Effects and Transmission Mechanism of Low-carbon Pilot Policies on Urban Eco-efficiency

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Abstract. This study aims to evaluate the impact of low-carbon policies on urban ecological efficiency, particularly in the context of promoting coordinated development in cities. Our analysis focused on 280 Chinese cities from 2006 to 2019. We employed the super-efficiency SBM model to measure ecological efficiency and utilized a combination of difference-in-differences (DID) models, including progressive DID and PSM-DID methods, for policy effect analysis. This approach was further strengthened by baseline assessments, matching regression, control group criteria, and event study methodology. Our findings reveal that low-carbon policies significantly enhance urban ecological efficiency, with technological innovation playing a pivotal mediating role. The effectiveness of these policies varied across regions, showing more pronounced results in eastern cities compared to western ones. Additionally, cities with lower initial environmental quality were found to be more responsive to these policies. Conclusively, this research underscores the vital role of low-carbon policies in fostering sustainable and coordinated urban development, providing crucial insights for effective policy implementation and environmental management.

Keywords: Low-carbon pilot policy; Eco-efficiency; Impact effect; Technological innovation; Transmission mechanism

1 Introduction

This paper examines the impact of China's low-carbon policies on urban ecological efficiency amidst escalating climate change challenges and industrialization. Climate change, a global crisis, offers China a pivotal opportunity to transform its economy, restructure industries, and build a moderately prosperous society. Rapid industrialization and urbanization have heightened energy demands, emphasizing the need to control greenhouse gas emissions and tackle climate change.

Initiated during China's swift urbanization, low-carbon policies aim to balance economic growth, improved living standards, climate action, carbon intensity reduction, and green growth. Since 2010, the National Development and Reform Commission has progressively implemented these policies across 81 cities. These pilots, crucial in accumulating diverse regional and industrial experiences, support China's green, low-carbon objectives and the "dual carbon" goals, integral to ecological civilization and environmental governance enhancement. This approach necessitates refining green policies and establishing effective incentive systems for green development.

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Ecological efficiency, crucial in assessing policy efficacy, reflects the balance between socio-economic output and ecological input. It's measured by the ratio of GDP to resource consumption and emissions, indicating a nation's green competitiveness. China has implemented strategies like promoting circular economies, clean production, energy efficiency, renewable energy development, and building resource-conserving societies to foster sustainable development and economic growth with minimized ecological impact.

This study explores the significance of low-carbon pilot policies in enhancing urban ecological efficiency during China's pursuit of high-quality economic development, offering valuable theoretical and practical insights into environmental policy effectiveness and urban development strategies.

2 Theoretical Analysis

This study critically examines the effects of China's low-carbon pilot policies on urban ecological efficiency, contributing significantly to both theoretical and practical aspects of urban development and environmental policy.

Recent studies by Zhang Hua [1], Dong Mei with Li Cunfang [2], and Wang J et al. [3] confirm significant emission reductions, underscoring policy effectiveness in carbon and energy consumption reduction. This is further corroborated by international research, such as the UK studies by Kırıkkaleli et al. [4] and Küfeoğlu & Hong [5], which demonstrate how advancements in energy productivity and the adoption of electric vehicles contribute significantly to emission reductions, highlighting the global relevance and efficacy of such policies.

Other Urban Factors: Enhanced green technology innovation and productivity, especially in larger cities, are highlighted by Hu Qiuguang and Ma Jintao [6], Zhang Yongqing and Du Zuoqin [7], further supported by a 2023 study.

"Dual Carbon" Goals Interaction: The interaction with China's ambitious goals is explored by Guo Shihong and Wang Xuechun [8], Zhang Yuesheng and colleagues [9], and complemented by Lei Y et al. [10].

Urban Ecological Efficiency: The study advocates including ecological efficiency in policy evaluations, aligning with a 2021 study showing improved ecological efficiency across China's provinces..

This paper positions itself as a comprehensive assessment of the low-carbon pilot policies, advocating for a nuanced understanding that encompasses both environmental and economic growth efficiencies. It employs a robust methodological approach, using the super-efficiency SBM model and a progressive difference-in-differences method, complemented by PSM-DID and event study methodology, to ensure empirical reliability. Moreover, it explores the mediating role of technological innovation and delves into policy impact heterogeneity across regions and environmental qualities.

The research is set against the backdrop of China's "dual carbon" goals announced by Xi Jinping at the United Nations General Assembly, and reflects on the low-carbon policies implemented since 2010. It aims to enrich the evaluation framework of China's urban pilot policy performance and provide empirical support for a synergistic policy framework that harmonizes urban environmental protection with economic growth. The study's findings are poised to offer actionable insights for policy refinement and effective implementation towards sustainable urban development.

3 Model building and data description

This research employs a comprehensive methodological framework to evaluate the impact of low-carbon pilot policies on urban ecological efficiency in Chinese cities, utilizing advanced models and techniques to ensure precise and meaningful results.

(1) Super-Efficiency SBM Model:

The study adopts the Super-Efficiency SBM model for efficiency assessment. Unlike traditional BCC and CCR models which require proportional changes in inputs or outputs, this model incorporates slack variables directly, addressing issues of excessive inputs or insufficient outputs. It operates in two stages: first applying the standard SBM model, followed by the Super-Efficiency SBM for units efficient in the standard SBM. This approach overcomes limitations in calculating efficiency values for all Decision Making Units (DMUs), offering a more nuanced assessment.The SBM model is as follows:

$$min\rho=\frac{1/m\sum_{i=1}^{m}(\bar{x}/x_{ik})}{1/(r_1+r_2)(\sum_{s=1}^{r_1}y^d/y_{sk}^d+\sum_{q=1}^{r_2}\overline{y^u}/y_{qk}^u)}$$

$$s.t.\qquad \bar{x}\geq\sum_{j=1}^{n}x_{ij}\lambda_j+w_i^-\qquad i=1,\dots,m$$

$$\overline{y^d}\leq\sum_{j=1}^{n}y_{sj}^d\lambda_j+w_s^d\qquad s=1,\dots,r_1$$

$$\overline{y^u}\geq\sum_{j=1}^{n}y_{qj}^u\lambda_j+w_q^u\qquad q=1,\dots,r_2$$

$$\lambda_j>0\qquad j=1,\dots,n$$

$$\bar{x}\geq x_k\qquad i=1,\dots,m$$

$$\overline{y^d}\geq y_k^d\qquad s=1,\dots,r_1$$

$$\overline{y^u}\geq y_k^u\qquad q=1,\dots,r_2$$

(2) Progressive Difference-in-Differences (DID) Model:

The paper uses the progressive DID model to analyze the dual differences caused by low-carbon policies—both before and after policy implementation, and between pilot and non-pilot cities. The DID model accounts for pre-policy differences among samples and contemporaneous differences due to the policy, aiming to identify the net effect on urban ecological efficiency.

$$ECO_{it}=\pi_0+\pi_1Policy_{it}+\delta X_{it}+\mu_{it}+\gamma_{it}+\varepsilon_{it}$$

(3) Mediating Effect Model:

The research investigates the mediating role of urban technological innovation in the policy's impact on urban ecological efficiency. It posits that policies foster innovation, which in turn improves efficiency. To analyze this, Baron & Kenny's stepwise regression method is employed. The mediating effect is tested through a series of steps involving significant regression coefficients, determining whether the effect is partial or complete.

$$ECO_{it}=\beta_0+\beta_1 Policy_{it}++\delta X_{it}+\mu_{it}+\gamma_{it}+\varepsilon_{it}$$

$$Pat_{it}=\theta_0+\theta_1 Policy_{it}++\delta X_{it}+\mu_{it}+\gamma_{it}+\varepsilon_{it}$$

$$ECO_{it}=\alpha_0+\alpha_1 Policy_{it}++\alpha_2 Pat_{it}+\delta X_{it}+\mu_{it}+\gamma_{it}+\varepsilon_{it}$$

Together, these models and methods form a robust research framework for this study. They allow for an in-depth analysis of the effects of low-carbon policies, providing insights into their effectiveness and the mechanisms through which they operate. This comprehensive approach is essential for understanding the multifaceted impacts of environmental policies on urban development and ecological efficiency.

(4) Variable Descriptions and Data Explanation

Dependent Variable:

The dependent variable is ecological efficiency, measured using a non-desired output super-efficiency SBM model within the DEA method. Input factors include employment numbers, urban built-up area, capital stock, and city energy use. Non-desired outputs are industrial emissions like sulfur dioxide, while desired outputs include GDP, tax revenue, and urban greenery.

Core Explanatory Variable:

Reflecting whether a city implemented low-carbon pilot policies in a given year (2010, 2012, 2017), this variable takes a value of 1 for pilot cities and 0 otherwise.

Mediating Variable:

Urban technological innovation, measured by the number of patent applications (Pat), is used as a mediating variable. Patents are chosen due to their timeliness and stability as performance indicators.

Control Variables:

To ensure accuracy, the model includes economic development level (PGDP), industrial structure (IS), government role (GOVIN), and urbanization level (Urb) as control variables.

Data Sources and Notes:

Data for 280 cities come from various Chinese statistical yearbooks and databases. Missing values are filled using geometric growth rate differences. Patent application numbers are adjusted to 1‰ of their original value for normalization, without affecting their significance.

In summary, this study employs a detailed and comprehensive data set, considering a range of variables to accurately assess the impact of China's low-carbon pilot policies on urban ecological efficiency. The approach combines ecological efficiency measures, policy implementation status, technological innovation, and various control factors to ensure a robust and credible analysis.

4 Empirical Results Analysis

The study presents a detailed analysis of the impact of low-carbon pilot policies on urban ecological efficiency using various econometric models and empirical data, offering a comprehensive insight into policy effectiveness and mechanisms.

(1) Progressive Difference-in-Differences Model Regression Results:

The study's multi-timepoint DID model analysis, processed through econometric software, reveals varied impacts of low-carbon policies**(see Table 1 for details)**. Initial results without control variables suggest a modest effect, which becomes more pronounced with the inclusion of city fixed effects and other control variables. The significant positive impact of these policies on urban ecological efficiency is demonstrated, with notable improvements in air quality and reductions in corporate pollution. These findings are supported by specific examples, such as Shenzhen and Beijing's coordinated plans and actions that align with and exceed the targets of China's Five-Year Plans.

Table 1 Results of baseline regression analysis

	(1)	(2)	(3)	(4)
VARIABLES	SBM	SBM	SBM	SBM
policy	0.0108	0.0479***	0.0230***	0.0219***
	(1.4765)	(8.6630)	(4.1315)	(3.9190)
GOVIN				0.0000
				(0.8322)
IS				-0.0000***
				(-3.0933)
Urb				0.0007
				(0.8510)
PGDP				0.0000**
				(1.9612)
regional fixed effect	No	Yes	Yes	Yes
Year fixed effect	Yes	No	Yes	Yes
N	3918	3918	3918	3918
r2_a	0.0628	0.5055	0.5707	0.5738

(2) PSM-DID Estimation Results:

The PSM-DID method further validates the DID results, showing a significant positive impact on urban ecological efficiency. This method involves calculating propensity scores, optimally matching control and experimental cities, and evaluating policy implementation propensity in control cities. The reduction in bias values and good matching effects indicated by **Figures 1 and 2**, along with positive and significant regression coefficients in **Table 2**, reinforce the reliability of these findings.

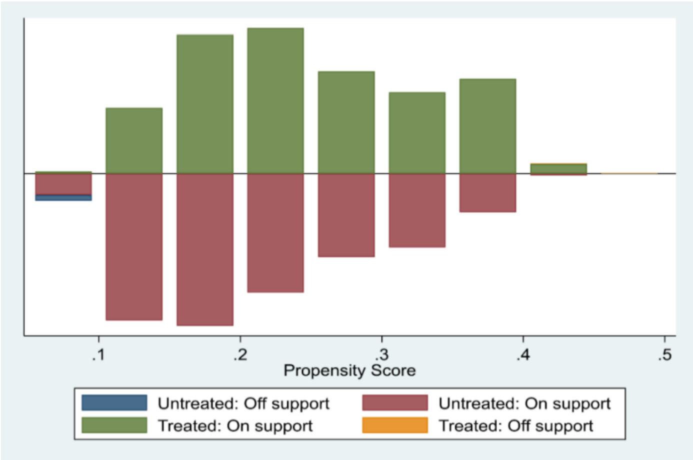

Fig. 1 Data balance test

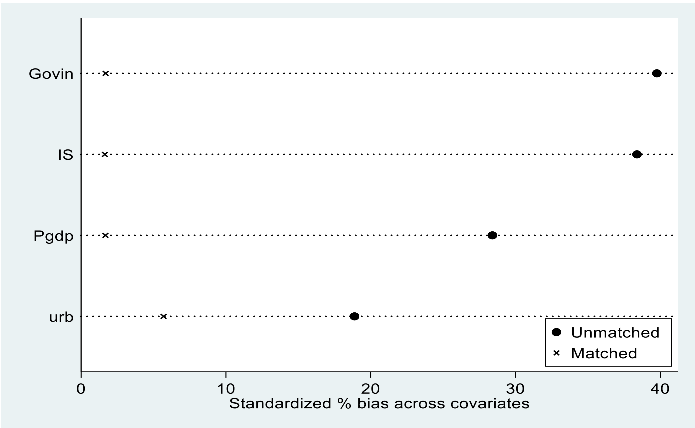

Fig 2 psmatch2 matching effect diagram

Table 2 Regression coefficients of policies before and after matching

	before matching SBM	after matching SBM
policy	0.0219***	0.0122**
	(3.9190)	(2.0153)
GOVIN	0.0000	0.0000
	(0.8322)	(0.0055)
IS	-0.0000***	-0.0001***
	(-3.0933)	(-3.5445)
Urb	0.0007	-0.0023**
	(0.8510)	(-2.1843)
PGDP	0.0000**	0.0000
	(1.9612)	(0.8689)
FE	Yes	Yes
N	3918	3887
r2_a	0.5738	0.6903

(3) Transmission Mechanism Analysis:

Using a mediating effect model, the study uncovers the role of urban technological innovation as a partial mediator in the relationship between policy implementation and urban ecological efficiency. Regression results in **Table 3** illustrate the significant positive influence of policies on innovation, confirming the partial mediating effect of technological innovation. Real-world examples, like the green industry developments in Pengshui Miao and Tujia Autonomous County, exemplify how low-carbon policies drive technological innovation and ecological industrial development.

Table 3 Regression results of mediating effects

VARIABLES	(1) SBM	(2) Pat	(3) SBM
policy	0.0219***	1.0763***	0.0178***
	(3.9186)	(3.6827)	(3.2005)
GOVIN	0.0000	0.0006***	0.0000
	(0.8315)	(5.2767)	(0.2025)
IS	-0.0000***	-0.0042***	-0.0000
	(-3.1019)	(-8.1159)	(-1.5409)
Urb	0.0007	-0.1770***	0.0014*
	(0.8522)	(-4.9001)	(1.7331)
PGDP	0.0000**	-0.0005***	0.0000**
	(1.9616)	(-4.5864)	(2.2883)
Pat			0.0038***
			(7.2362)
N	3918	3918	3918
r2_a	0.5738	0.7157	0.5874

Overall, this study thoroughly analyzes the effectiveness and mechanisms of low-carbon pilot policies in enhancing urban ecological efficiency. It not only confirms the positive impact of these policies but also sheds light on the crucial role of technological innovation in mediating this relationship. The empirical findings and methodological rigor provide valuable insights for policymakers and contribute to the broader understanding of sustainable urban development strategies.

5 Further Analysis

This study's analysis of regional and environmental quality heterogeneity offers insights into the varied effects of low-carbon policies in Chinese cities. In the Eastern Region, these policies significantly impact urban ecological efficiency, likely due to advanced economic development and higher policy standards. In the Central Region, they consistently enhance ecological efficiency, with a more pronounced effect after considering relevant factors. However, in the Western Region, the impact is insignificant, possibly due to historical reliance on high-pollution energy sources and limited urban governance. Economic disparities, resource endowments, and city size are key factors in these regional differences**(see Table 4 for details)**.

Table 4 Results of regional heterogeneity test

	East		Middle		West	
policy	0.0342***	0.0268***	-0.0124*	-0.0139*	0.0311	0.0210
	(4.0074)	(3.0443)	(-1.7008)	(-1.9030)	(1.5490)	(1.0291)
GOVIN		0.0000**		-0.0000***		0.0000
		(2.2858)		(-2.9647)		(0.8092)
IS		-0.0000***		0.0000		-0.0001**
		(-3.2883)		(1.0473)		(-2.0899)
Urb		-0.0026**		0.0031***		0.0021
		(-2.4625)		(2.8845)		(0.6686)
PGDP		0.0000		0.0000		0.0000**
		(0.4237)		(0.3227)		(2.1122)
FE	Yes	Yes	Yes	Yes	Yes	Yes
N	1562	1562	1630	1630	436	436
r2_a	0.6857	0.6930	0.5450	0.5538	0.4424	0.4607

Referring to Lin Shoufu and Dong Xiaoqing[11], the effect of implementing low-carbon pilot policies may depend on the quality of the environment in which the pilot group is located.The study finds low-carbon policies more effective in cities with lower environmental quality, improving ecological efficiency by 3.6% compared to cities without such policies. In contrast, cities with higher environmental quality show no significant improvement**(see Table 5 for details)**. This suggests that low-carbon policies are most effective in areas needing environmental enhancement, helping to bridge the environmental disparity gap. This understanding is crucial for developing tailored environmental policies for different regional and environmental contexts.

Table 5 Test results of heterogeneity of environmental quality

	poor quality	better quality
policy	0.0360***	0.0088
	(3.2893)	(1.6070)
GOVIN	0.0000**	-0.0000*
	(2.3373)	(-1.6583)
IS	-0.0000	-0.0000***
	(-1.4984)	(-3.6200)
Urb	0.0021	-0.0006
	(1.5334)	(-0.4978)
PGDP	0.0000**	-0.0000*
	(2.2986)	(-1.7904)
N	1942	1932
r2_a	0.4694	0.7583

6 Conclusions

We measure eco-efficiency using the super-efficiency SBM model, analyze policy effects using the Difference in Difference (DID) model, and assess policy impacts and their robustness using baseline, matching regression, control criteria, and event study methods. This paper provides valuable insights for policy implementation and environmental management.

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