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Do Urban Innovation Policies Reduce Carbon Emission? Empirical Evidence from Chinese Cities with DID

Ling Luo [1], Yang Fu [1,*] and Hui Li [2]

[1] Department of Public Management, School of Government, Shenzhen University, Shenzhen 518060, China
[2] Department of Human Resource Management, College of Management, Shenzhen University, Shenzhen 518060, China
* Correspondence: fuyang@szu.edu.cn

Abstract: The Chinese government launched the Pilot Scheme of National Innovative Cities in 2008, and it has continued to expand the scope of the program in order to achieve more high-quality and sustainable development. This pilot scheme encourages scientific and technological innovations to solve the problems of urban development against the background of climate change by promoting the sustainable transformation and upgrading of the urban economy. This article attempts to examine whether the innovative city pilot helps improve the city's carbon emissions. Moreover, through which mechanisms does the pilot affect the carbon emissions of Chinese cities? The authors use the Pilot Scheme of National Innovative Cities as a quasi-natural experiment and apply the difference-in-difference (DID) method to investigate the impact of innovative city pilot policy on the carbon emissions of pilot cities and the underlying mechanisms.

Keywords: national innovative city; carbon emission; difference-in-difference model; policy effectiveness

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1. Introduction

In 2020, China formally proposed the "carbon peaking and carbon neutrality" target, marking the beginning of a comprehensive low-carbon transformation of its economy and society over the next 40 years. Although China's CO_2 emissions have entered a period of slow growth, the process of carbon neutrality has not been on a smooth track. According to the China Carbon Neutral Development Report 2022, China's CO_2 emissions have long kept pace with economic growth, indicating that China's economic growth is still largely driven by resource consumption. Its economic growth has not been entirely decoupled from carbon emissions. As the largest contributor of CO_2 emissions of the world, China still needs to work extremely hard to realize the vision of carbon peaking and carbon neutrality. As the center of economic activities, cities are the main source of CO_2 emissions [1]. According to UN-Habitat, cities consume 78% of the world's energy and over 60% of greenhouse gas emissions come from urban areas. Cities are therefore crucial to China's fight against climate change.

In order to promote the transformation to a more low-carbon urban development model, it is imperative to explore new models of urban development. In 2008, Shenzhen was announced as the first national innovative city, marking the official launch of the Pilot Scheme of National Innovative Cities. By 2022, a total of 103 cities (municipal districts) had been included in the list of China's pilot cities. After development of more than ten years, national innovative cities have gradually become the growth pole of regional economic development and regional technological innovation. The innovation, economic and ecological effects of the innovative city have received extensive attention from scholars, but few studies have examined the impact of innovative city policy on carbon emissions.

Therefore, this paper treats the pilot policy of national innovative cities as a quasi-natural experiment to examine the impact of innovative city policy on carbon emissions. With the CO_2 emissions data published by the China City Greenhouse Gas Working Group

(CCG), we have taken per capita CO_2 emissions as the core explanatory variable and applied a time-varying DID model to assess the policy effects and mechanisms of innovative city construction on carbon emission reduction. The contributions of this paper are mainly reflected in the following two points: Firstly, this paper explores the intrinsic correlation between the innovative city and CO_2 emissions, expanding the research on innovative cities and providing theoretical and empirical support for a better understanding of the role of innovation on carbon emissions. Additionally, this paper verifies the role of the innovative city in low-carbon emission reduction. This paper can provide empirical inspiration for future policies to further employ innovative city policies and promote urban green and low-carbon transformation.

2. Literature Review

2.1. The National Innovative City Pilot Policy

The national innovative city pilot scheme is a major strategic decision in China's endeavors to build an innovative nation. Currently, the policy has been implemented for more than ten years. Is this pilot policy effective? How can the effectiveness of innovative cities be monitored and evaluated? How should the pilot policy be further optimized in the future? To answer these questions, scholars have discussed and debated on the effects of innovative cities from different research perspectives.

The first topic of interest in the literature is the impact of innovative city development on technological innovation, which is the main objective of the policy. The National Development and Reform Commission (NDRC) emphasized in its 2010 notice on the pilot scheme that "the project of national innovative cities should be oriented towards achieving innovation-driven development, with the enhancement of independent innovation capacity as the major task". Zhou and Li examined the impact of national innovative city pilot policies on urban innovation in three dimensions, dynamic effects, heterogeneity and impact pathways, and found that innovative city pilot policies significantly increased innovation at the city level [2]. With a framework of intra- and inter-urban collaborative innovation, Wang et al. measured and analyzed the collaborative innovation efficiency of 75 innovative cities in China, and found an increasing trend in intra-urban collaborative innovation efficiency [3]. Zhang and Wang found that the Pilot Scheme of National Innovative Cities had a significant positive impact on the knowledge innovation efficiency (KIE) and knowledge transformation efficiency (KTE) of industry–academia–research knowledge flows [4]. After a series of empirical analyses, scholars have reached a relatively consistent conclusion that the effects of innovation policies on science and technology innovation are positive and beneficial.

The second topic of interest in the literature is the environmental impact of the national innovative city policy. In recent years, the Chinese government has become increasingly aware of the environmental crisis, and the concept of green development has become an inevitable requirement for the transition towards a modern, high-quality economic system. Therefore, many scholars have conducted extensive research on the impact of innovative city policy on the ecological environment in recent years. Gao and Yuan constructed a quasi-natural experiment research based on the pilot policy and found that innovative city construction had a positive effect on the pollution reduction [5]. Fan et al. systematically investigated the correlation between urban innovation efficiency and air pollution, and found that the improvement of innovation efficiency in innovative cities had an improvement effect on haze control than in the non-innovation pilot cities [6]. Zhang et al. used propensity score matching with difference-in-difference (PSM-DID) to verify that the pilot policy had a significant positive impact on green technological progress [7].

In addition, the pilot policy has had a positive impact on many other aspects of urban development, including city brand development [8], financial development [9], etc. In summary, the existing studies are generally positive about the policy effects of innovative city pilots. However, the policy is still ongoing as the new round of technological innovation

and industrial transformation is reshaping the global innovation landscape. Thus, the policy effects of the pilot scheme are still yet to be verified.

2.2. Influencing Factors on CO_2 Emissions

There are many factors that influence carbon dioxide emissions, including economic development, industrial structure, energy consumption and urbanization. Many scholars have begun to reflect on the ecological damage caused by the traditional, urban expansion model as the environmental and ecological issues loom large. Wang et al. found that urbanization is the most important factor in the annual increase in CO_2 emissions in Chinese provinces [10]. Based on a study of Bangladesh with data from 1973 to 2014, scholars found that population density, urbanization and GDP growth were harmful to the environment [11]. To break the dilemma of total CO_2 control and economic and social development, we need to promote the green transformation of our economy and society, in which scientific and technological innovation plays a pivotal role. However, the contribution of technological innovation to environmental quality, especially CO_2 emissions, is uncertain.

On the one hand, the prevailing view is that technological innovation is conducive to CO_2 emission reduction. In fact, the detection [12], storage [13] and utilization [14] of CO_2 are inseparable from support given to technological innovation. With the importance of technological innovation in green and low-carbon development, many scholars hold a positive attitude towards the role of technological innovation in reducing carbon emissions. Wang and Zhu explored the impact of innovation in energy technology on carbon emissions using a spatial econometric model [15]. The results show that innovation in renewable energy technology is beneficial for reducing CO_2 emissions in China. Another study focused on the complex interaction between innovation and CO_2 emissions in the BRICS economies, arguing that innovation activities contribute to CO_2 emissions in the BRICS countries of Russia, India, China and South Africa, with the exception of Brazil [16]. Using annual data from 1990 to 2018, Godil et al. found a significant role for technological innovation in reducing CO_2 emissions from the transport sector in China [17].

On the other hand, some studies have found that technological innovation does not have much effect on carbon emissions control, and it may even have a negative impact. By measuring exogenous and oil price-induced technological change, Kumar and Managi found that, in contrast to developed countries, technological change in developing countries reduces their GDP and increases their carbon emissions [18]. Yu and Du, after dividing China's provinces into groups with fast and slow economic growth, found that while innovation had a significant effect on reducing CO_2 emissions in the fast growth group, its influence was essentially marginal for the slow growth group [19]. Su et al. measured the technological innovation in the BRICS economies using three tools: fixed broadband, fixed telephone and mobile cellular [20]. The study found that the first two innovation tools increased CO_2 emissions. In summary, there is still an academic debate on whether technological innovation improves or worsens CO_2 emissions.

2.3. Literature Gap

The above literature review shows that there has been a great deal of academic research on the pilot policy of innovative cities in China, but less research has been conducted on the relationship between pilot cities and CO_2 emissions from the perspective of policy effectiveness and mechanisms. In addition, the conclusion that urbanization has exacerbated environmental pollution forces us to find a new type of urban development model to break the impasse between environmental protection and social and economic development. The national innovative city pilot is a promising attempt. Innovative cities emphasize technological innovation as the core driving force of economic and social development, which is an important measure to solve a series of problems in urban growth. The question is, can this new urban development model curb the increase in urban carbon emissions so as to realize the transition towards a greener urban economy? To answer this question, this

study uses the time-varying DID model to evaluate the policy effect of the Pilot Scheme of National Innovative Cities and explores the underlying mechanisms through which the policy exerts its influences.

3. Policy Background and Research Hypotheses

3.1. Policy Background

The essence of a policy pilot is based on the concept of "experiment". Before the official implementation and promotion of the policy on a larger scale, the government tends to choose a more flexible and gradual policy pilot plan in order to avoid the risks brought about by policy uncertainty, which is also known as "crossing the river by feeling the stones". Since the economic reform and opening-up, policy pilots have been often practiced in China's policy reforms and have become an important part of the national governance system. Moreover, science and technology innovation is a complex field involving a wide range of factors, such as funding support, talent attraction and institution building, and there are huge differences in science and technology innovation systems among regions. As a result, a one-size-fits-all policy is clearly not appropriate.

In 2006, the central government formally proposed the goal of building an innovative country, and the construction of innovative cities was also listed as an important part of the national innovation system. In order to fully mobilize urban innovation potentials and explore differentiated innovation development paths with local conditions, the pilot project on innovative cities was officially launched. In 2008, the National Development and Reform Commission approved Shenzhen to be the first national pilot city in China, and after more than ten years of development, the pilot cities in China have blossomed across the nation. As of January 2022, a total of 103 cities (districts) have been successively included in the list of pilot city construction nationwide (see Table 1 for details).

Table 1. Time distribution of National Innovative Cities in China.

Year	Pilot Cities	Total
2008	Shenzhen	1
2010	Dalian, Qingdao, Xiamen, Shenyang, Xi'an, Guangzhou, Chengdu, Nanjing, Jinan, Hefei, Changsha, Suzhou, Wuxi, Yantai, Haidian (Beijing), Binhai (Tianjin), Tangshan, Baotou, Harbin, Yangfu (Shanghai), Ningbo, Jiaxing, Luoyang, Wuhan, Shapingba (Chongqing), Lanzhou, Shijiazhuang, Taiyuan, Changzhou, Fuzhou, Nanchang, Jingdezhen, Nanning, Haikou, Guiyang, Kunming, Baoji, Yinchuan, Changji, Shihezi, Changchun, Zunyi	42
2011	Qinghuangdao, Hohhot, Lianyungang, Zhenjiang, Xining	5
2012	Nantong, Urumqi, Zhengzhou	3
2013	Hangzhou, Taizhou, Yangzhou, Yancheng, Huzhou, Pingxiang, Jining, Nanyang, Xiangyang, Yichang	10
2018	Jilin, Xuzhou, Shaoxing, Jinhua, Maanshan, Wuhu, Quanzhou, Longyan, Weifang, Dongying, Zhuzhou, Hengyang, Foshan, Dongguan, Yuxi, Lhasa, Hanzhong	17
2022	Baoding, Handan, Suqian, Huaian, Wenzhou, Taizhou, Zibo, Weihai, Rizhao, Linyi, Dezhou, Shantou, Changzhi, Chuzhou, Bengbu, Tongling, Xinyu, Xinxiang, Jingmen, Huangshi, Xiangtan, Liuzhou, Mianyang, Deyang, Yingkou	25

3.2. Research Hypotheses

3.2.1. The Role of the National Innovative City Pilot Policy in Promoting Carbon Emissions Reduction

Innovation in science and technology is important to support for achieving carbon emission reduction as innovation is intrinsically related to low-carbon development. According to the theory of environmental economics, technology and industrial structure are the key factors affecting the degree of regional environmental pollution [21]. Technology refers to the effective reduction of pollutant emissions through technological progress

in the production and upgrading of low-carbon technologies. To a certain extent, this theory reveals that scientific and technological innovation can enhance the capacity of a city to protect and improve the environment. According to the previous literature review, a large number of studies have proven that innovative city policy can significantly promote scientific and technological innovation in pilot cities, which provides a strong support for carbon emission reduction. In addition, the evaluation indicators for the pilot policy includes "total energy consumption per 10,000 yuan of GDP", "CO_2 emission intensity per unit of GDP" and "forest coverage", which indicate that the pilot policy is targeting green development. It indicates that the pilot policy relies on scientific and technological innovation to solve the problems of green development, and thus promoting low-carbon emission reduction is an important task in the process of innovative city development. Based on the above analysis, this paper proposes the hypothesis as follows:

H1: *The national innovative city pilot policy can be effective in reducing CO_2 emissions.*

3.2.2. The Pathway of Innovative City Pilot Policy to Promote Carbon Emission Reduction

The construction of innovative cities is also a process of promoting a low-carbon economy and achieving high-quality development. It is foreseeable that the implementation of the policy will have an increasingly significant impact on the reduction of carbon emissions in China. Thus, what are the mechanisms through which the innovative city pilot promotes low-carbon emission reduction? Based on the theoretical analysis of existing studies, this paper will explore the carbon-emission reduction path of the pilot policy from three aspects: green technology innovation, industrial transformation and upgrading, as well as government financial investment in science and technology.

Firstly, pilot cities can reduce carbon emissions through the effects of green technological innovation. Unlike general technological innovation, green innovation has a dual externality, i.e., it can have positive externalities on both knowledge and the environment [22]. The official documents explicitly include a set of green development indicators for the comprehensive performance evaluation of innovative cities. These assessment indicators and requirements will have a binding effect on the pilot cities, prompting them to resort to technological upgrading to solve environmental problems. They help the pilot cities to achieve the goals of carbon emission reduction. A number of studies have provided empirical evidence on the emission reduction effect of green technology innovation [23,24]. Additionally, pilot cities may reduce carbon emissions by transforming and upgrading their industrial structure. Industrial upgrading is an extremely important step to mitigate the environmental impact of economic activities. The "Guidelines for Innovative City Development" clearly states that efforts should be made to promote industrial transformation and upgrading and to nurture industries with national and global competitiveness. In addition, the Index for Innovative City Evaluation includes the number of high-tech enterprises and knowledge-intensive industries. This has reduced the energy and labor-intensive industries in pilot cities, while vigorously promoting new industries, represented by high-tech industries, strategic emerging industries and modern production services with a lower degree of pollution and energy consumption. It may indirectly reduce CO2 emissions of the pilot cities. It is generally agreed that upgrading industrial structures has positive effects on reducing carbon emissions, as reported in studies on industrial structures [25,26]. Third, the pilot cities may reduce carbon emissions by increasing government financial investment in science and technology. Both innovative R&D and environmental improvements require strategic leadership and external intervention from the government. Innovative R&D activities are generally characterized by high risks, long investment cycles and low direct economic returns. This results in a lack of incentives in the private sectors to invest in technology R&D. Due to the existence of externalities, environmental improvement relies not only on market forces but also on government intervention. The most direct and effective form of government intervention is through government financial support. The "Guidelines for Innovative City Development" requires that local financial investment in science and technology be further increased. Meanwhile, government financial support is a

motivation for industries. R&D subsidies, tax concessions and special funds can reduce the external risks of technological innovation activities and thus mobilize the vitality and enthusiasm of enterprises in innovation. On the other hand, government expenditure also has a leading effect, i.e., through green innovation funding and other means, to guide the development of green innovation in a region. Based on the above analysis, this paper proposes the hypothesis as follows:

H2: *The pilot policy of a national innovative city can reduce CO_2 emissions by enhancing green technology and innovation, promoting the upgrading of industrial structures and increasing government spending on technological innovation.*

4. Research Design

4.1. Time-Varying DID Model

The difference-in-difference method (DID) is a common approach to policy evaluation, and its theoretical framework is based on a "natural experiment". The implementation of the pilot policy of innovative cities provides a natural "quasi-natural experiment" for this study, separating the pilot cities and non-pilot cities as treatment and control groups, respectively, in an experiment.

Two dummy variables need to be set before using the DID method: (1) The experimental group and the control group dummy variable (*treat*). The experimental group is defined as 1, indicating that the sample is the pilot city. The control group is defined as 0, indicating that the sample is a non-pilot city. (2) The policy period dummy variable (*period*). Since the pilot cities are in different time batches, this paper defines the starting year and subsequent years of a city enrolled in the National Innovative City Pilots as 1 and the remaining years as 0. This dummy variable is set according to the list of pilot cities shown in Table 1. The net effect of policy implementation of the innovative cities policy is defined by the interaction term of two dummy variables, i.e., $did = treat \times period$.

The implementation of the pilot policy is a gradual and progressive process, and the enrollment of pilot cities involves multiple time points. The traditional DID model is a "single-point-in-time" model, which is not suitable for evaluating policy effects at multiple points in time. Based on this, a time-varying DID model was constructed to test the net effect of being selected as an innovative city on the level of urban innovation capacity. Based on the above analysis, the time-varying DID is set as shown in Equation (1).

$$lnpce_{it} = \alpha_0 + \theta treat_i \times period_{it} + X'_{it}\beta + u_i + \lambda_t + \varepsilon_{it} \quad (1)$$

where i denotes the city, t denotes the year, and the explanatory variable $lnpce_{it}$ represents the per capita carbon emissions of city i in year t; the core explanatory variable $\theta treat_i \times period_{it}$ is a DID estimator; the focus of this study is on the effect of the pilot policy on urban carbon emissions, which is reflected by the regression coefficient θ and its significance level. $X'_{it}\beta$ denotes the set of all control variables, ε_{it} is the random error term, and u_i and λ_t denote the city- and time-fixed effects, respectively.

4.2. Variable Selection

Dependent variable: In order to observe whether the pilot policy of national innovative city is effective in reducing urban carbon emissions, the logarithm of carbon emissions per capita ($lnpce$) was chosen as the dependent variable in this study. The data of total CO_2 emissions of each city were obtained from the China City Greenhouse Gas Working Group (CCG). Based on the more mature and widely used international methodologies for accounting urban CO_2 emissions, and taking into account the actual situation of Chinese cities, the CCG calculates the direct and indirect emissions of cities in China. Direct emissions refer to all direct emissions within the administrative boundary of the city, and indirect emissions are calculated by multiplying the outward power transfer within the city boundary by the emission factor of the regional grid in which the city is located.

Independent variable: The policy effect of the pilot policy of the national innovative city on urban carbon emissions was chosen as the independent variable. As mentioned

earlier, the net effect of policy implementation needs to be set as the interaction term of two dummy variables, i.e., $did = treat \times period$. The list of pilot cities and the pilot time were obtained from the official documents published on the official website of the Ministry of Science and Technology to ensure the accuracy of the data.

Control variables: In order to better examine the impact of the pilot policy on urban carbon emissions, the following variables were controlled.

(1) Per capita GDP (denoted as *pgdp*). In general, regions with higher levels of economic development are more sensitive to environmental quality [27]. The level of economic development and income in a region can have a significant impact on the level of energy consumption and CO_2 emissions in that region. We therefore used the real per capita GDP to measure the level of economic development of cities.

(2) Energy consumption structure (denoted as *ecs*). Relevant studies show that the share of coal consumption in total energy consumption is mainly used to indicate the energy consumption structure [28]. China is a major coal-consuming country and one of the main sources of carbon emissions. Coal dominates the energy consumption in China, and thermal power generation is the major source for coal consumption. Therefore, we chose urban electricity consumption per capita to measure the energy consumption structure.

(3) Industrialization level (denoted as *struct*). The level of industrialization is also one of the key factors influencing urban carbon emissions. The second industry accounts for a large share of the economy in China, which may increase regional carbon emissions. With evidence from the literature, the output share of the second industry in the entire economy was chosen as a parameter [29].

(4) Openness (denoted as *open*). Related studies have shown that trade can scale up production and thus affect carbon emissions [30]. In this study, we chose the share of the value of the total export and import goods of the GDP to characterize this openness.

(5) Government support (denoted as *gov*). There is no definite conclusion on the role of government in carbon emission reduction. Some scholars believe that the government plays a more important role than enterprises in promoting carbon emission reduction [31]. There are also arguments that local governments will choose to sacrifice some environmental benefits in order to achieve economic growth [32]. However, regardless of the debates, government behavior is a key factor that cannot be ignored in carbon emissions. This study used the ratio of general government consumption expenditure to GDP to reflect the impact of local governments on the regional economy and society.

(6) Urbanization (denoted as *urban*). Related studies show that higher urbanization level on the one hand facilitates production agglomeration and economic growth and, on the other hand, the infrastructure construction required for urbanization increases carbon emission pressure [33]. This paper uses the ratio of the urban population to regional population as a parameter for urbanization.

Mediation variables: As mentioned in the previous section, the pilot policy of the national innovative city mainly reduces regional carbon emissions by enhancing the green technology innovation of pilot cities, promoting regional industrial structure transformation and increasing government expenditures on science and technology innovation. Therefore, we chose green technology innovation as a mediator for carbon emission. The city's green technology innovation was measured by the number of green inventions obtained in that year; the industrial transformation was estimated by the ratio of added value of the tertiary sector to the added value of secondary sector; and the level of government investment in science and technology was measured by the government's expenditure in science and technology innovation as a percentage of the general budget expenditure of the local government.

4.3. Sample Selection and Data Sources

Control variable data for the study was obtained from the China City Statistical Yearbook in previous years and the annual statistical bulletin of each city. Patent data were obtained from the National Intellectual Property Database. Some of the missing data were filled in by using the linear fitting method. Based on the panel data collected from 2005 to 2020 of the Chinese cities, this paper further treated the sample as follows: Firstly, this paper took cities as the research unit, so municipal areas such as Haidian (Beijing) and Binhai (Tianjin) were excluded. Secondly, the data availability of some cities was poor, especially those in Tibet and Xinjiang, so those cities were also excluded from the sample. In addition, since Shenzhen was the only pilot city established in 2008, the policy effect it represents may be biased, so this study excluded Shenzhen from the sample and took 2010 as the starting year of the pilot policy. Finally, the sample of this paper contained a total of 281 cities, including 70 pilot cities and 211 non-pilot cities. Table 2 shows the statistical characteristics of the main variables.

Table 2. Descriptive statistics of the variables.

Variables	Obs	Mean	Std	Min	Max
lnpce	4496	2.019	0.738	0.266	5.107
pgdp	4496	4.207	3.171	0.010	29.05
ecs	4496	2977	5430	27.39	110,000
struct	4496	47.10	11.22	9.000	90.97
open	4496	0.204	0.386	0.000	8.134
gov	4496	0.179	0.101	0.043	1.220
urban	4496	51.51	16.15	6.967	100.0

5. Empirical Results and Discussion

5.1. Parallel Trend Test

Before conducting a formal analysis of policy effects, it is necessary to examine whether the treatment group (pilot cities) and the control group (non-pilot cities) are comparable through a parallel trend test. If the pilot cities and non-pilot cities have the same temporal trend before the implementation of the pilot policy, it means that the sample passes the parallel trend test and fulfils the prerequisites of the DID model. As can be seen from Figure 1, the estimated pilot policy effects before 2010 display 0 at 95% confidence intervals, indicating that there was no significant structural difference between pilot cities and non-pilot cities before the pilot policy and that the parallel trend hypothesis was satisfied. In addition, Figure 2 shows the dynamic trends of carbon emissions per capita between pilot cities and non-pilot cities from 2005 to 2020, where the red dashed line represents the starting year of the pilot policy. It can be seen that the changing trends of pilot cities and non-pilot cities before 2010 were basically the same, which further verifies the validity of the hypothesis of parallel trends.

In Figure 2, the carbon emission reduction effect of the pilot policy of national innovative city can be interpreted. It is not difficult to find that the growth of carbon emissions per capita in the pilot cities showed a significant slowdown after the implementation of the pilot policy. Moreover, the per capita carbon emissions of the pilot cities were even lower than those of the non-pilot cities in the years after the implementation of the policy. However, it is worth noting that since 2016, the per capita carbon emissions of non-pilot cities have shown a clear downward trend, while the growth rate of pilot cities has also shown a more obvious slowdown. This paper speculates that the main reason for this phenomenon may be that China has made important arrangements for low-carbon emission reduction at this time point. In fact, 2016 is of great significance for China's low-carbon development. In this year, China took the lead in signing the "Paris Agreement" and actively promoted its implementation, demonstrating to the world its determination and will to be more proactive in addressing climate change. This iconic move also means that China will take more active and bold actions to achieve the "carbon peaking and carbon

neutrality" goals. The above also implies that Figure 2 does not directly confirm that the pilot policy of the national innovative city scheme has promoted the low-carbon emission reduction in cities or not, as it does not completely exclude other factors; further empirical tests are still needed.

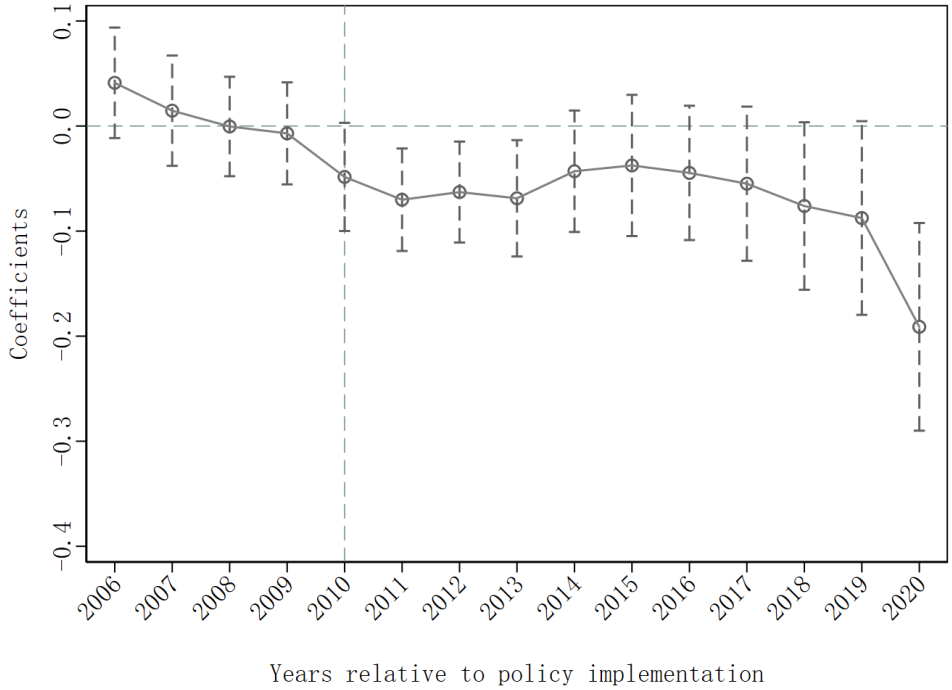


Figure 1. Parallel Trend Test.

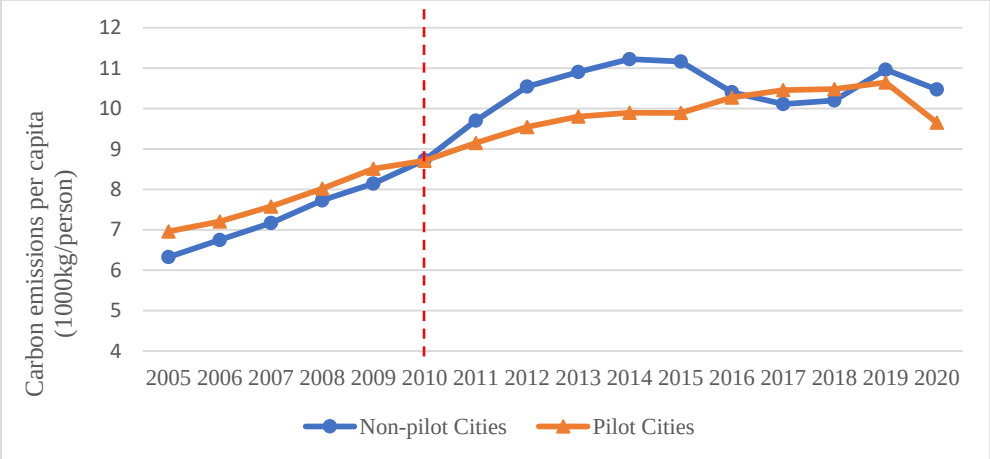


Figure 2. Carbon emissions per capita in pilot cities vs. non-pilot cities.

5.2. Baseline Regression

Based on Equation (1), the regressions are conducted to examine the low-carbon emission reduction effect of the pilot policy of the national innovative city scheme. The specific results are shown in regressions (1)–(3) in Table 3. The table shows the basic information of regression coefficients, significance levels and fixed effects controls for each variable. Regression (1) and Regression (2) show that the estimated coefficients of the policy dummy variables were significantly negative at the 1% level with or without the inclusion of control variables, controlling for both year and city two-way fixed effects. Regression (2) shows that under the influence of the national innovative city pilot policy, the average per capita carbon emissions of the pilot cities were reduced by about 8.38%. Regression (3) was

estimated for the general OLS, i.e., without controlling for fixed effects, and its results were also significant at the 1% level. From the statistical results of the baseline regressions, it can be tentatively concluded that carbon emissions per capita in the pilot cities are significantly reduced under the influence of the pilot policy.

Table 3. Baseline Regression and PSM-DID test results.

Variables	Benchmark Regression			PSM-DID	
	(1)	(2)	(3)	(4)	(5)
did	−0.0969 ***	−0.0838 ***	−0.178 ***	−0.0899 ***	−0.0835 ***
	(−7.20)	(−5.85)	(−6.05)	(−6.56)	(−5.76)
pgdp		0.00905 ***	0.0479 ***		0.0122 ***
		(2.74)	(12.36)		(3.34)
ecs		0.00000726 ***	0.0000375 ***		0.0000213 ***
		(3.74)	(21.69)		(6.95)
struct		0.00541 ***	0.0205 ***		0.00643 ***
		(7.32)	(24.61)		(7.93)
open		0.0658 ***	−0.168 ***		0.0662 ***
		(4.98)	(−7.41)		(4.22)
gov		0.537 ***	0.666 ***		1.105 ***
		(4.10)	(7.12)		(5.85)
urban		0.00180 *	0.0129 ***		0.000161
		(1.93)	(17.42)		(0.16)
_cons	2.030 ***	1.512 ***	0.0116	2.058 ***	1.440 ***
	(587.85)	(22.10)	(0.20)	(556.83)	(18.67)
City-fixed effects	Y	Y	N	Y	Y
Year-fixed effects	Y	Y	N	Y	Y
R^2	0.9304	0.9334	0.4719	0.9272	0.9321
N	4496	4496	4496	3991	3991

Note: *t* statistics in parentheses, * $p < 0.10$, *** $p < 0.01$. Regressions (4) and (5) dropped three singleton observations.

5.3. Robust Test

5.3.1. PSM-DID

In order to better fulfil the demonstration and leading role of innovative cities, the central government often consciously chooses cities with more innovative potential and economic strength as the experimental targets for innovative city pilot policies. In other words, the selection of pilot cities is influenced by the will of the government and has non-random characteristics. However, the non-randomness of the sample may lead to selection bias of the DID model. To eliminate the selection bias, the propensity score matching (PSM) method was used to construct a new control group so that the individual characteristics of the experimental group and the control group were as similar as possible and then the DID model was used again to estimate the policy effects according to the matching results.

Sample matching was performed using the kernel matching method and the final sample size after matching was 3994. Figure 3 shows that the majority of samples are retained when propensity score matching is performed, indicating that the samples are well matched. Figure 4 visualizes the changes in the standardized deviations of each variable between the experimental and control groups before and after matching. Compared to before matching, the points representing each variable after matching were closer to the vertical line representing the standard error of 0. This means that the standardized deviation of each variable was reduced after matching and that the differences in individual characteristics between the experimental group and the control group were better balanced. With the PSM results, the policy effects were further estimated based on the matched sample. Regression (4) and regression (5) in Table 3 show the test results of PSM-DID before and after the inclusion of control variables, with estimated coefficients of −0.0899 and −0.0835, respectively. Both were significant at the 1% level, which again confirms the results of the baseline regression. The above results indicate that the pilot policy of the

national innovative city scheme can reduce the carbon emission level of the pilot cities and that the conclusion is still robust.

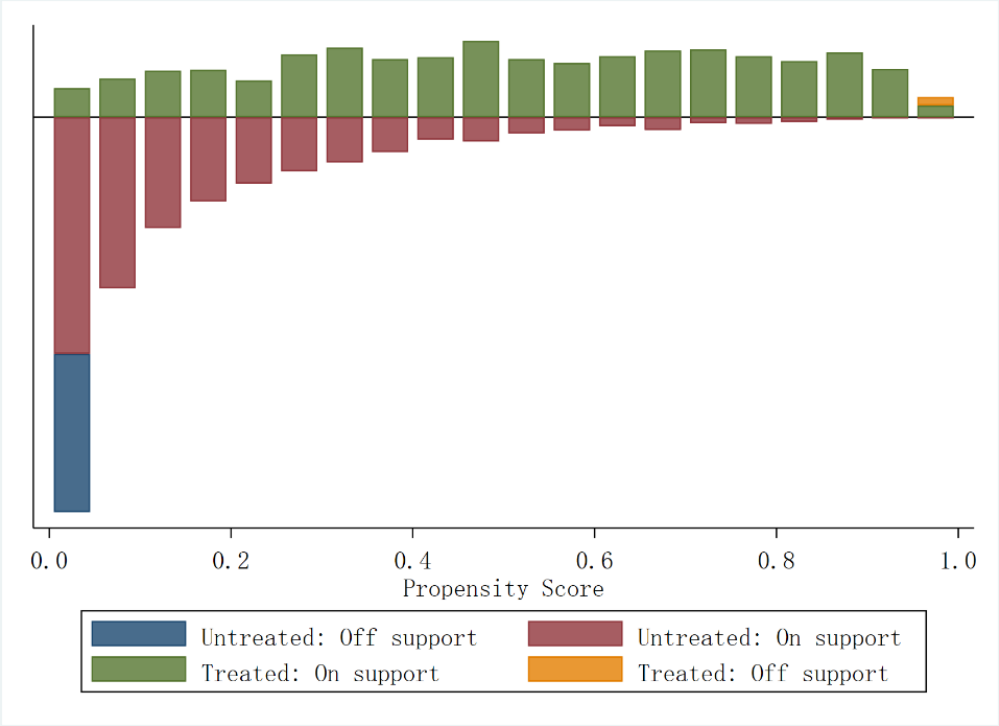


Figure 3. Common range of propensity scores.

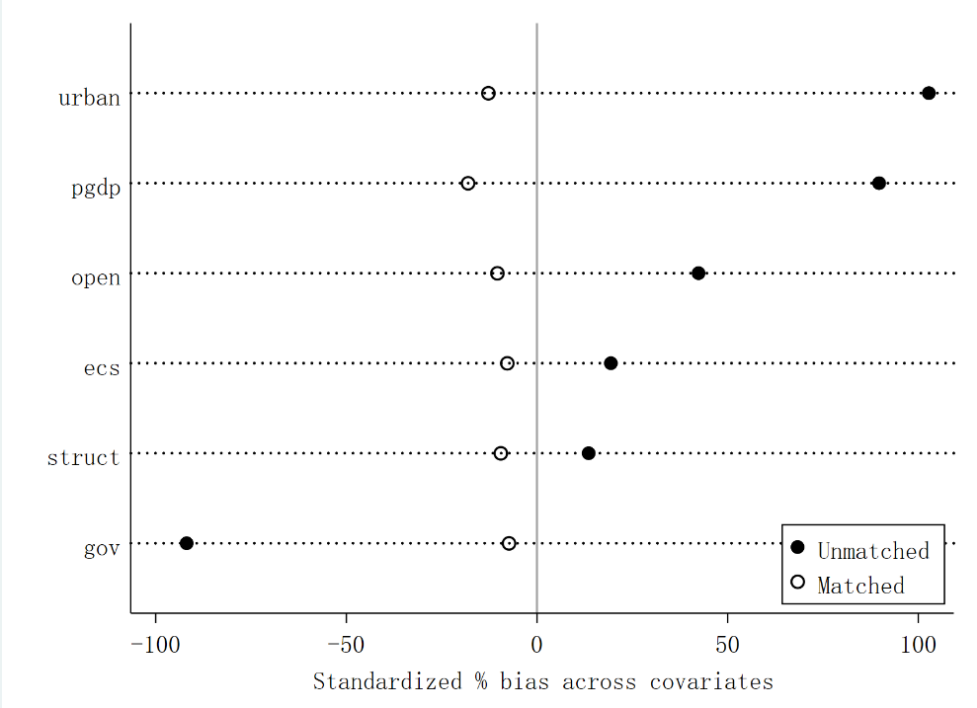


Figure 4. Standardized deviation of each variable.

5.3.2. Replacing Dependent Variable

Under different research perspectives or different spatial and temporal conditions, scholars will attempt to construct different indicator systems to measure and assess regional

carbon emissions. In addition to per capita carbon emissions, existing studies also use indicators such as total carbon emissions [34], carbon performance [35], carbon intensity [36] and carbon productivity [32,37]. Among them, carbon productivity refers to the output GDP per unit of CO_2 emissions, which is one of the main quantitative indicators of low-carbon economy and has been widely used by scholars. Based on this, this indicator was again chosen as an alternative indicator for DID estimation in this paper, and the specific results are shown in Regressions (1) and (2) in Table 4. It can be seen that the regression coefficients were significant at the 1% confidence level, regardless of whether the influence of control variables was taken into account or not. The carbon emission reduction effect of the pilot policy was again confirmed.

Table 4. Robustness Test Results.

Variables	Replacing the Dependent Variable		Excluding Low-Carbon Pilot Policies	
	(1)	(2)	(3)	(4)
did	0.202 ***	0.111 ***	−0.0888 ***	−0.103 ***
	(10.64)	(5.69)	(−4.96)	(−5.24)
pgdp		0.0430 ***		0.0242 ***
		(6.59)		(4.80)
ecs		−0.0000125 ***		0.00000661 ***
		(−7.02)		(3.25)
struct		0.00591 ***		0.00565 ***
		(6.64)		(6.46)
open		−0.0446 ***		0.0925 ***
		(−3.48)		(4.21)
gov		−0.770 ***		0.686 ***
		(−4.30)		(5.21)
urban		0.00454 ***		0.000540
		(5.12)		(0.50)
_cons	0.657 ***	0.159 *	1.990 ***	1.448 ***
	(158.59)	(1.95)	(524.41)	(19.18)
City-fixed effects	Y	Y	Y	Y
Year-fixed effects	Y	Y	Y	Y
R^2	0.8034	0.8315	0.9314	0.9349
N	4496	4496	3440	3440

Note: *t* statistics in parentheses, * $p < 0.10$, *** $p < 0.01$.

5.3.3. Excluding the Influences from Other Policies

As one of the particular governance practices in China, pilots are widely used in various areas of governance. With the 2020 action target of controlling greenhouse gas emissions, China launched the low-carbon city pilot in 2010. According to the current list of pilot cities, there are 36 cities that overlap with the pilot policy list. This also indicates that the carbon emission reduction effect of the pilot policy of the national innovative city scheme may be affected by the low-carbon city pilot. In order to exclude the interference of the low-carbon pilot policy, the above 36 overlapping cities were removed from the sample, and the specific results are shown in Regressions (3) and (4) of Table 4. It is not difficult to find that the pilot policy can still have a significant inhibitory effect on urban carbon emissions even when other policy interferences are excluded.

5.4. Placebo Test

In fact, policies are influenced by various observable and unobservable factors, and we cannot exhaust all possible control variables, leading to a potentially biased assessment of policy effects. To ensure the robustness and reliability of the conclusions, further placebo tests were conducted to remove the effects of other unknown factors on urban carbon emissions. In the placebo test we randomized the interaction term 500 times to see if the coefficients were significantly different from the baseline regression. Figure 5 shows the

p-value-coefficient scatterplots of the explanatory variables (*did*) and the kernel density distribution of the t-values after randomizing the treatment group. The dashed line perpendicular to the *x*-axis represents the true coefficients estimated from the baseline regression and the dashed line perpendicular to the *y*-axis is $p = 0.1$. Two pieces of information can be interpreted from this figure as follows: (1) Most of the coefficients and t-values are concentrated around 0 and are far from the true value, indicating that the baseline regression coefficient-0.0838 is a low probability event. (2) Most of the dispersion of the *p*-values is above the dashed line at $p = 0.1$, indicating that the majority of the estimated coefficients were not significant at the 10% level. All of these results illustrate the basic fact that the policy effect of the pilot policy of the national innovative city scheme on the reduction of low-carbon emissions is not influenced by other unobserved factors.

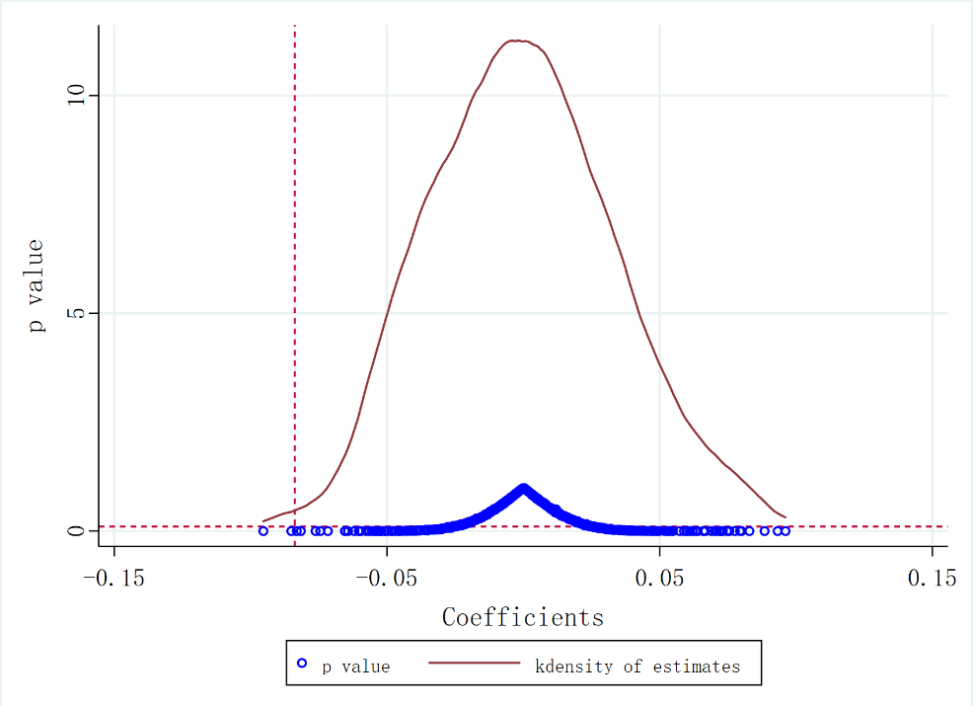


Figure 5. Placebo Test.

5.5. Mechanism Test

The previous analysis shows that the pilot policy of the national innovative city scheme can significantly reduce the carbon emission level of pilot cities. This conclusion passes a series of robustness tests with strong reliability, but the logical path and mechanism underpinning it are yet to be explored. In this regard, this study drew on the existing literature to construct a mechanism test formula as shown in Equation (2). X_{it} represents three mechanism variables; namely, green technology innovation, science and technology expenditure and industrial structural transformation; did_{it} represents the interaction term between the policy time dummy (*period*) and the pilot city dummy (*treat*); η_i and λ_t denote the city- and time-fixed effects, respectively; δ_{it} is a random disturbance term [38].

$$X_{it} = \alpha_0 + \alpha_1 did_{it} + \eta_i + \lambda_t + \delta_{it} \quad (2)$$

The results of the mechanism analysis are presented in Table 5. The coefficients of all three mechanism variables were significantly positive at the 1% level, which implies that under the influence of the pilot policy of the national innovative city scheme, the improvement of green technology innovation, the increase in government expenditure on science and technology innovation and the upgrading of industrial structure can positively influence the effect of the pilot policy of the national innovative city scheme on urban carbon emission reduction.

Table 5. Transmission Mechanism Test.

Variables	Green Technology Innovation		Science and Technology Expenditure		Industrial Structure Transformation	
	(1)	(2)	(3)	(4)	(5)	(6)
did	153.4 ***	74.33 ***	0.710 ***	0.324 ***	0.0561 ***	0.0350 ***
	(13.23)	(4.25)	(9.73)	(4.03)	(3.67)	(2.63)
pgdp		40.81 ***		0.174 ***		−0.00384
		(5.85)		(6.70)		(−1.07)
ecs		−0.00280 ***		−0.00000554 *		−0.00000572 ***
		(−4.01)		(−1.72)		(−4.58)
struct		−1.788 ***		0.00204		−0.0283 ***
		(−4.00)		(0.75)		(−28.90)
open		−82.18 ***		−0.252 **		−0.00148
		(−3.04)		(−2.18)		(−0.10)
gov		35.55		−2.084 ***		0.559 ***
		(0.67)		(−6.41)		(4.01)
urban		−4.246 ***		−0.00234		−0.00300 ***
		(−5.19)		(−0.60)		(−3.76)
_cons	46.91 ***	206.2 ***	1.306 ***	1.085 ***	0.939 ***	2.361 ***
	(16.70)	(4.63)	(83.37)	(4.24)	(241.38)	(38.10)
City-fixed effects	Y	Y	Y	Y	Y	Y
Year-fixed effects	Y	Y	Y	Y	Y	Y
R^2	0.6947	0.7243	0.6928	0.7186	0.8339	0.9048
N	4496	4496	4496	4496	4496	4496

Note: *t* statistics in parentheses, * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

6. Conclusions and Implications

Science and technology innovation is pivotal to carbon emission reduction. The pilot policy of national innovative cities, with innovation-driven development as the core strategy for urban economic and social development, plays an important supporting role in promoting the low-carbon transformation of the cities in China. This paper treated the pilot cities as a quasi-natural experiment and empirically tested the effect of the pilot policy of the national innovative city scheme on reducing carbon emissions using a time-varying DID model. It further analyzed the multiple mediating mechanisms of green technology innovation, industrial structural upgrading and government financial expenditure on science and technology.

The main findings are as follows: (1) The pilot policy significantly reduced urban CO_2 emissions in pilot cities, and the robustness of this result has been fully tested. (2) The carbon emission reduction effect of the pilot policy gradually diminished in the following years. The results of the parallel trend test show that the growth rate of CO_2 emissions per capita in the pilot cities slowed down significantly after 2010 but picked up again around 2016, indicating that the policy still needs to be improved in order to achieve a sustainable policy effect. (3) The pilot policy can promote the low-carbon development of pilot cities and thus reduce carbon emissions by improving green technology innovation, accelerating the upgrading of industrial structures and increasing government financial investment in science and technology.

With the above key findings and empirical analysis, this paper makes the following recommendations for low-carbon transformation in China. (1) The pilot policy should be continued and expanded. The empirical results show that the pilot is one of the representative policies that effectively reduce carbon emissions. The carbon emission reduction effect of the policy is a good balance between economic and social development and environmental protection. In this regard, local governments in pilot cities should summarize and refine their practices to provide reference for non-pilot cities so as to better achieve the goal of innovation-driven low-carbon development. (2) The policy design for the national innovation pilot cities scheme should be improved. Specifically, the evaluation indicators of the pilot city play a guiding role in the development goals of the city. In order to fully release the low-carbon emission reduction effects of the pilot policy, it is necessary for relevant government departments to strengthen the evaluation of low-carbon development. Additionally, as the number of pilot cities is still growing, the focus of innovative city

development should gradually shift from quantity to quality. In this regard, government departments also need to ensure the quality of pilot cities by improving environmental regulations and strengthening the monitoring of pilot processes. (3) To promote collaborative innovation in urban innovation systems. Firstly, the green innovation vitality of innovation subjects should be fully mobilized through the protection and support of green patents. Secondly, to promote industrial upgrading and optimize the regional industrial structure. Cities should focus on the development of high-tech industries and modern service industries by speeding up the process of high-tech transformation of traditional industries. Finally, for the local governments of pilot cities, they are suggested to increase financial investment in technological innovation, especially green innovation, so as to accelerate the development of green and low-carbon oriented innovation systems.

In recent years, innovations in science and technologies have been increasingly important to achieve the goals of "carbon peaking and carbon neutrality". This study took China's national strategic program in the field of scientific and technological innovation—the national innovative city pilot scheme—as an example to explore and verify the effect of this pilot policy on reducing carbon emissions in pilot cities and its underpinning mechanisms. This paper provides solid proof that scientific and technological innovation empowers the process of carbon peaking carbon neutrality, which is of great significance for the transformation of Chinese cities to a greener and more sustainable future.

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