	Level of economic development	Pgdp	Gross urban product per capita	China City Statistical Yearbook, National Bureau of Statistics
	Population density	Den	Population per unit area of the city	
	FDI ratio	Fdi	Utilization of foreign direct investment as a proportion of GDP	
	Expenditure on science and technology	Tech	The proportion of science and technology expenditure in government expenditure	
	Financial development	Fde	The ratio of loans outstanding by financial institutions to GDP	

research. Out of 277 sample data, the control group consists of 217 cities that are not part of the treatment group, while the treatment group consists of 60 cities that have been approved as pilot projects. The data sources for each variable refer to Table 1.

4. Empirical Analysis

4.1. Propensity score matching

We used control variables as a set of covariates, calculated propensity scores by using the logit model, performed Mahalanobis distance matching, and then proposed 54 sample observations. To ensure the effectiveness of the Mahalanobis distance matching method, the balance of sample matching was first tested (shown in Table 2). The discrepancy has significantly decreased both before and after the matching process. The absolute values of the standardized deviation in the treatment group after matching are mostly below 10%, with only Pgdp and Fde slightly greater than 10%, which is within an acceptable range. Except for Fdi, the standard deviation of the two groups of samples significantly decreased after matching. The t-values after matching, except for Fde, were all less than 1, and the probability p-values of t were all greater than 0.1. Neither of the tests passes the 10% significance level, suggesting the t-test results do not reject the hypothesis that there is no systematic bias in the data of the two groups of samples. The above findings indicate that there is no substantial difference between the two groups. Consequently, the employed matching method is deemed reasonable, and the PSM is considered successful.

4.2. Difference-in-difference estimation

The coefficients of the primary explanatory variable are estimated to be negative after adding control variables and using PSM, and the significance level is 10% after using PSM (shown in Table 3). This suggests that following the introduction of the low-carbon city policy, carbon emissions in pilot cities experienced a significant reduction, amounting to a 1% decrease in emissions, which confirms the carbon reduction effect of the policy, as evidenced by H1.

Table 2
Results of propensity score matching balance test

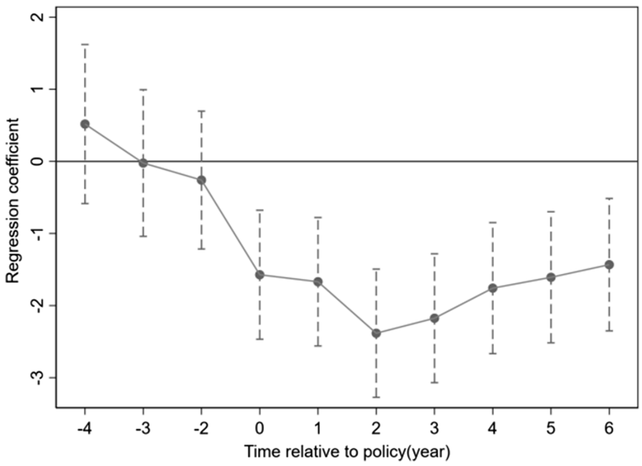
Variable	Before matchmaking U After matchmaking M	Mean value		Standardization deviation	Standardization deviation decline range/%	t-test	
		Treatment group	Control group			T-value	p-value
Pgdp	U	61722	47425	14.5	80.0	2.70	0.007
	M	61722	64575	−2.9		−0.40	0.689
Den	U	426.94	399.25	8.1	−66.5	1.91	0.057
	M	426.74	380.85	13.4		2.58	0.010
Fdi	U	0.00359	0.00257	24.9	69.0	5.59	0.000
	M	0.00359	0.00391	−7.7		−1.14	0.256
Tech	U	1.3139	0.9917	35.1	63.2	7.86	0.000
	M	13139	1.4324	−12.9		−1.86	0.063
Fde	U	61722	47425	14.5	80.0	2.70	0.007
	M	61722	64575	−2.9		−0.40	0.689

Table 3
The regression results

Variable	Full sample (1)	Full sample (2)	PSM-DID (3)	PSM-DID (4)
ttreat	0.134	−0.065	−0.383***	−0.399***
	(1.48)	(−0.73)	(−5.59)	(−5.81)
Control variable	NO	YES	NO	YES
Urban fixed effect	YES	YES	YES	YES
Year fixed effect	YES	YES	YES	YES
Observed value/one	3010	3010	2956	2,935
R^2	0.193	0.208	0.375	0.402

Note: *, **, *** respectively represent significance levels of 10%, 5%, and 1% with *t*-values in parentheses, the same below

Figure 3
Results of parallel trend analysis



4.3. Robustness test

4.3.1. Parallel trend test

The conditions of the difference-in-difference model require the fulfillment of the following conditions: there should be no systematic divergence in the trajectory of carbon emissions between pilot policy cities and non-pilot cities prior to the implementation of the policy. Even if there is a difference between them, it remains constant. To test whether the use of the difference-in-difference model meets this prerequisite, we adopt the time trend chart method. As shown in Figure 3, 2013 (the horizontal axis scale is 1) was the first year of implementing the policy. Prior to 2013, the trend of carbon emissions in pilot cities and non-pilot cities was basically paralleled, with a fixed difference. After 2013, especially in 2014 (the horizontal axis scale is 2), a notable variation in carbon emissions was detected between pilot and non-pilot cities, suggesting a delay in the policy's influence on the pilot cities. Through comprehensive research and analysis of the collected data, parallel trend tests can be conducted.

4.3.2. Placebo test

We set an interaction period for placebo testing and take 2015 as the implementation year for all pilot cities to reduce the influence of non-observational influences on the pilot city. In each of the sample cities, we conduct 500 and 1000 samples, respectively. We selected 60 cities at random as the virtual treatment group and the remaining 217 locations as the control group for every testing. We then conducted regression analysis on Model (2) separately. Repeat the regression 500 and 1000 times to generate 500 and 1000 dummy coefficient estimates respectively. The results of random sampling in Figure 4 indicate that the stochastic regression estimation coefficient β is concentrated near 0 and follows normal distribution. The β in Figure 4 is −0.399, far from the random sampling coefficient, indicating the outcomes are not significantly affected by other unknown factors (in Figure 4).

Figure 4
Placebo test results: (1) 500 random regressions and (2) 1000 random regressions

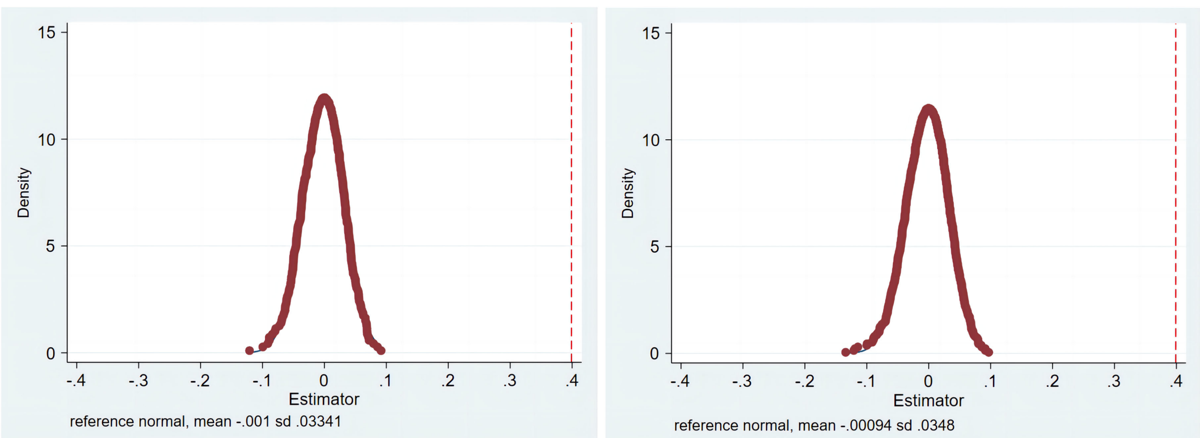


Table 4
Results of replacing the explained variable and excluding the extreme values on the sample

Variable	(1)	(2)	(3)	(4)
ttreat	−0.003*	−0.082***	−0.326***	−0.339***
	(1.94)	(−5.56)	(−3.12)	(−3.31)
Control variable	YES	YES	YES	YES
Urban fixed effect	YES	YES	YES	YES
Year fixed effect	YES	YES	YES	YES
Observations	3010	3010	2980	2980
R^2	0.202	0.149	0.532	0.508

4.3.3. Replace dependent variables and exclude the influence of sample extreme values

The variations in economic development and population across cities may significantly affect urban carbon emissions. As a result, we have replaced the dependent variable with carbon emissions intensity and per capita carbon emissions to more accurately reflect the impact of these factors on the cities. Carbon emissions intensity (cp) reflects the increased carbon emissions when GDP increases by one unit, while per capita carbon emissions (cd) take into account the effects of population. Columns (1) and (2) in Table 4 reports the outcomes of replacing explained variables. Despite the influence of economic and population factors, the efficacy of the policy in reducing urban carbon emissions remains evident. This result confirms the robustness of the baseline regression results.

For the explanatory and control variables, respectively, we apply a 1% bilateral tail reduction technique to lessen the influence of extreme values on the regression findings. In rows (3) and (4) of Table 4, it can be found the result is still significantly negative, and the fitting degree is higher than ones in Table 3. This result further verifies the results in Table 3.

4.4. Mechanism analysis

The initial column of model (4) and the first to second columns of model (3) in Table 5 demonstrate how the policy profoundly affects the industrial structure, with a notable impact on the tertiary industry that surpasses the 1% significance level test. Therefore, Hypothesis H2 is supported. This indicates the implementation can encourage the transition and upgrading of urban secondary industry to the tertiary industry, which is mainly due to the policy orientation of local governments and the active transformation of enterprises. It can be seen from the third column of model (3) and the second column of model (4) that the impact of the policy on clean energy consumption is significantly positive, which passes the significance level of 1%, so H3 is verified. At present, China mainly uses wind power and hydropower to generate electricity, the use of electric energy greatly reduces the consumption of coal resources. From the fourth column of model (3) and the third column of model (4), the policy has increased the urban innovation index by about 14%, and the influence coefficient on carbon emissions is negative and substantial at the 1% level, demonstrating that the development of low-carbon emissions reduction and green environmental protection

Table 5
Results of mechanism analysis

	Model (3)				Model (4)		
	M_1						
	The proportion of secondary industry in GDP	The proportion of tertiary industry in GDP	M_2	M_3	Carbon	Carbon	Carbon
ttreat	0.715	6.459***	0.626***	1.372*			
	(0.61)	(10.18)	(9.04)	(1.92)			
M_1 The proportion of secondary industry in GDP					−0.001		
					(−0.83)		
The proportion of tertiary industry in GDP					−0.021***		
					(−10.17)		
M_2						−0.007***	
						(−12.61)	
M_3							−0.009***
							(−9.32)
Control variable	YES	YES	YES	YES	YES	YES	YES
N	3878	3878	3835	3842	3834	3834	3834
R^2	0.345	0.245	0.607	0.120	0.354	0.638	0.735

Table 6
Results of heterogeneity test

Variable	Eastern city	Central city	Western city
ttreat	−0.416***	−0.392***	0.013
	(−6.742)	(−4.146)	(0.081)
Constant term	3.986***	3.655***	2.714***
	(44.942)	(31.582)	(21.555)
Observed value	1108	1074	592
R^2	0.882	0.783	0.132

technologies is aided by increased urban innovation. This, in turn, helps to reduce carbon emissions, thereby supporting Hypothesis H4.

4.5. Heterogeneity analysis

In accordance with their geographic location, Chinese cities are divided into three groups: eastern, central, and western cities. We then look at how the policy affects the three cities that were previously discussed.

The results of the heterogeneity analysis on the impact of the policy on carbon emissions are presented in Table 6. It is possible to conclude that the strategy in the eastern and central areas had a significant influence on lowering urban carbon dioxide emissions given that the explanatory variables' coefficients in columns 2 and 3 are statistically significant and negative. On the other hand, column 4's positive and statistically insignificant coefficient of the dependent variable reveals that the strategy in the western areas did not successfully lower urban carbon emissions. This can be explained by the fact that middle- and eastern-based cities have seen faster economic growth and have more developed, comprehensive policy frameworks. With increasingly stringent environmental regulations in recent years, many heavily polluting companies from the eastern and central regions have relocated to the western area, resulting in the "Pollution Haven" phenomenon. Therefore, the policy has not been effective in western regions.

5. Conclusions and Suggestions

5.1. Conclusions

The international community has come to an agreement to advocate environmentally conscious development. The low-carbon city pilot policy is attracting a lot of discussion from the academic and practical domains as it becomes increasingly vital in eliminating urban carbon emissions. We conduct a quasi-natural experimental analysis of the effects of the policy on urban carbon emissions using the PSM-DID model. Moreover, we employ mediator models to thoroughly investigate the mediating influence of industrial structure optimization, clean energy substitution, and green technology innovation. Finally, the empirical results are subjected to robustness tests, leading to the following conclusions:

1) The selected cities' carbon emissions are significantly reduced as a result of the low-carbon city pilot policy. Based on the outcomes, the pilot cities' carbon emissions are around 36.5 percent lower in comparison to those of non-pilot towns.
2) Three theoretical avenues are put out in our theoretical framework to explore the policy's effects: energy substitution, the industrial structure, and green technology advancement. The data collected show that industrial structure optimization, clean energy substitution for fossil fuels, and the emergence of green technologies are the three main ways in which policy functions.
3) There exists variation in the implementation of low-carbon city pilot policy across different metropolitan areas. The results show that the carbon reduction effect of cities in the eastern and central regions is more significant than that of cities in the western areas.

5.2. Policy implications

Firstly, the government should vigorously promote the policy and further expand the pilot city scope. The central government should reasonably carry out top-level policy design and further expand the scope with appropriate scale and speed. Local governments should improve the efficiency of urban low-carbon transition and resolutely follow the regulations of low-carbon city pilot policy at the urban level. Various regulatory measures that are adapted to the specific conditions of the area are also required, taking into account the industrial structure and resource endowment of the city.

Secondly, China should attach importance to the enforce of the policy at every level. At the macro-level, government departments should optimize the urban carbon governance system, coordinate and plan the three key areas of transportation, construction, and production, and improve the construction of carbon peak infrastructure system; At the meso-level, China vigorously develop advanced manufacturing, encourage low-carbon technology innovation in industries, and further promote the industrial intelligence; At the micro level, enhance environmental awareness and sense of responsibility of citizens, encourage enterprises to innovate low-carbon technologies and innovate production processes to meet pollution emissions standards.

Thirdly, in the execution of the policy, local government should not follow a one-size-fits-all approach. According to its own regional characteristics, the western region should strengthen control over fossil energy use and carbon emissions, get rid of dependence on resources, and promote the low-carbon transition of high-carbon industries. The central and eastern regions ought to keep leading the way in cutting carbon emissions and aggressively promoting low-carbon sectors like clean and renewable energy.

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Ethical Statement

This study does not contain any studies with human or animal subjects performed by any of the authors.

Conflicts of Interest

The authors declare that they have no conflicts of interest to this work.

Data Availability Statement

Data are available from the corresponding author upon reasonable request.

Author Contribution Statement

Xinyu Liu: Conceptualization, Methodology, Formal analysis, Investigation, Resources, Data curation, Writing – original draft, Visualization, Project administration. **Mengya Li:** Conceptualization, Software, Formal analysis, Investigation, Resources, Writing – original draft, Visualization. **Chengjing Wang:** Conceptualization, Validation, Formal analysis, Investigation, Resources, Writing – original draft, Visualization. **Ping Lu:** Writing – review & editing, Supervision, Project administration, Funding acquisition.

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