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The Impact of Low-Carbon City Construction on Urban Green Total Factor Productivity

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Abstract: This paper takes the national low-carbon city pilot program implemented in China since 2012 as a quasi-natural experiment. Based on panel data from 285 cities spanning 2009 to 2022, it employs the PSM-DID method to systematically evaluate the impact of the low-carbon city pilot policy on green total factor productivity. The study finds that, overall, the implementation of low-carbon city pilots has a significant promoting effect on the improvement of green total factor productivity. This conclusion remains robust after accounting for identification assumptions and a series of other factors that might interfere with the estimation results. Further results indicate that urban technological innovation capacity and the transformation and upgrading of industrial structure serve as important mechanisms through which low-carbon city pilots enhance urban green total factor productivity.

Keywords: Low-carbon city pilot; Green total factor productivity; PSM-DID.

1. Introduction

The report of the 20th National Congress of the Communist Party of China stated that high-quality development is the primary task in building a modern socialist country in all respects, and green total factor productivity is an important driver for achieving high-quality economic development. Green total factor productivity considers all production within a country or region as a whole, taking into account all input factors (including capital, labor, resource usage) and all output factors (including economic output and pollutant emissions), resulting in a ratio of total input to total output. Its influencing factors are complex and diverse, with the implementation of low-carbon policies being an important and long-term element. Since the launch of the first batch of pilot cities in 2010, and subsequent expansions with the second batch in 2012 and the third batch in 2017, the state has established 81 low-carbon pilot cities or regions nationwide. Achieving "carbon peak" and "carbon neutrality" has become the fundamental goal of environmental reform in these low-carbon pilot cities [1], naturally becoming a crucial support for their economic development. Therefore, revealing their impact on green total factor productivity and the underlying mechanisms has become important and urgent. Since the policy's implementation, low-carbon city pilots have positively optimized resource allocation in pilot cities, promoted low-carbon technological innovation, reduced carbon emissions, and protected the ecological environment. They have also become a key force in promoting regional industrial structure optimization and upgrading, and achieving green, high-quality development. Simultaneously, technological innovation and industrial structure adjustment have played significant roles, becoming two important engines in the process of low-carbon city construction [2], and providing a positive driving force for regional cities to overcome transformation challenges and escape development difficulties. In practice, the government's role in enhancing green total factor productivity has received considerable attention, primarily focusing on whether the effect of government environmental regulation aligns with the "compliance cost theory" or the "innovation compensation theory." Existing research indicates that industrial agglomeration, fiscal decentralization, and industry heterogeneity are important factors influencing the effectiveness of environmental regulation. This paper aims to evaluate the effectiveness of low-carbon city pilot policies on green total factor productivity using PSM-DID and measures the green total factor productivity of 254 prefecture-level cities using the super-efficiency SBM model with undesirable outputs.

2. Research Hypotheses

2.1. The Impact of Low-Carbon Pilots on Urban Green Total Factor Productivity

The effects of low-carbon pilot policies are mainly reflected in three aspects: First, the impact on carbon emissions and energy consumption. Through initiatives such as establishing low-carbon indicator systems, setting carbon emission targets, and promoting clean energy production, low-carbon pilot cities have positively contributed to urban low-carbon development [4], significantly reducing air pollution indices like API [5] and haze pollution [6]. They have also played a significant role in improving energy conservation performance related to carbon emissions and electricity consumption [7, 8, 9]. Second, the spillover effects of low-carbon city construction on economic growth. Existing research suggests that low-carbon city construction significantly promotes foreign direct investment [10, 11] and exhibits heterogeneous characteristics in its impact on urban technological innovation levels; for instance, resource-based cities, large cities, and western cities have not benefited from low-carbon policies in terms of technological innovation [12]. Additionally, low-carbon pilot policies have a positive green growth effect, which is more pronounced in eastern cities [3]. Third, the impact of low-carbon city pilots on green total factor productivity in the context of high-quality development. Research in this area is gradually increasing, with existing studies generally agreeing that low-carbon pilot policies can enhance green total factor productivity, though typical heterogeneous characteristics are also observed [13, 14, 15]. Considering the characteristics of China's political system, government support is a key factor for low-carbon policies to enhance green total factor productivity. On the one hand, the central government's policy support and the sense of honor and positive incentives generated by low-carbon pilots increase local governments' enthusiasm for implementing low-carbon projects and meeting assessment targets, thereby strengthening the impetus for urban low-carbon industrial development and becoming a crucial engine for improving green total factor productivity. On the other hand, the setting of carbon emission reduction targets also creates a forcing effect, making technological innovation, rational industrial layout, and transformation and upgrading the necessary paths for pilot cities to cultivate sustainable development momentum. Based on the above analysis, this paper proposes the following hypothesis:

H1: Low-carbon pilots positively influence the improvement of urban green total factor productivity.

2.2. Pathways of Impact of Low-Carbon Pilots on Urban Green Total Factor Productivity

In the process of low-carbon city construction, on the one hand, the emission reduction targets set by the government serve as an intrinsic motivation for enterprises to undertake technological upgrades and reduce environmental costs. To cope with the environmental regulations inherent in low-carbon city construction, enterprises, as rational agents, whether choosing to relocate, upgrade technology, or transform their business models to adapt to low-carbon development needs, inevitably undergo an innovation process. Technological innovation becomes an effective way to enhance corporate green technological innovation capabilities, reduce carbon emissions, and achieve sustainable development [17]. Concurrently, the construction of related infrastructure, the introduction of human capital, and innovation services also optimize the external environment for corporate operations. On the other hand, low-carbon city construction allocates more resource endowments to high-value-added and technology-intensive industries. The resulting industrial agglomeration effects, scale effects, and positive spillover effects not only provide growth momentum for regional economic development but also offer critical opportunities for technological innovation in pilot cities. Once an economy reaches a certain stage of development, technological innovation and upgrading become key to enhancing total factor productivity [18]. Based on this, the following hypothesis is proposed:

H2: Technological innovation capability is a mediating factor through which low-carbon pilots promote the improvement of urban green total factor productivity.

Government departments in low-carbon pilot cities employ a top-down approach to transform traditional industries by establishing formal and informal environmental regulation systems, such as carbon emission trading schemes, implementing encouraging policies and action plans, mandating interventions for environmentally impactful enterprises, and cultivating low-carbon industries. These actions promote the development of emerging low-carbon industries and drive industrial transformation and upgrading, providing new momentum for green economic growth [16]. Furthermore, low-carbon city construction facilitates the optimization and upgrading of industrial structures by actively developing high-value-added and technology-intensive low-carbon industries. This promotes the transformation of urban functions from industrialization to services and commerce. In particular, the application of the "Internet Plus" across various sectors of the national economy accelerates the digital transformation of traditional industries, significantly improving resource allocation efficiency and innovation efficiency across sectors [19]. Based on this, the following hypothesis is proposed:

H3: Optimizing the industrial structure is a mediating factor through which low-carbon pilots promote the improvement of urban green total factor productivity.

3. Research Design

3.1. Model Specification

This paper selects 81 pilot cities as the treatment group and the remaining 204 prefecture-level cities as the control group to examine the impact of low-carbon city pilot implementation on urban green total factor productivity. The Difference-in-Differences (DID) method is employed to estimate the net effect of the policy. The Propensity Score Matching (PSM) method is used to select non-pilot cities (control group) that match the pilot cities (treatment group) to mitigate "selection bias." The specific models are as follows:

$$SD_{it}=\beta_0+\beta_1\text{PDGP}+\beta_2\text{Open}+\beta_3\text{Human}+\beta_4\text{Third}+\beta_5\text{ECO}+\beta_6\text{Tech}+\beta_7\text{POP}+\beta_8\text{road}+\varepsilon_{it}$$

$$GTFP_{it}=\alpha_0+\alpha_1\text{Policy}*\text{city}+\alpha_2*\text{Convars}+\gamma_t+\omega_t+\varepsilon_{it}$$

Among them, Model (1) is the Logit regression model for propensity score matching (PSM). The dependent variable SD_{it} is a dummy variable indicating whether the city is a low-carbon pilot city, assigned a value of 1 if it is a pilot area, and 0 otherwise. Model (2) is a two-way fixed effects model for difference-in-differences estimation. $GTFP_{it}$ is the dependent variable, representing the green total factor productivity of city i in year t. The core explanatory variable is the interaction term (policy*city) between the group dummy variable city and the time dummy variable policy.

3.2. Variable Description

3.2.1. Dependent Variable

Urban Green Total Factor Productivity (GTFP). The Global Malmquist Luenberger index based on the SBM directional distance function with undesirable outputs is used to measure urban green total factor productivity. Human and capital inputs, along with energy consumption, are included in the input indicators. Economic output and green ecological benefits are considered desired outputs, while environmental pollution indices are treated as undesired outputs.

3.2.2. Core Explanatory Variable

Low-Carbon City Pilot Policy. This includes three dummy variables: city, policy, and policy*city. The group variable city is assigned a value of 1 if the city belongs to a pilot area, and 0 otherwise. policy is the pilot year dummy, assigned a value of 1 for years during which the pilot policy is in effect, and 0 otherwise.

3.2.3. Mediating Variables

Industrial structure rationalization is measured using the reciprocal of the Theil Index (TLL = 1/TL), following the approach of Gan et al. [20]. The calculation formula is:

$$\text{TL}=\sum_{i=1}^{n}(Y_i/Y)\ln(\frac{Y_i}{Y}/\frac{L_i}{L})$$

Where Yi/Y represents the industrial structure and Li/L represents the employment structure. Technological innovation is proxied by the number of invention patents obtained by the city (Invg).

3.2.4. Control Variable

Regional economic development level (PGDP), measured by the logarithm of urban per capita GDP; Regional openness (FDI), measured by the proportion of actual utilized foreign direct investment to urban GDP; Human capital level (Human), measured by the proportion of university students per 10,000 population to the total population; Industrial structure (Third), measured by the proportion of value added by the tertiary industry to GDP; Regional financial development level (ECO), measured by the ratio of year-end deposits and loans of financial institutions to GDP; Regional science and technology expenditure level (Tech), measured by the proportion of science and technology expenditure to local government fiscal expenditure. Additionally, population density (POP, logarithm of population density) and per capita road paved area (road) are introduced to control for the impact of population agglomeration and infrastructure construction on urban green total factor productivity. This paper uses panel data from 285 prefecture-level cities from 2009 to 2022 for empirical testing. All data are sourced from the China City Statistical Yearbook and various provincial statistical yearbooks.

4. Empirical Results and Analysis

4.1. Propensity Score Matching

The propensity score matching method requires satisfying the conditional independence and common support assumptions. Following the approach of Ma Lingyuan et al. [21], the 5-nearest neighbor matching and kernel matching methods were used for PSM balance testing and kernel density testing. Table 1 shows that before matching, there were significant mean differences in all explanatory variables between the treatment and control groups. After matching, the mean differences for each explanatory variable were no longer significant, and the standardized differences decreased substantially. Additionally, the pseudoR^2 of the Probit estimation decreased significantly from 0.28 to 0.008 after matching. This indicates that the matched variables have very weak explanatory power for whether a city was approved as a low-carbon pilot city, implying that after matching, the selection of low-carbon pilot cities is random and satisfies the conditional independence assumption.

Table 1. PSM balance test results

Variable	Sample	Mean Treated	Mean Control	%Bias	%Reduction	T-test(P-value)	V(T)/V(C)
PGDP	Unmatched	11.067	10.142	138.6	98.6	20.14(0.000)	0.50
	Matched	11.057	11.044	2.0		0.299(0.768)	0.96
FDI	Unmatched	0.36652	0.30303	22.0	87.2	3.30(0.001)	0.62
	Matched	0.26601	0.37417	-2.8		-0.33(0.743)	0.55
ECO	Unmatched	1.4086	0.80244	100.5	97.6	20.13(0.000)	2.23
	Matched	1.4044	1.4192	-2.4		-0.19(0.847)	0.42
Human	Unmatched	4.0583	1.4996	89.4	96.9	19.40(0.000)	2.99
	Matched	4.0579	3.9777	2.8		0.26(0.793)	0.83
Tech	Unmatched	0.2618	0.02535	2.2	-190.7	0.28(0.708)	0.15
	Matched	0.2586	0.02343	6.3		1.34(0.179)	0.67
POP	Unmatched	5.2161	4.5307	20.6	39.9	3.68(0.000)	1.42
	Matched	5.1829	4.7708	12.4		1.54(0.123)	1.57
Road	Unmatched	37.153	21.584	46.5	81.9	8.39(0.000)	1.49
	Matched	37.027	34.205	8.4		1.06(0.291)	1.82
Third	Unmatched	45.406	48.834	-37.3	97.5	-5.50(0.000)	0.55
	Matched	45.453	45.54	-0.9		-0.10(0.918)	0.40
PsedR2	Unmatched	0.280					
	Matched	0.008					

Figure 1 shows that before matching, there was almost no overlap between the treatment and control groups, indicating large differences in propensity scores. After matching, the kernel density function shows that most samples lie within the common support region, suggesting the matched sample is of good quality and satisfies the common support assumption.

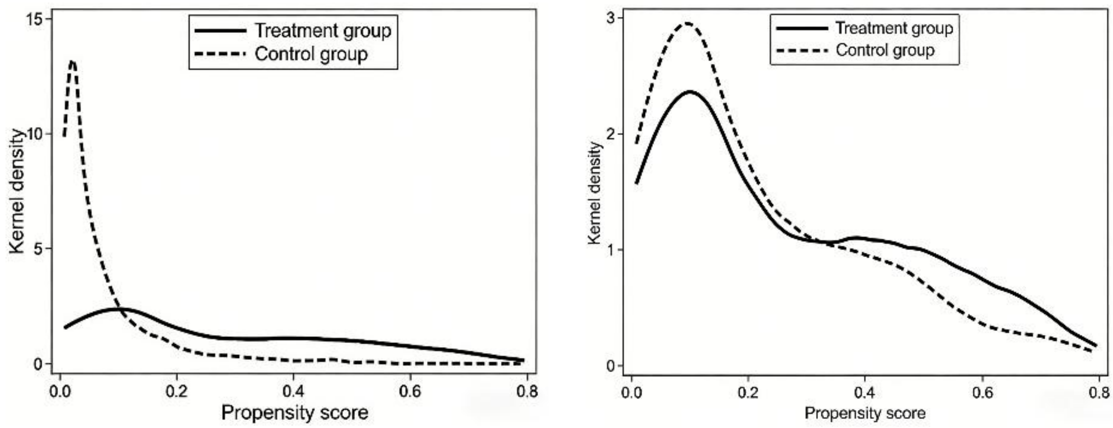

Figure 1. (a) Kernel density before matching, (b) Kernel density after matching

4.2. Baseline Regression Results and Analysis

According to the regression results in Table 2, low-carbon pilots have a positive promoting effect on urban green total factor productivity, and all are highly significant at the 1% level. Furthermore, the coefficients for the impact of low-carbon pilots under OLS and FE estimation are highly consistent, and the coefficients decrease after adding control variables. This indicates that the significant promoting effect of low-carbon pilots on urban green total factor productivity is robust, thereby validating H1.

Table 2. Impact of low-carbon city pilot policy on urban green total factor productivity

Variable	OLS		FE	
	(1)	(2)	(3)	(4)
Policy*city	0.02990	0.022204	0.02990	0.02204
	(5.49)	(4.42)	(5.02)	(3.73)
_cons	0.40339	0.35000	0.37949	0.21213
	(19.73)	(2.46)	(72.53)	(2.31)
Control Variable	No	Yes	No	Yes
Time, Province, Individual FE	Yes	Yes	Yes	Yes
Observations	3694	3494	3694	3949
R-squared	0.7202	0.7410	0.5426	0.5820

4.3. Parallel Trends Test

The parallel trends assumption test results show that before the implementation of the low-carbon transformation pilot, the difference in urban green total factor productivity between the experimental and control groups was not significant, satisfying the parallel trends assumption. From the year of implementation of the low-carbon transformation pilot, the policy significantly improved urban green total factor productivity. Figure 2 shows that the impact coefficient gradually increases after the pilot period.

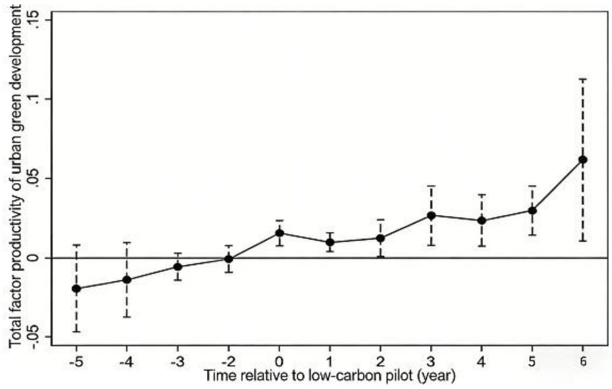

Figure 2. Dynamic effects of DID

4.4. Robustness Checks

4.4.1. Placebo Test

According to the results of 500 placebo tests in Figure 3, the distribution of estimated coefficients is basically centered around zero, and the P-values for most estimates are greater than 0.1, indicating that the sample independent variable did not have a significant effect on green total factor productivity.

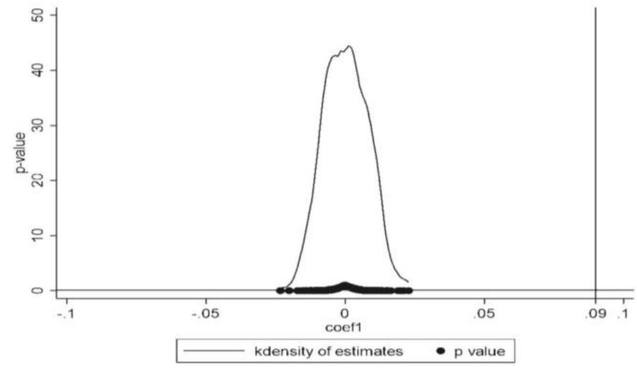

Figure 3. Placebo test

4.4.2. Controlling for Other Policy Shocks

Dummy variables for two external policy shocks closely related to technological innovation were introduced: the "Building an Innovative Country" policy proposed at the Fifth Plenary Session of the 16th CPC Central Committee, and the National Independent Innovation Demonstration Zones approved starting in 2009. If a city was approved as a National Innovative City Pilot or a National Independent Innovation Demonstration Zone in year t, it was assigned a value of 1, otherwise 0. The specific regression results are shown in Table 3. The regression coefficient for policy*city remains significantly positive at the 1% level.

4.4.3. Other Methods

First, controlling for potential omitted variables: the interaction term of province and time fixed effects was further introduced to control for variables that might vary over time and space. The results, shown in Table 3, indicate that the coefficient for policy*city remains significantly positive at the 1% level. Second, regression was performed using a subsample after removing the top and bottom 1% of samples. The results, shown in Table 3, again confirm that the pilot policy's effect remains significantly positive at the 1% level, further validating that the low-carbon pilot policy promotes total factor productivity.

Table 3. Robustness checks

Variable	Controlling for National Independent Innovation Demonstration Zones	Controlling for National Innovative City Pilots	Controlling for Both	Controlling for Potential Omitted Variables	Subsample Excluding Top/Bottom 1%
	(1)	(2)	(3)	(4)	(5)
Policy*city	0.02088	0.01829	0.01772	0.02218	0.01713
	(3.46)	(3.09)	(2.93)	(3.76)	(4.23)
_cons	0.21062	0.23633	0.23538	-0.53900	0.22574)
	(2.30)	(2.59)	(2.57)	(-0.54)	(3.58)
Control Variables	Yes	Yes	Yes	Yes	Yes
Time, Province, Individual FE	Yes	Yes	Yes	Yes	Yes
Observations	3494	3494	3494	3494	3494
R-squared	0.5821	0.5857	0.5820	0.5820	0.7187

4.5. Mediation Effect Test

A mediation mechanism test model was used to further analyze the mechanism through which low-carbon pilot policies promote green total factor productivity. Based on the Hayes mediation effect model, the following recursive equations were constructed:

$$GTFP_{i,t}=\alpha_0+\alpha_1 policy_{0i,t}*city_{i,t}+\alpha_2\text{Convars}+\gamma_t+\omega_t+\varepsilon_{it}$$

$$Mediator_{i,t}=\beta_0+\beta_1 policy_{0i,t}*city_{i,t}+\beta_2\text{Convars}+\gamma_t+\omega_t+\varepsilon_{it}$$

$$GTFP_{i,t}=\theta_0+\theta_1 policy_{0i,t}*city_{i,t}+\theta_2 Mediator_{i,t}+\theta_3\text{Convars}+\gamma_t+\omega_t+\varepsilon_{it}$$

Where $Mediator_{i,t}$ represents the mediating variable, including technological innovation (Invg) and industrial structure rationalization (Tll). The results of the mediation mechanism test are shown in Table 4.

Columns (1)-(3) in Table 4 use technological innovation (Invg) as the mediating variable. Column (1) shows that technological innovation has a significantly positive effect on urban green total factor productivity at the 1% confidence level. Column (2) shows that the pilot policy effect is significantly positive at the 1% confidence level; compared to non-pilot cities, the level of technological innovation in pilot cities increased by approximately 9.79%. In practice, low-carbon policies are somewhat distinct from strict environmental regulations; the carbon emission reduction targets or plans set by local governments can stimulate relevant market entities to engage in technological innovation or R&D to compensate for the environmental cost losses under carbon emission constraints. In column (3), the estimated coefficient for policy*city is 0.01434, which is highly significant at the 1% level and its absolute value is smaller than the coefficient value of 0.02204 in the baseline model (Table 2). This indicates that technological innovation is indeed an important mechanism through which the pilot policy promotes urban green total factor productivity, thereby validating H2.

Columns (4)-(6) in Table 4 use industrial structure rationalization as the mediating variable. Column (4) shows that industrial structure rationalization has a significantly positive effect on urban green total factor productivity at the 1% confidence level, indicating that industrial structure rationalization significantly improves green total factor productivity. The evolution towards technology-intensive and high-value-added types is key to industrial structure rationalization and is an important manifestation of industrial coordination and structural allocation rationality. Industries with high technological content and high added value can continuously provide new growth momentum for economic development under resource constraints and environmental pollution limitations, thus benefiting the improvement of urban green total factor productivity. In column (6), the estimated coefficient for policy*city is 0.01334, which is highly significant at the 1% level and its absolute value is smaller than the coefficient value of 0.02204 in the baseline model (Table 2). This indicates that industrial structure rationalization is another important mechanism through which the pilot policy promotes urban green total factor productivity, thereby validating H3.

Table 4. Meditation effect test

Variable	(1)	(2)	(3)	(4)	(5)	(6)
	GTFP	Invg	GTFP	GTFP	TII	GTFP
Policy*city		0.09794	0.01434		0.00119	0.01334
		(16.62)	(2.34)		(3.14)	(3.83)
Invg (Tech. Innovation)	0.09026		0.07869			
	(5.34)		(4.47)			
TII (Ind. Structure Rational.)				0.57500		0.43944
				(2.37)		(1.87)
_cons	0.20571	-0.00305	0.21237	1.01772	0.13649	1.31287
	(2.25)	(-0.03)	(2.32)	(17.94)	(47.29)	(23.56)
Control Variables	Yes	Yes	Yes	Yes	Yes	Yes
Time, Province, Individual FE	Yes	Yes	Yes	Yes	Yes	Yes
Observations	3494	3494	3494	3453	3541	3453
R-squared	0.5838	0.4184	0.5845	0.3958	0.2456	0.5329

5. Conclusions and Implications

Low-carbon pilots have effectively promoted the improvement of urban green total factor productivity. The above conclusions remain valid after considering the identification assumptions of DID and a series of other factors that might interfere with the findings. Technological innovation and industrial structure rationalization are important mediating factors through which the pilot policy affects urban green total factor productivity. Based on the research conclusions, the following insights are derived:

First, local governments should attach great importance to the positive effect of the pilot policy on improving urban green total factor productivity and continue to promote the construction of low-carbon pilot cities to ensure high-quality regional economic development under the dual constraints of environmental resources. They should benchmark the relevant mechanism paths affecting urban green total factor productivity, leverage demonstration effects, and maximize the implementation of related policies.

Second, by increasing innovation investment and improving talent incentive mechanisms, coordinated development of technological innovation and human resources can be achieved, truly playing the decisive role of technological innovation in enhancing urban green total factor productivity and cultivating new sources and drivers for high-quality development. Simultaneously, by establishing urban technology innovation interaction platforms and reducing government intervention, an innovation atmosphere for the free flow of factor resources can be created, building a favorable technological innovation environment for improving urban green total factor productivity.

Third, optimize the layout of urban industrial structures, improve the transformation path of technological innovation achievements across the three industries, enhance the transformation effect of technological innovation in technology-intensive and high-value-added industries, and promote scientific research, technology transformation, and application as integral parts of the innovation chain and network. This will drive regional industrial structure transformation and upgrading, achieve integrated development across various industries, and continuously form new industrial forms, formats, and business models.

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