Do Multi-Pilot Policies Accelerate Carbon Neutrality? A Reassessment of Low-Carbon City and Innovative City Policies Using a Double Machine Learning Model

Authors:

Qiao Wang[1#]; Jiapeng Li[2#]; Yang Wang[3]

#: These authors are co-first authors of the article.

Author Information: Jiapeng Li (corresponding author)

Corresponding Address: Faculty of Social Science,University of Macau.

Email Addresses: 19806330308@163.com

Affiliation:

Faculty of Social Science,University of Macau.

Affiliation:

[1]*College of Public Administration, Huazhong Agriculture University, Wuhan, Hubei, the People's Republic of China.*

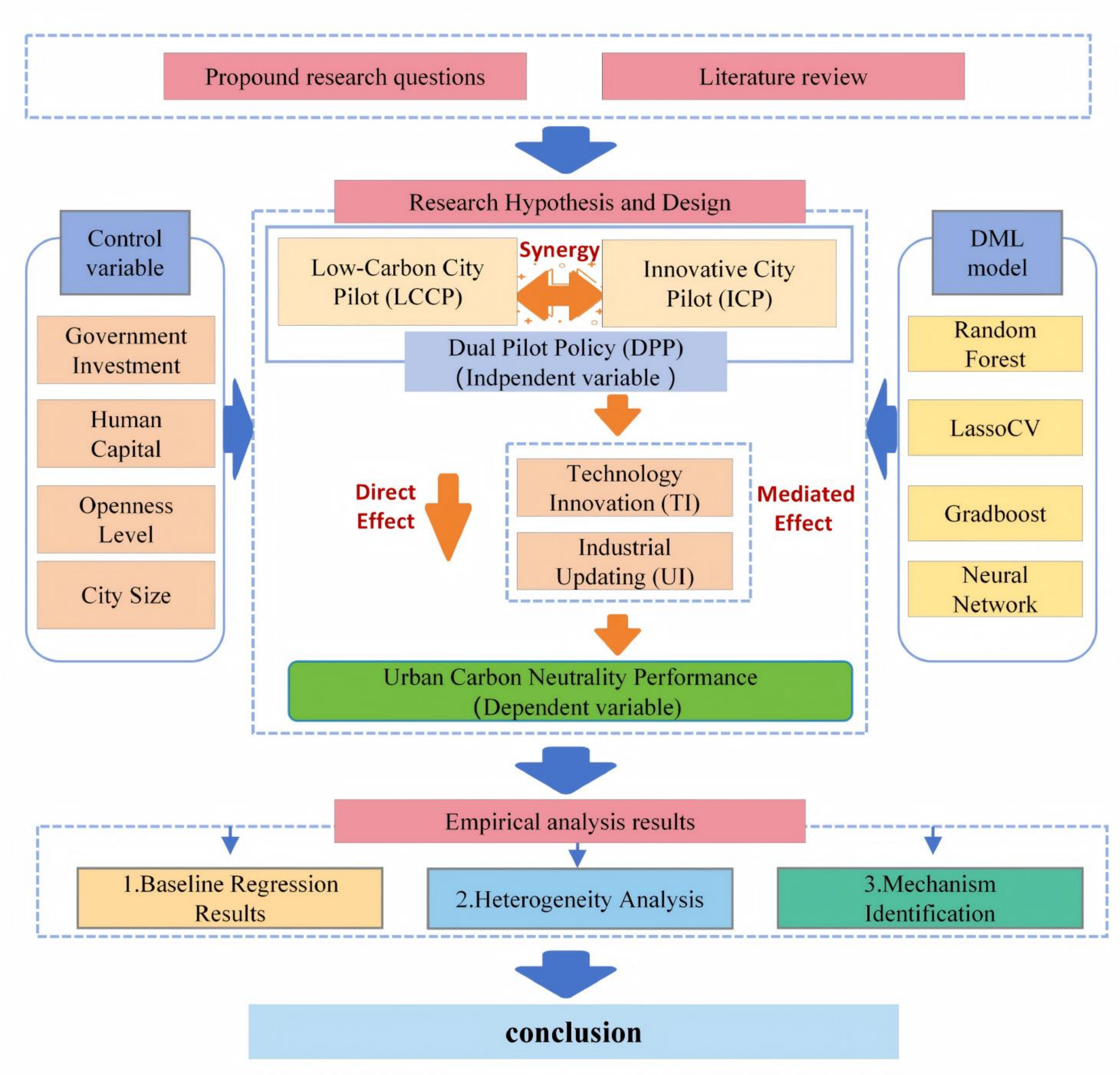
[2]*Faculty of Social Science,University of Macau,Taipa,Macau, the People's Republic of China.*

[3]*National Research Center of Cultural Industries,Central China Normal University.Wuhan,Hubei,the People's Republic of China*

Financial Support:

1. Project supported by the National Natural Science Foundation of China (No. 72204092).
2. Project supported by the Fundamental Research Funds for the Central Universities of Ministry of Education of China (No. 510322189)

Graphical Abstract



Abstract: Achieving carbon neutrality requires not only setting ambitious goals but also effectively integrating existing policy instruments. Although multiple pilot programs have been launched to promote green transformation, empirical evidence on whether these initiatives can synergistically advance regional low-carbon transition processes remains fragmented. This study reassesses the impacts of two landmark policies in China—the Low-carbon City Pilot (LCCP) and the Innovative City Pilot (ICP). We introduce an urban carbon neutrality performance (UCNP) index covering development foundation, low-carbon status, and emission reduction trends, thereby providing a comprehensive evaluation framework for the research. Based on data from 266 Chinese cities over the period 2010–2020, this paper employs a Double Machine Learning (DML) approach to examine the individual effects, synergistic effects, and underlying mechanisms of these two policies. Baseline regression results indicate that both the LCCP and ICP significantly enhance UCNP, and the two policies exhibit a notable synergistic effect. Moreover, compared with cities participating in only a single pilot, cities designated as dual pilot cities demonstrate stronger policy effects in improving UCNP. Heterogeneity analysis reveals that the impact of the dual pilot policy (DPP) on urban carbon neutrality performance is more pronounced in non-resource-based cities and coastal cities. This study also finds that policy effects vary across different pilot batches. Mechanism analysis shows that dual pilot cities influence the carbon neutrality process through two mediating channels: technological innovation and industrial upgrading. The findings indicate that the two pilot policies exert significant positive effects on advancing urban carbon neutrality processes. To further promote regional green and low-carbon development, policymakers and implementers urgently need to strengthen the coordination of policy objectives, policy contents, and policy instruments among different pilot policies.

Keywords: low-carbon city pilots; innovative city pilots; urban carbon neutrality performance; double machine learning; synergistic effect; dual pilot policy; technological innovation; industrial upgrading

1.Introduction

The escalating threat of global climate change has catalyzed a universal consensus on the urgency of achieving carbon neutrality. As the world's largest carbon emitter and a pivotal driver of global economic growth, China has committed to a dual-target strategy: peaking carbon dioxide emissions by 2030 and achieving carbon neutrality by 2060 (the *Dual Carbon goals*). This ambitious transition requires more than just incremental adjustments; it necessitates a fundamental systemic transformation of urban developmental paradigms. Given that cities are the primary functional units for energy consumption and carbon emissions, the Chinese government has strategically deployed a series of policy experiments, most notably the Low-Carbon City Pilot (LCCP) and the Innovative City Pilot (ICP). These initiatives are designed to serve as 'testing grounds' for green governance, with the expectation that successful localized experiences can be scaled into nationwide strategies. However, as the 'Dual Carbon' framework enters a phase of deep implementation, the effectiveness of these historical pilots in fostering long-term, synergistic decarbonization—rather than isolated successes—remains a critical yet under-explored question in both academic and policy circles.

Scholars have extensively investigated the individual impacts of the ICP and the LCCP policies. Studies have affirmed the positive role of the ICP in enhancing urban innovation capacity (Zhou and Li, 2023; Lai et al., 2024), facilitating industrial restructuring (Zhao and Toh, 2023), and contributing to carbon emission reduction (Ren et al.,2024). Similarly, the LCCP has been shown to effectively reduce urban carbon emissions and air pollution (Li et al.,2025; Shu et al.,2025; Wang et al.,2024), while promoting green technology innovation and industrial upgrading (Chen et al., 2022; Zhao et al., 2025). The efficacy of both pilot policies in curbing urban carbon emissions has been validated by various scholars, providing empirical support for leveraging their demonstrative role under the 'dual carbon' goals. However, compared with the pursuit of single-dimensional indicators such as total carbon emissions or carbon emission intensity alone, the "dual carbon" goals focus holistically on the low-carbon transition process of cities, placing greater emphasis on whether a city has continuously maintained a low-carbon status and whether it has established a clear trend of carbon emission reduction. Based on the above discussion, constructing a comprehensive urban carbon neutrality performance (UCNP) indicator in accordance with the specific content of the "dual carbon" goals, and re-evaluating the policy effects of ICP and LCCP based on this indicator, constitutes one of the innovative contributions of this study relative to existing research.

Moreover, although the effectiveness of these two pilot policies has been individually validated in scholarly research, existing studies have predominantly been conducted from a single-policy evaluation perspective, overlooking potential interactions between different pilot policies. In practice, as two pilot initiatives focusing on distinct domains, when they jointly operate toward a common policy objective, they may generate complementary, substitutive, or even neutral effects. If the goals of different policies are not well coordinated, crowding-out effects may arise between them (Crespi et al.,2015). Therefore, assessing the interactive effects among different types of pilot policies is crucial for understanding their true effectiveness. Many scholars also emphasize that excessive focus on a single policy should be avoided, and instead, a comprehensive perspective should be adopted to examine the synergies between different policies.Accordingly, moving beyond a single-policy evaluation framework to examine the interaction between LCCP and ICP in the process of improving UCNP—specifically, exploring whether they generate complementary, substitutive, or neutral effects—constitutes the second innovative contribution of this study compared with prior research.

To address the above limitations, this study, from the perspective of the "dual carbon" strategy, investigates the individual effects, synergistic effects, and underlying mechanisms of the Low-carbon City Pilot (LCCP) and the Innovative City Pilot (ICP) on urban carbon neutrality performance (UCNP), based on panel data of 266 Chinese cities from 2010 to 2020. The main contributions of this study are fourfold.

First, existing studies have largely examined the impact of single-domain policies on urban low-carbon development. However, in actual urban carbon neutrality processes, policies from multiple domains play active roles. This indicates that different policies are not isolated but are closely linked with the potential for policy synergy. Therefore, this study constructs a research framework based on collaborative governance theory, attempting to explore the synergistic effects of LCCP (an environmental policy) and ICP (an innovation policy) – two representative policies from different domains – in China's carbon neutrality process, thereby revealing the linkages and roles of policies across domains in urban low-carbon development. Second, China's carbon neutrality actions are not merely about reducing total regional carbon emissions, but rather about achieving high-quality economic and social development while improving regional environmental quality. Hence, traditional low-carbon assessment indicators can no longer effectively summarize the current state of low-carbon development across Chinese cities from a holistic perspective. Based on existing research and data, this study constructs a UCNP indicator that integrates low-carbon development status, emission reduction trends, and development foundations, to better capture the low-carbon development levels of the sample cities. Third, we employ a Double Machine Learning (DML) model to better handle non-linear and high-dimensional data, thereby overcoming problems inherent in traditional econometric models such as the "curse of dimensionality". Finally, we apply a causal mediation approach to reveal the mediating roles of technological innovation and industrial upgrading in the process through which the dual pilot policy enhances UCNP. Based on the above findings, this study not only enriches the academic discussion on China's green transition but also provides a replicable policy evaluation framework for other developing countries committed to reconciling economic growth with carbon neutrality goals.

2.Literature review

Although the Chinese government explicitly articulated the strategic vision of achieving the "dual carbon" goals in 2020, the central government had in fact integrated energy conservation and emission reduction into the national strategic development plan as early as 2006. Carbon emissions subsequently became a binding indicator in local government performance assessments. Against this backdrop, the central government successively launched the LCCP and ICP. Consequently, although existing literature has not focused specifically on the relationship between these two pilot policies and the realization of the “dual carbon” goals, scholars have examined whether the policies influence urban carbon emissions.

In evaluating the effects of the ICP, apart from exploring its technological innovation and industrial restructuring effects, scholars have also paid attention to its carbon reduction impact. For instance,Ge et al (2023) employed a DID approach to empirically test the carbon emission effects of the ICP and its underlying mechanisms. Using firm-level data,Yang(2023)investigated the direct impact and spatial spillover effects of the pilot on corporate carbon emission efficiency. Differing from other scholars,Fan et al (2024) introduced carbon intensity as an indicator to assess the policy’s carbon reduction effect, demonstrating that the ICP reduces urban carbon emissions through two pathways: technological innovation and structural optimization. Meanwhile, Wang et al (2022) pointed out that the inhibitory effect of the ICP on carbon intensity exhibits significant spatial, resource-based, and city-size heterogeneity, and follows an inverted U-shaped relationship with population size. Regarding the evaluation of the LCCP, some scholars have employed causal inference methods such as difference-in-differences and synthetic control methods, using carbon emission intensity as a measure of carbon performance, to empirically examine the impact of the pilot on urban carbon emission performance. These studies have further analyzed its mechanisms and heterogeneous effects (Shu et al.,2025;Zeng et al.,2023;Gao and Wang,2024;Liu and Xu,2022).

Additionally, literature closely related to this study focuses on evaluating the combined or synergistic effects of innovation policies and environmental policies. In fact, scholarly attention to the interactive effects between policies in the fields of innovation and the environment dates back to 1990 (Flanagan et al.,2011). Within the environmental domain, the effectiveness of different policy mixes has increasingly become a focal point of academic inquiry. However, a consensus has not yet been reached on whether the effects of policy combinations are superior to those of single policies. Li and Yao (2020) examined the impact of a single carbon tax policy versus a policy mix including a carbon tax on the reduction of coal production capacity, verifying that the policy mix outperformed the single policy. Xu et al (2023) demonstrated that green credit policies and fiscal subsidy policies exert a positive synergistic effect on the green invention patent innovation activities of strategic emerging enterprises. In contrast, while exploring the synergistic effects between the carbon emissions trading system and green low-carbon policies, Wei (2022) found that the carbon reduction system exhibits a certain "crowding-out effect" on green low-carbon policies. Sun and Deng (2022) also pointed out that existing environmental policies and low-carbon policies have produced a negative synergistic effect in curbing urban carbon emissions, failing to further achieve the goal of "pollution and carbon reduction" and instead exacerbating urban carbon emissions. Dhanshyam and Srivastava (2021) indicated that the effects of policy combinations could be superior to those of single policies, but appropriate choices must consider temporal and spatial factors. In practice, when different policies jointly target the same objective, their synergistic outcomes may not always be complementary nor always conflicting; policies may generate synergistic innovation effects or resource competition effects (Borrás and Edquist,2013).In the field of innovation policy, scholars have also validated the synergistic effects of multiple policy combinations. Costantini et al (2017) argued that a mix of demand-pull and technology-push policies can better promote green innovation, although the effect may diminish if the number of policies exceeds a certain threshold. Based on the Chinese context, Chen (2022) explored the synergistic effects of the national innovative enterprise policy, the national innovative city policy, and the high-tech enterprise policy mix in enhancing firm innovation performance. Hou and Shi (2024) verified the synergistic effect of the dual pilot policies—Innovative City and Green Financial Reform Zone—on elevating the level of urban green innovation.

Overall, the existing literature has extensively explored whether these two types of pilot policies help pilot cities reduce carbon emissions, and empirical studies have generally provided affirmative answers. This offers a theoretical foundation for the present study to empirically examine whether these two pilot policies facilitate pilot cities' progress in advancing urban carbon neutrality. However, the introduction of the “dual carbon” goals has set new requirements for evaluating pilot policies. Simply focusing on whether the two pilot policies can reduce urban carbon emissions can no longer effectively capture the increasingly complex and systemic low-carbon transition actions in China today. New research urgently needs to adopt a dynamic and sustainable perspective, construct a new and comprehensive carbon neutrality performance indicator under the guidance of the “dual carbon” goals, and thereby reassess the actual effects of the two pilot policies. Furthermore, although scholars have separately discussed policy mixes or synergies in the innovation and environmental domains, few studies have investigated the combination of innovation policies and environmental policies and their synergistic effects. In particular, under the context of China’s pursuit of the “dual carbon” goals, little attention has been paid to how—and whether—pilot policies in the innovation domain and those in the environmental domain can achieve synergistic effects. Based on the above discussion, this study will introduce a comprehensive carbon neutrality performance indicator and systematically examine the individual effects, synergistic effects, heterogeneity, and mediating mechanisms of the two pilot policies on urban carbon emission performance. Finally, based on the empirical findings, a comprehensive analysis of the two pilot policies will be conducted.. Based on the above discussion, this study systematically examines the individual effects, synergistic effects, heterogeneity, and mediating mechanisms of LCCP and ICP on UNCP, and provides a comprehensive analysis of the two types of pilot policies based on the empirical results.

3.Policy background and Research hypothesis

3.1 Policy background

The ICP and LCCP are initiatives launched by the Chinese government in batches to address global climate change, promote national innovation, and respond to climate challenges. In 2008, the National Development and Reform Commission initiated the National Innovative City pilot program, designating Shenzhen as the first pilot city. In practice, innovative cities rely on innovation drivers such as technology, knowledge, and human resources, demonstrating strong innovation capacity. They play a significant role not only in achieving high-quality development within their own regions but also in radiating and leading development in other regions. China’s ICP has undergone seven batches of gradual expansion, reflecting a point-to-area diffusion pattern. By 2022, a total of 103 national innovative pilot cities had been approved.

The LCCP, as a large-scale, top-down policy experiment launched by the Chinese government to fulfill its international carbon reduction commitments, was first implemented in 2010. The initial batch included five provinces, including Guangdong, and eight cities, including Shenzhen. Subsequently, the central government launched the second and third batches in 2012 and 2017, respectively. To date, a total of 81 low-carbon pilot cities have been approved in three batches nationwide, demonstrating a point-to-area diffusion trend. The LCCP represents an institutional arrangement by the central government to explore pathways for achieving both emission reduction and development, and it plays a positive role in aligning with the national “dual carbon” strategy and advancing the “dual carbon” goals (Zhuang,2020;Qi et al.,2020).

Figure 1 illustrates the evolution of the central government’s launch and approval of the ICP and LCCP. As shown, 2010 and 2017 were years when both pilot programs were implemented simultaneously, during which the central government approved and designated a large number of cities for piloting. However, not every year saw new pilot approvals, reflecting the incremental nature of China’s reform process and the “point-to-area” progression of policy piloting. Figure 2 presents the spatial distribution of the LCCP and ICP cities. As indicated, most pilot cities are located in central and eastern regions. LCCP cities tend to be resource-based cities with dense manufacturing activities, while ICP cities are often emerging cities with a solid innovation foundation. Spatially, the two types of pilot cities exhibit a certain degree of clustering. Moreover, cities designated as both ICP and LCCP are primarily concentrated in eastern coastal areas.

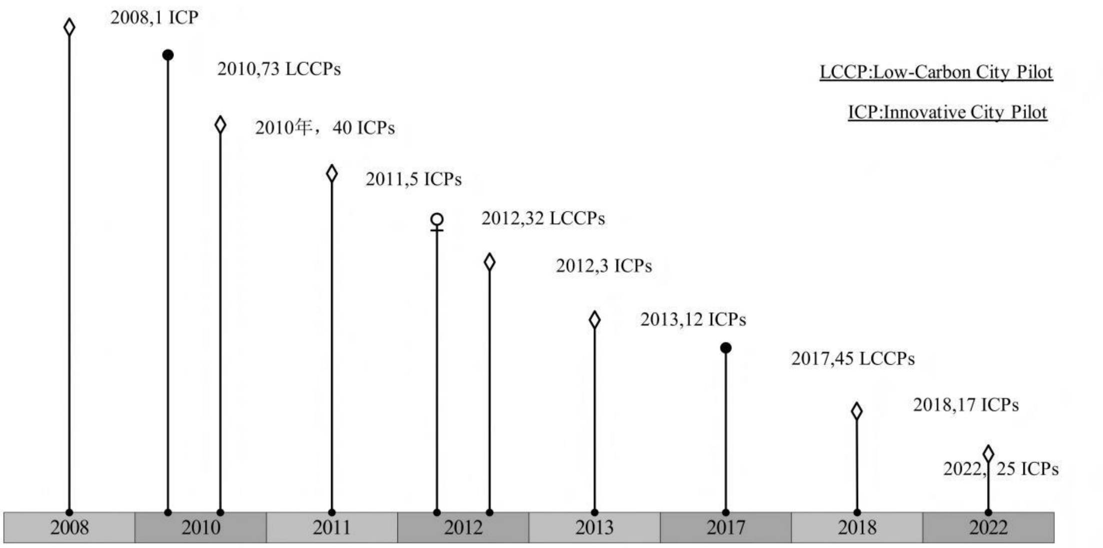


Figure 1. Batch Evolution of Low-Carbon City and Innovative City Pilots

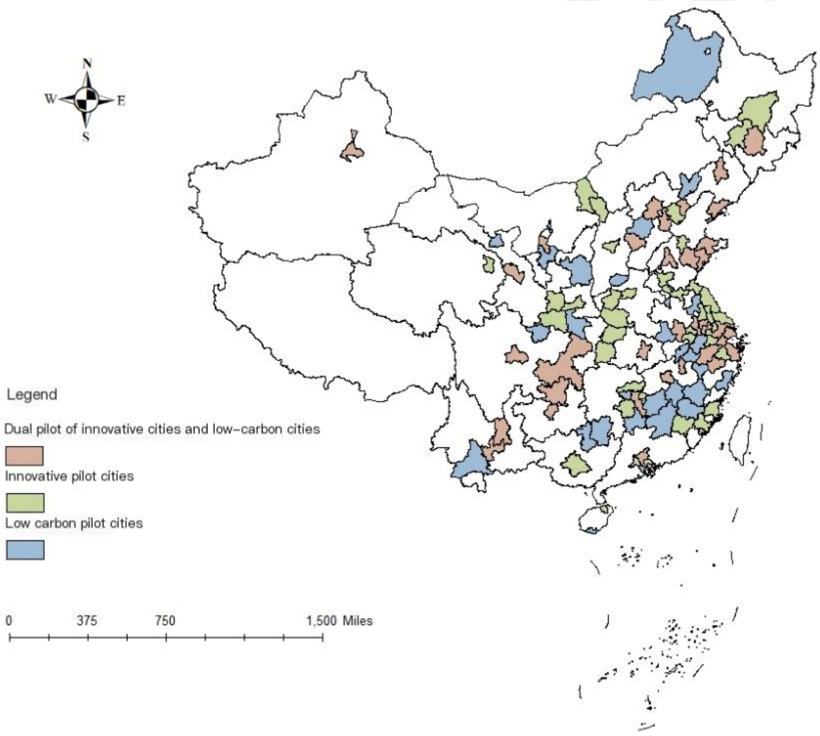


Figure 2. Spatial Distribution of Low-Carbon Cities and Innovative City Pilots in China

3.2 Research hypothesis

3.2.1 Direct Effects of LCCP, ICP, and the Dual Pilot Policy on UCNP

(1) Independent Effect of LCCP on UCNP

As the first large-scale, top-down policy experiment launched by the central government to fulfill its international carbon reduction commitments, the LCCP serves as a crucial institutional arrangement in the process of achieving the "dual carbon" goals. Its core objective of promoting regional green and low-carbon transition aligns inherently with the ultimate aims of the "dual carbon" strategy. In practice, pilot cities foster intrinsic drivers for urban carbon reduction and low-carbon development by establishing dedicated low-carbon development funds, implementing fiscal and tax incentives, and deploying a package of green finance policies to encourage green innovation among market entities and guide the growth of local green industries. Simultaneously, a shift in local governance philosophy—from a singular focus on GDP growth toward achieving a win-win scenario for both the environment and the economy—helps cultivate a societal atmosphere conducive to low-carbon development. This shift reshapes the perceptions of enterprises and the public regarding energy conservation, emission reduction, and low-carbon development. Once citizen values coalesce into a social consensus within pilot cities, it not only motivates proactive green and low-carbon behaviors but also exerts public oversight, imposing constraints on market entities such as enterprises, thereby forming an extrinsic driver for urban carbon reduction and low-carbon development. Under the combined effect of internal and external factors, compared with non-LCCP cities, LCCP exhibits a more significant and earlier-mover policy effect in improving UCNP.

(2) Independent Effect of ICP on UCNP

Technological innovation is widely regarded as a crucial pillar for promoting the process of carbon emission reduction (Li et al.,2021). With the core objective of enhancing regional technological innovation capacity, the ICP aims to boost urban innovation by improving institutional environments, supplying essential resources, and establishing industry-university-research collaboration platforms. This policy serves as a lever to drive the transformation and upgrading of industrial structures, improve energy efficiency, and enhance ecological environments in pilot cities(Wang et al.,2022;Yu et al.,2022). Consequently, it acts as a significant catalyst for promoting regional energy conservation, emission reduction, and green sustainable development. In practice, the ICP and the core objectives emphasized by the "dual carbon" strategy—energy conservation, emission reduction, and low-carbon sustainable development—constitute a relationship of means and ends. By employing technological innovation as a key instrument, the policy continuously supplies momentum for regional carbon reduction and low-carbon development. Therefore, ICP can continuously exert the demonstrative effect of pilot policies in improving UCNP.

(3) Synergistic Effect of LCCP and ICP on UCNP

Hermann Haken, the founder of synergetics, posits that synergy is the overall effect arising from the coordinated interaction of various parts within a system. The process of China's low-carbon transition is extremely complex, urgently requiring cross-sector collaboration among multiple actors, joint efforts across different administrative levels, and the coordinated alignment of various measures to form a combined force and generate policy synergy. The ICP and the LCCP belong to two distinct policy initiatives, differing across dimensions such as the responsible agencies, core objectives, and specific policy instruments. The intrinsic driver enabling their orderly collaboration to promote regional low-carbon transition stems precisely from the holistic synergistic effects generated by inter-departmental coordination, goal alignment, and the layering of policy measures.

First, the implementing entities of the two pilot policies exhibit synergy. These policies are promulgated by different central government ministries and involve coordination among multiple central and local departments during implementation, requiring various local agencies to perform their respective duties and cooperate. In practice, the policy synergy resulting from the joint efforts of science/technology and environmental protection departments may strengthen the positive impact of pilot cities on carbon reduction pathways, such as promoting technological innovation, optimizing industrial structure, and reducing energy intensity (Zheng et al.,2021). Second, the goals of the two pilot policies are synergistic. The core objective of the ICP is to promote technological innovation, while that of the LCCP is to achieve low-carbon development. Technological innovation and green low-carbon development are not mutually exclusive; instead, green technological innovation driven by their synergy becomes a crucial driver for advancing the process of carbon emissions reduction (Zhang et al.,2021). Finally, the specific implementation measures of the two pilot policies are layered. To promote the construction of innovative cities and low-carbon cities, pilot cities typically employ industrial policy tools aimed at optimizing energy consumption structures and facilitating industrial transformation and upgrading, alongside a series of fiscal and taxation measures such as funding subsidies and green finance. This layered approach aims to achieve both technological innovation and green low-carbon development.

Under the combined influence of these multiple channels—the joint effect of policy entities, the synergistic effect of policy goals, and the layered effect of policy measures—the dual-pilot framework is more conducive to accumulating resources. It provides institutional assurance, financial reserves, and resource supply for improving the carbon neutrality performance, thereby fostering factor accumulation and resource intensification for energy conservation and emission reduction. Furthermore, cities designated as dual pilots send a positive signal of central government endorsement and support to the outside world, highlighting a reputation effect and further enhancing their ability to attract resources.

Therefore, compared with single-pilot cities, cities that have received both LCCP and ICP pilot policies may exhibit stronger carbon emission reduction effects and more stable and sustained emission reduction trends, thus demonstrating a more significant and earlier-mover policy effect in enhancing carbon neutrality performance.. For an ICP, further designation as a LCCP can steer urban low-carbon transformation through policy guidance. Conversely, for a LCCP, additional designation as an ICP can elevate its innovation capacity, providing a driving force for its green development.

Based on the above discussion, this paper proposes the following two hypotheses.

H1: Cities concurrently approved for both the LCCP and ICP policies can effectively enhance UNCP.

H2: Compared with a single pilot policy, the dual pilot policy (DPP) is more effective in improving UNCP.

3.2.2 Mechanisms through which dual pilot cities enhance the UNCP

(1) *Technological innovation effect*

The Porter hypothesis suggests that stringent environmental regulations help promote firms' adoption of innovative technologies or engagement in innovative behaviors. Existing literature has also identified the mediating role of technological innovation in the process through which various environmental policies influence regional low-carbon transition (Dong et al., 2026; Lei & Xu, 2025). As a typical environmental policy aimed at improving the environment and achieving regional sustainable development, the implementation of LCCP has effectively promoted the enhancement of regional innovation capacity. During the pilot construction phase, low-carbon pilot cities are granted various policy incentives and financial supports. With the help of special support funds and investment and financing instruments, LCCP can effectively guide capital into green industries and green innovation fields, stimulate firms' motivation to engage in innovation activities, and thereby improve the overall innovation capacity of cities (Chen et al., 2022). At the same time, LCCP imposes stricter binding targets on regional environmental quality, which increases firms' emission costs and forces them to carry out innovation activities to reduce production costs (Zou et al., 2022).

For ICP, enhancing the level of urban technological innovation is the core goal of ICP. ICP uses policy incentives, innovation subsidies, and improvements in the business environment to stimulate firms to adopt innovative technologies and engage in R&D activities, thereby enhancing urban innovation capacity (Lai et al., 2024). Both LCCP and ICP, through policy and fiscal instruments, guide capital and factors into innovation fields to enhance urban innovation capacity. The two policies exhibit synergy in their policy instruments.

Based on the above discussion, this paper proposes H3.

H3: DPP cities enhance UCNP by strengthening urban technological innovation capacity.

(2) *Industrial structure upgrading effect*

Traditional environmental regulatory policies aim at improving environmental quality as a single policy goal, with limited implementation effectiveness. In contrast, LCCP has more diverse policy goals. While focusing on regional environmental quality, it also attends to economic benefits and governance efficiency (Zhao et al., 2025). First, LCCP can use instruments such as carbon taxes, resource taxes, and green bonds to introduce a number of emerging green industries into the local market, thereby improving the regional industrial structure (Hou et al., 2023). Second, LCCP sets new pollution emission standards and more stringent pollution control measures, which raise the market entry costs for high-pollution and high-emission firms and force already-entered high-pollution, high-emission firms to exit the market or seek transformation (Zhong et al., 2025). The regional industrial structure will gradually evolve toward a new structure dominated by low-energy, low-pollution enterprises.

ICP can effectively promote regional industrial structure upgrading. ICP can use policy incentives, financial support, and the provision of public services to effectively guide productive factors such as technical talent and capital into high-value-added, technology-intensive enterprises, improve the efficiency of technology commercialisation and overall productivity, and thereby promote industrial transformation and upgrading (Luo et al., 2025). At the same time, ICP accelerates the diffusion and renewal of technical knowledge. With the help of emerging technologies, high-energy-consumption industries can break away from traditional development paths and move toward high-value-added industries (Yin et al., 2025).

Based on the above discussion, this paper proposes H4.

H4: DPP cities enhance UCNP by promoting regional industrial structure upgrading.

Figure 3 illustrates the pathways through which the ICP and LCCP collectively influence the achievement of the UNCP in pilot cities, depicting both the driving effect of a single pilot policy and the achievement pathways under the synergistic effect of the dual pilots.

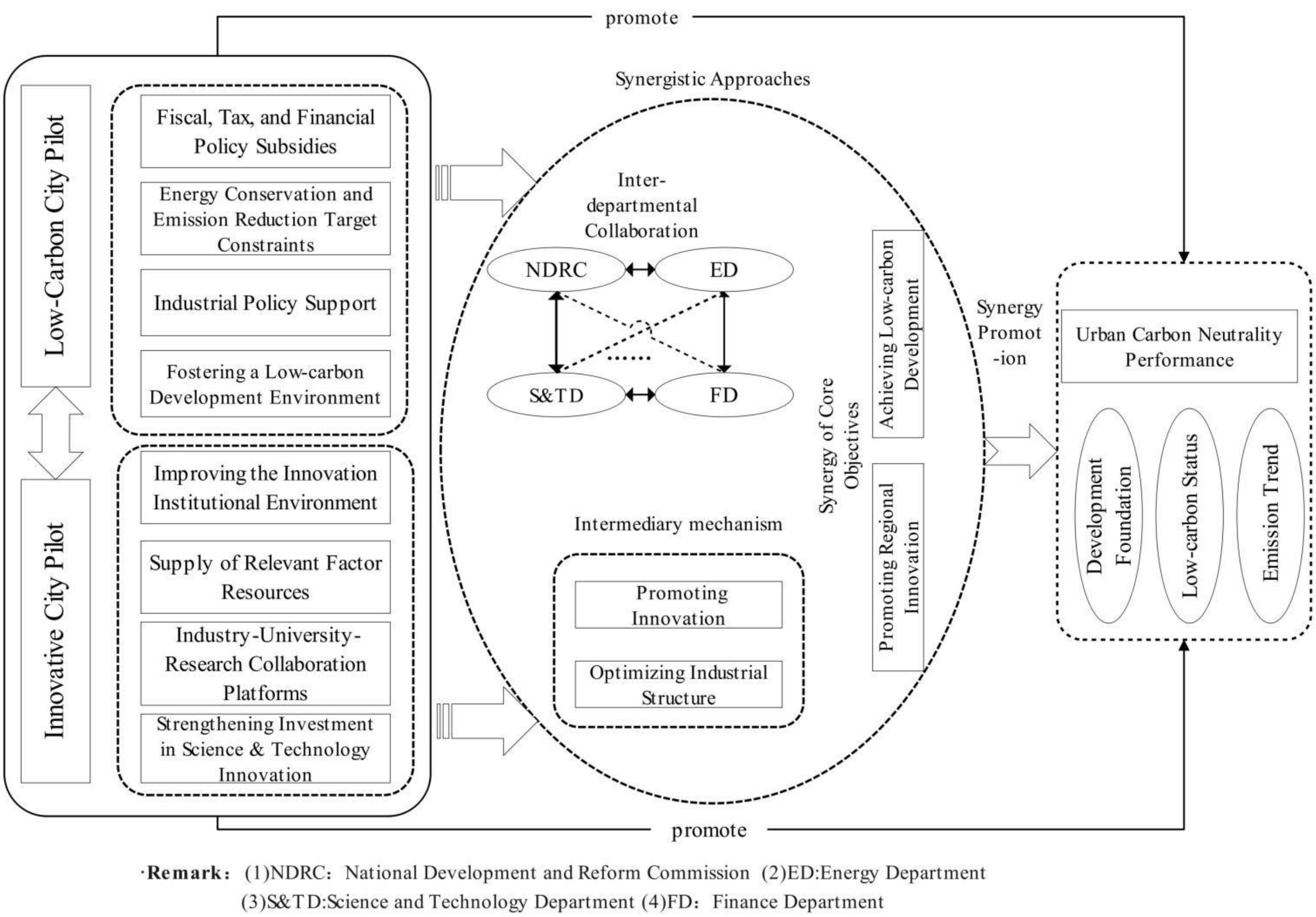


Figure 3. An Integrated Analytical Framework for LCCP and ICP in Advancing the UCNP.

4.Research design

4.1 Research model

To empirically examine the actual effects of LCCP and ICP on improving UNCP, this study employs a Double Machine Learning (DML) approach to investigate the following questions: (1) whether LCCP and ICP exert a significant synergistic effect on improving UNCP; (2) whether dual-pilot (DPP) cities are more conducive to improving UNCP than single-pilot cities; and (3) the mediating mechanisms through which DPP improves UNCP.

The DML method was proposed by Chernozhukov et al. (2018). Compared with traditional econometric models (e.g., DID, OLS), DML has advantages in handling high-dimensional data and effectively avoids problems such as the "curse of dimensionality". At the same time, DML employs cross-fitting and orthogonalization techniques to reduce the risk of overfitting and ensure that the estimates are insensitive to first-stage model misspecification, thereby guaranteeing unbiased and robust results. In recent years, it has been widely applied in causal inference (Ai et al., 2025; Zhao et al., 2024).

LCCP and ICP are not randomly assigned; there may be systematic differences between pilot and non-pilot cities in terms of economic foundations, city size, and government governance capacity. Direct application of traditional regression methods is therefore susceptible to sample selection bias and omitted variable problems. The DML approach can flexibly fit the relationships between control variables and policy variables as well as outcome variables, and uses orthogonalization to isolate the influence of confounding factors, thereby better identifying the net effects of the pilot policies on UCNP.

In the baseline regression, this paper adopts the Random Forest algorithm. As an ensemble learning method, Random Forest can effectively capture interaction effects among control variables through multi-dimensional partitioning of the feature space, and is robust to multicollinearity.

This paper constructs the following partial linear model:

$$UNCP_{it} = \theta D_{it} + g(X_{it}) + \mu_i + \lambda_t + \varepsilon_{it} \tag{1}$$

$$D_{it} = m(X_{it}) + \mu_i + \lambda_t + \nu_{it} \tag{2}$$

Where i denotes city, t denotes year; $UNCP_{it}$ denotes urban carbon neutrality performance; D_{it} is the core policy variable, representing LCCP, ICP or DPP respectively; X_{it} is the set of control variables, including government intervention level, city size, human capital level, and openness level; μ_i and λ_t denote city fixed effects and year fixed effects, respectively; ε_{it} and ν_{it} are random disturbance terms. This paper focuses on coefficient θ, i.e., the impact of the pilot policies on UCNP after controlling for city characteristics and time trends.

In the estimation process, DML first estimates the effects of the control variables on $UNCP_{it}$ and D_{it} separately, obtaining the residual terms for both:

$$\Delta UNCP_{it} = UNCP_{it} - g(X_{it}) \tag{3}$$

$$\Delta D_{it} = D_{it} - m(X_{it}) \tag{4}$$

Then, $\Delta UNCP_{it}$ is regressed on ΔD_{it} to obtain the estimated policy effect. This approach reduces the interference of non-linear relationships among control variables on the estimation results, making the identification of policy effects more robust.

Based on the above model, this paper first tests the independent effects of LCCP and ICP on UCNP separately, to determine whether these two pilot policies can independently enhance the carbon neutrality performance of pilot cities. Next, this paper takes DPP as the core explanatory variable to examine whether dual-pilot cities that have been approved for both types of pilot policies have stronger policy effects in improving UCNP, and further compares the differences between dual-pilot cities, single-pilot cities, and non-pilot cities. If the estimated coefficient of DPP is significantly positive and larger than the coefficients of either single pilot policy, this indicates a synergistic effect between LCCP and ICP.

4.2 Dependent Variables

This study uses urban carbon neutrality performance (UCNP) as the dependent variable. Following the methodology of Wang et al (2023)., we establish a comprehensive evaluation index system for UCNP, integrating three primary dimensions: low-carbon status, emission trends, and development foundation. Specifically, the low-carbon status dimension characterizes the current state of urban decarbonization, encompassing three secondary indicators: energy consumption, socio-economic structure, and carbon emission intensity. The emission trends dimension reflects the effectiveness of mitigation efforts, utilizing the carbon emission decoupling index and the carbon emission growth rate as secondary indicators. Finally, the development foundation dimension represents the inherent capacity for emission reduction, comprising four secondary indicators:

environmental resilience, capacity building, degree of public engagement, and carbon sequestration. To ensure objectivity, the entropy weight method (EWM) is applied to calculate the composite UCNP scores. The detailed architecture of the indicator system is delineated in Table 1.

Table 1 . Measurement System of UCNP

Primary Indicator	Secondary Indicator	Tertiary Indicator	Measurement Indicator
Low-Carbon Status	Energy Consumption	Total Electricity Consumption Intensity (kWh/10,000 CNY)	Electricity consumption per unit of GDP
		Energy Consumption Structure (%)	Share of coal consumption
	Socioeconomic Structure	Industrial Structure (%)	Share of secondary industry
		Public Transport Vehicles per Capita (vehicles/10,000 persons)	-
		Municipal Solid Waste Harmless Treatment Rate (%)	-
Emission Trend	Carbon Emission Level	Total Carbon Emissions (10,000 tons)	-
		GDP Carbon Emission Intensity (tons/10,000 CNY)	Carbon emissions per unit of GDP
	Carbon Emission Decoupling Index		Decoupling index between economic development and carbon emissions
	Carbon Emission Change Rate		Year-on-year change rate of carbon emissions
Development Foundation	Resilience	GDP Energy Intensity (tce/10,000 CNY)	Energy consumption per unit of GDP
		Energy Carbon Intensity (10,000 tons/10,000 tce)	Carbon emissions per unit of energy consumption
		Service Industry Share (%)	Share of tertiary industry
	Capacity Building	Share of Energy Conservation & Environmental Protection Investment (%)	Share of environmental expenditure in general public budget expenditure
		Science and Education Expenditure (10,000 CNY)	-
	Public Participation	Per Capita Residential Electricity Consumption (kWh/person)	-
		Green Patents per 10,000 Population (patents/10,000 persons)	-
	Carbon Sink	Green Space Area (hectares)	-

4.3 Independent Variables

The core independent variable of this paper is the dual pilot policy (DPP), i.e., whether a city has been concurrently awarded both the LCCP and ICP pilot policies by the central government. To accommodate the DML algorithm, this study adopts a dichotomous variable format, assigning a value of 1 to city samples that have been awarded both pilot policies, and 0 to non-dual pilot cities (including single-pilot cities and non-pilot cities). The list of LCCP is sourced from the lists of low-carbon pilot cities published over the years by China's National Development and Reform Commission (NDRC). The list of ICP is sourced from the lists of innovative pilot cities published over the years by the Ministry of Science and Technology of China.

4.4 Mechanism variable

(1) Technological innovation capacity (TI). Following relevant studies (Zhang and Liu, 2022), this paper takes the logarithm plus one of the number of granted utility model patents in the city at the end of the year as a proxy variable for urban technological innovation capacity.

(2) Industrial upgrading (UI). Following relevant studies (Zhang et al.,2024), this paper adopts the ratio of the annual added value of the three major industries to the city's annual GDP as a proxy variable for industrial upgrading.

4.5 Control Variables

This paper considers relevant factors that may influence UNCP and introduces the following four control variables: (1) *Government intervention level*: measured by the ratio of government general public budget expenditure to the city's annual GDP. (2) *City size*: measured by the logarithm of the city's annual permanent resident population. (3) *Human capital level*: measured by the ratio of the number of students enrolled in higher education institutions in the city to the city's annual permanent resident population. (4) *Openness level*: measured by the ratio of total imports and exports to the city's GDP.

4.6 Data Sources and Descriptive Statistics

Based on panel data from 266 Chinese cities covering the period 2010–2020, this paper evaluates the two pilot policies, LCCP and ICP. The relevant data are sourced from public databases such as the China City Statistical Yearbook and the annual government work reports of each city. Data on technology patents are obtained from the Chinese Research Data Services Platform (CNRDS). The descriptive statistics of the main variables are presented in Table 2.

Table 2. Descriptive Statistics of Variables

Variable Name	Observations	Mean	Std.Dev	Min	Max
UNCP	2926	0.1134	0.0582	0.0651	0.7668
City Size (ln)	2926	5.9429	0.6457	3.8067	8.1362
Government Investment Level	2926	0.2008	0.1056	0.0439	1.4852
Openness Level	2926	0.0025	0.0026	0	0.0194
Human Capital Level	2926	0.0191	0.0249	0	0.1330
Technology Innovation (ln)	2926	6.7530	1.6923	0	11.7101
Industrial Updating	2926	2.2897	0.1475	1.8312	2.8357

5.Empirical analysis results

5.1 Analysis of Baseline Regression Results

Based on panel data from 266 prefecture-level and above cities in China from 2010 to 2020, this paper employs the Double Machine Learning (DML) method to systematically identify whether the Low-carbon City Pilot (LCCP), the Innovative City Pilot (ICP), and the dual pilot policy (DPP) formed by their combination contribute to improving urban carbon neutrality performance (UNCP). Table 3 reports the baseline regression results. Overall, both single pilot policies and the dual pilot policy have a significant positive impact on UNCP, indicating that under the guidance of the “dual carbon” goals, the pilot policies have generally played an active role in institutional incentives and development guidance.

Table 3. Baseline Regression Results

	CE	CE	CE	CE	CE	CE	CE
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
P1	0.0166^{***} (0.0024)						
P2		0.0217^{***} (0.0029)					
P3			0.0208^{***} (0.0061)				
P4				0.0187^{***} (0.0053)			
P5					0.0238^{***} (0.0060)		
P6						0.0612^{***} (0.0044)	
P7							0.0314^{***} (0.0047)
Control variable	YES	YES	YES	YES	YES	NO	YES
Year FE	YES	YES	YES	YES	YES	YES	YES
City FE	YES	YES	YES	YES	YES	YES	YES
Obs.	2926	2926	409	628	2371	2926	2926

Note: Standard errors are reported in parentheses. ***p<0.01, **p<0.05, *p<0.1. The same applies to the table below.

Column P1 shows that the estimated coefficient of LCCP is 0.0166 and is significant at the 1% level, indicating that LCCP significantly improves UNCP. This means that compared with cities without LCCP implementation, pilot cities perform better in terms of low-carbon development status, emission reduction trend shaping, and the accumulation of relevant development foundations. This result is consistent with the theoretical expectation that low-carbon pilots promote the achievement of the carbon neutrality through green governance, energy structure adjustment, and low-carbon institutional constraints. Column P2 further shows that the estimated coefficient of ICP is 0.0217, also significant at the 1% level, indicating that ICP also significantly improves UNCP, and its individual effect is stronger than that of LCCP. This result suggests that innovation-oriented institutional arrangements not only enhance cities' capacity to access innovation resources but also provide sustained impetus for urban green and low-carbon transformation by increasing the supply of green technologies, improving factor allocation efficiency, and promoting industrial structure optimisation.

When examining the policy effect of DPP, columns P6 and P7 present estimates from the perspectives of "controlling only for year and city fixed effects" and "further incorporating control variables", respectively. The results show that the regression coefficients of DPC are 0.0612 and 0.0314, respectively, both significant at the 1% level. Column P7 represents the core result after including control variables, year fixed effects, and city fixed effects, indicating that under stricter control conditions, the dual pilot policy still significantly improves UNCP, demonstrating strong robustness and credibility. In other words, in cities concurrently approved for both LCCP and ICP, the two pilot policies exert a significant synergistic effect in improving UNCP. Hypothesis H1 is thus verified.

To further compare the differences between DPP and single pilot policies, this paper conducts tests under different sample specifications. Columns P3 and P4 compare DPP within the LCCP and ICP samples, respectively. The results show that the coefficients of DPP are 0.0208 and 0.0187, respectively, both significant at the 1% level, indicating that even within the group of cities that have already implemented a single pilot policy, DPP still exhibits stronger policy effects. Column P5 compares DPP cities with "cities without any pilot policy", with a coefficient of 0.0238, also significant at the 1% level, further demonstrating that DPP significantly improves UNCP. Taken together, columns P3–P5 show that compared with single-pilot cities, DPP cities have a stronger policy advantage in improving the UNCP, supporting Hypothesis H2.

In terms of coefficient magnitudes, the core regression coefficient of DPP (0.0314) is higher than that of LCCP (0.0166) and also higher than that of ICP (0.0217), indicating that the superposition of the two pilot policies does create stronger institutional synergy. In other words, DPP exhibits better emission reduction promotion and low-carbon transition effects than either single pilot, suggesting a certain degree of synergistic enhancement between environmental governance policies and innovation-driven policies. At the same time, the estimated coefficient of DPP does not exceed the sum of the two single-pilot coefficients, indicating that although policy superposition exhibits synergistic characteristics, this synergy is not a simple linear accumulation, nor is it a full “1+1>2” effect.

5.2 Robustness analysis

To ensure that the baseline regression results are not driven by model specifications or algorithm choices, this paper conducts robustness tests from within the DML framework using various parameter settings and machine learning algorithms. The results are presented in Table 4. Overall, regardless of whether the sample splitting ratio is changed or the machine learning algorithm is replaced, the estimated coefficient of DPP remains consistently positive and significant at the 1% level, indicating that the core conclusions of this paper are highly robust.

Table 4. Robustness analysis

	(1)	(2)	(3)	(4)	(5)
	kfolds=3	*kfolds=7*	*lassocv*	*gradboost*	*nnet*
DPP	0.0310***	0.0288***	0.0294***	0.0346***	0.0311***
	(0.0039)	(0.0043)	(0.0041)	(0.0081)	(0.0081)
Control variable	YES	YES	YES	YES	YES
Year FE	YES	YES	YES	YES	YES
City FE	YES	YES	YES	YES	YES
Obs.	2926	2926	2926	2926	2926

5.2.1 Changing the sample splitting ratio

In terms of adjusting cross-fitting parameters, this paper sets the k-fold cross-fitting to 3-fold and 7-fold, respectively. The results show that the estimated coefficients of DPP are 0.0310 and 0.0288, respectively, both significantly positive and very close to the baseline result of 0.0314. This indicates that our identification results are not sensitive to changes in sample splitting methods, and the sample splitting process on which DML estimation relies does not substantially alter the positive impact of DPP on UNCP. In other words, the promoting effect of DPP is not an incidental result under a specific cross-validation setting but exhibits strong sample stability.

5.2.2 Replacing the machine learning algorithm

This paper sequentially employs LassoCV, Gradient Boosting, and Neural Network (Nnet) to replace the Random Forest algorithm used in the baseline model. The results show that when using LassoCV, the coefficient of DPP is 0.0294; when using Gradient Boosting, the coefficient is 0.0346; and when using Neural Network, the coefficient is 0.0311, all significant at the 1% level. Although different algorithms differ in nonlinear fitting capacity, variable selection methods, and model complexity, the estimation results remain highly consistent in direction, significance, and magnitude. This suggests that the conclusion that DPP significantly improves UNCP does not depend on a specific machine learning method but exhibits strong methodological robustness.

In terms of the range of coefficient fluctuations, the results from various robustness tests are all concentrated between 0.0288 and 0.0346, which are largely consistent with the baseline regression result of 0.0314, indicating that adjustments in model specification do not alter the substantive impact of DPP. On the one hand, this enhances the credibility of our causal identification results; on the other hand, it shows that in the realistic context where high-dimensional control variables and potential nonlinear relationships coexist, the DML framework can identify the net policy effect relatively stably. Based on this, it can be concluded that the significant promoting effect of DPP on UNCP is highly robust, and the core conclusions above are not attributable to specific specifications or biases from a single algorithm.

5.3 Heterogeneity analysis

Given significant differences among cities in terms of resource endowments, geographical conditions, and policy start times, the impact of pilot policies on regional green development may not be homogeneous. To further identify the differentiated performance of policy effects, this paper conducts heterogeneity analysis from three dimensions: resource endowments, urban location, and pilot batches. The results are presented in Tables 5 and 6. Overall, the dual pilot policy (DPP) exhibits more pronounced policy effects in non-resource-based cities and coastal cities. Moreover, cities that received pilot status earlier show a more significant positive effect on UCNP. These pieces of evidence indicate that the policy effects have obvious condition dependence.

5.3.1 Resource Endowments

Based on the list of national resource-based cities published in the ' National Plan for Sustainable Development of Resource-Based Cities (2013-2020) ' issued by the State Council of China, this paper divides the sample into resource-based cities and non-resource-based cities. In the resource-based city subsample, the estimated coefficient of DPP is 0.0041 but is not statistically significant. In contrast, in the non-resource-based city subsample, the estimated coefficient of DPP is 0.0295 and is significant at the 1% level. This indicates that DPP has a stronger effect on enhancing UCNP in non-resource-based cities, while its policy effect is relatively limited in resource-based cities. A possible explanation is that resource-based cities have long relied on resource extraction and heavy industrial development, characterized by heavy industrial structures, rigid energy consumption, and prominent path dependence. Even with the dual incentives of low-carbon and innovation policies, it is difficult to achieve green technology diffusion, industrial restructuring, and energy system optimisation in the short term. In contrast, non-resource-based cities have relatively flexible industrial structures, higher degrees of marketisation, and more efficient allocation of innovation factors, making them more capable of translating DPP into technological progress and green transformation outcomes; therefore, the policy effects are more easily realised.

5.3.2 Urban Location

Differences in regional location can affect the governance effects of pilot policies (Wang et al., 2023). Based on the current regional status of China's economic and social development, this paper divides the sample into coastal cities and inland cities. The estimated coefficient for DPP in the coastal city subsample is 0.0298, significant at the 1% level. In the inland city subsample, the estimated coefficient of DPP is 0.0153, also significant at the 1% level, but notably lower than that for coastal cities. This result indicates that DPP has a more pronounced effect on improving carbon neutrality performance in coastal cities. One possible explanation is that coastal regions generally have higher levels of economic development, more systematic market mechanisms, greater openness, and richer reserves of innovation resources, providing a better institutional environment and practical foundation for the implementation of low-carbon and innovation policies. Particularly in terms of green finance, digital infrastructure, agglomeration of scientific and technological talent, and industrial chain synergy, coastal cities typically have first-mover advantages, making it easier for them to translate pilot policies into tangible low-carbon development performance. In contrast, although inland cities can also benefit from the dual pilot policy, their policy release effects are relatively weaker due to reasons such as lagging technology diffusion, higher industrial transformation costs, and relatively insufficient environmental governance capacity.

Table 5. Heterogeneity analysis (a)

	Resource endowment		Urban Location	
	Resource-based cities	*Non-Resource-based cities*	*Coastal cities*	*Inland cites*
DPP	0.0041	0.0295^{***}	0.0298^{***}	0.0153^{***}
	(0.0052)	(0.0046)	(0.0054)	(0.0045)
Control variable	YES	YES	YES	YES
Year FE	YES	YES	YES	YES
City FE	YES	YES	YES	YES
Obs.	1155	1771	1188	1738

5.3.3 Batch Effects

To further examine the differences across pilot batches, this paper further incorporates different batches of low-carbon pilot cities and innovative pilot cities as explanatory variables. First, the batch effects of LCCP are examined. Considering that the first batch of pilot cities (2010) and the second batch (2012) were designated close in time, and that the number of cities in the first batch is relatively small, this study combines these two batches into one group for analysis. The regression results are presented in Table 6. Second, this paper examines the batch effects of ICP. Following a similar approach as for the low-carbon pilot policy, and considering that the first batch of ICP cities (2008, with only one pilot city), the third batch (2011), and the fourth batch (2012) are all too few in number and close in time to the second batch (2010), these are uniformly treated as one batch. The original fifth batch of ICP cities (2013) is treated as the second batch, and the sixth batch (2018) as the third batch. The regression results are shown in Table 6.

Rows 1–2 of Table 6 present the batch effects of LCCP. The results indicate that the first to third batches of LCCP cities have a significant impact on UCNP ($p < 0.01$). In terms of effect magnitudes, compared with the third batch of LCCP cities (coefficient of 0.0110), the first and second batches exhibit more pronounced emission reduction effects (coefficient of 0.0212).

Rows 3–5 reveal the regression results for the six batches of ICP cities, all showing significant impacts on UCNP ($p < 0.01$). Similarly, compared with the fifth batch of ICP cities (coefficient of 0.0113) and the sixth batch (coefficient of 0.0189), the first four batches of ICP cities demonstrate stronger policy effects (coefficient of 0.0384).

The batch effects analysis of the two pilot policies suggests that the emission reduction effects generated by pilot cities increase over time. This reflects the long-term and persistent nature of pilot policy construction, as well as the long-term process of regional sustainable transformation.

Table 6. Heterogeneity analysis (b)

	CE	CE	CE	CE	CE
	(1)	(2)	(3)	(4)	(5)
LCCP B1~B2	0.0212^{***} (0.0011)				
LCCP B3		0.0110^{***} (0.0025)			
ICP B1~B4			0.0384^{***} (0.0109)		
ICP B5				0.0113^{***} (0.0017)	

ICP B6					0.0189*** (0.0036)
Control variable	YES	YES	YES	YES	YES
Year FE	YES	YES	YES	YES	YES
City FE	YES	YES	YES	YES	YES
Obs.	2926	2926	2926	2926	2926

5.4 Mechanism identification

The baseline regression results above indicate that DPP can significantly enhance UNCP. However, the transmission pathways through which DPP affects UNCP still require further explanation. Following the relevant research of Farbmacher et al. (2022), this paper employs a causal mediation analysis approach to reveal the mechanisms through which DPP influences UNCP from two pathways: industrial upgrading and technological innovation. The results are presented in Table 7. Overall, both technological innovation and industrial upgrading constitute important transmission channels through which DPP enhances UNCP, and Hypotheses H3 and H4 are validated.

Table 7. Mechanism identification

	Total	dir.treat	dir.control	indir.treat	indit.control
TI	0.0940*** (0.0167)	0.0690*** (0.0164)	0.0280*** (0.0079)	0.0661*** (0.0171)	0.00251*** (0.0041)
UI	0.0896*** (0.0162)	0.0161*** (0.0164)	0.0091* (0.0058)	0.0805*** (0.0168)	0.0088*** (0.0033)
Control variable	YES	YES	YES	YES	YES
Year FE	YES	YES	YES	YES	YES
City FE	YES	YES	YES	YES	YES
Obs.	2926	2926	2926	2926	2926

5.4.1 Technological Innovation (TI) Channel

The results show that the total effect of the TI pathway is 0.0940 and is significant at the 1% level. The direct effect in the treatment group (dir.treat) is 0.0690, the direct effect in the control group (dir.control) is 0.0280, the indirect effect in the treatment group (indir.treat) is 0.0661, and the indirect effect in the control group (indir.control) is also significantly positive. These findings indicate that DPP not only directly enhances UNCP but also further promotes UNCP improvement by strengthening urban technological innovation capacity. Specifically, on the one hand, DPP compels enterprises to increase R&D investment and promote green technology application through low-carbon governance constraints and innovation system incentives; on the other hand, it continuously improves the efficiency of urban green transformation by enhancing the regional innovation ecosystem, strengthening knowledge spillovers, and improving access to innovation resources. Thus, technological innovation serves as an important mediating channel through which DPP affects UCNP.

5.4.2 Industrial Upgrading (UI) Channel

The results show that the total effect of the UI pathway is 0.0896, significant at the 1% level. The direct effect of the treatment group is 0.0161, the direct effect of the control group is 0.0091, and the indirect effect is 0.0805, all passing the significance tests. Compared with the technological innovation pathway, the indirect effect of UI is stronger, indicating that DPP's promotion of UCNP is largely achieved by facilitating the shift of industrial structure from energy-intensive and high-emission sectors towards technology-intensive, knowledge-intensive, and low-carbon service sectors. In other words, DPP not only promotes "greener technology" but also drives "better structure", with the latter exhibiting a more prominent explanatory power in the transmission of policy effects.

Combined with the theoretical analysis above, LCCP emphasises energy conservation, emission reduction, green governance, and environmental constraints, while ICP emphasises access to innovation resources, institutional incentives, and technological progress. The two types of policies exhibit clear complementarity at the instrument level. It is precisely under this dual effect of "environmental regulation + innovation drive" that, on the one hand, cities reduce carbon emissions per unit of output through green technology R&D and application, and on the other hand, they reshape long-term development paths through the upgrading and greening of industrial structures, ultimately achieving UCNP improvement. Therefore, technological innovation and industrial upgrading are not isolated from each other but together constitute two key mechanistic chains through which DPP affects UCNP.

6.Conclusions and Policy Implications

6.1 Conclusions

Based on panel data from 266 Chinese cities spanning the period 2010–2020, this study employs a Double Machine Learning (DML) model to investigate the impacts of the Low-carbon City Pilot (LCCP), the Innovative City Pilot (ICP), and the dual pilot policy combining the two (DPP) on urban carbon neutrality performance (UCNP), as well as the underlying mechanisms. The results show that both pilot policies contribute to enhancing UCNP and exert a significant synergistic effect in doing so. These findings provide new empirical evidence for re-evaluating the functional boundaries and institutional value of policy pilots in the context of the "dual carbon" goals.

(1) Both LCCP and ICP significantly improve UCNP, and the promoting effect of DPP is even stronger. Baseline regression results indicate that LCCP and ICP each have a significant positive impact on UCNP, suggesting that both environment-oriented low-carbon institutional arrangements and technology-oriented innovation policy designs can drive urban green and low-carbon transitions to varying degrees. Furthermore, the estimated coefficient of DPP is not only significantly positive but also larger than that of either single pilot policy, indicating that when low-carbon governance and innovation-driven policies are combined in the same city, they generate stronger institutional synergy and transition momentum. Thus, the two research hypotheses H1 and H2 proposed in this paper receive empirical support. Moreover, although DPP exhibits significant synergy-enhancing characteristics, its synergistic effect has not yet reached a simple multiplicative level. This paper finds that the effect size of DPP, while larger than the individual effects of LCCP and ICP, does not exceed the sum of their coefficients. This suggests that there may be diminishing marginal returns, incentive asymmetry, policy friction, or resource crowding-out between the two pilot policies, preventing DPP from fully realizing the ideal "1+1>2" effect. This empirical finding partially corroborates the view in related studies that environmental regulation may increase firms' production costs and crowd out resources, thereby weakening carbon emission performance (Lei & Kocoglu, 2025).

(2) The implementation effects of DPP exhibit significant heterogeneity, clearly influenced by cities' resource endowments, geographical locations, and pilot batches. In non-resource-based cities, DPP has a significant promoting effect on UCNP, whereas in resource-based cities the effect is not significant. In coastal cities, the effect size of DPP is markedly larger than in inland cities. Among different pilot batches, cities that were designated pilots earlier by the central government show more pronounced policy effects.

(3) Technological innovation and industrial structure upgrading are two key transmission mechanisms through which DPP promotes UCNP improvement. DPP not only directly enhances UCNP but also indirectly boosts UCNP in pilot cities by strengthening urban technological innovation capacity and promoting industrial structure upgrading. On the one hand, DPP increases the supply of green technologies and the efficiency of innovation diffusion through innovation incentives, green constraints, and resource channelling, thereby strengthening the endogenous impetus for low-carbon transition. On the other hand, DPP optimises industrial development directions, compresses the space for energy-intensive and high-emission industries, and fosters the growth of service sectors and technology-intensive industries, facilitating a shift of urban development models from extensive to green-intensive patterns.

6.2 Policy Implications

Based on the above findings, this paper argues that in the new stage of comprehensively improving the urban carbon neutrality performance, greater attention should be paid to the integration, optimisation, and differentiated implementation of existing low-carbon and innovation pilot policies. The following policy recommendations are proposed.

(1) Efforts should be made to enhance the institutional articulation between LCCP and ICP, promoting the "dual pilot" from policy superposition to policy coupling. In the process of improving the urban carbon neutrality performance at both central and local levels, it is insufficient to merely assign multiple pilot policies to the same city; greater emphasis should be placed on the

content alignment and mechanism integration among different policies. Specifically, at the policy design level, coordination among departments such as science and technology, development and reform, industry and information technology, and ecological environment should be strengthened. A cross-departmental coordination mechanism should be established to achieve a higher level of consistency between innovation policies, industrial policies, and low-carbon policies in terms of target systems, assessment criteria, financial support, and implementation pathways. In particular, the technological innovation tasks in ICP should be aligned with the emission reduction requirements in LCCP, forming a closed loop among green technology R&D, low-carbon industry cultivation, and carbon emission governance, rather than advancing separately and in isolation. Only by enhancing the intrinsic coupling between the two pilot policies can their synergistic potential be truly unleashed.

(2) Technological innovation should be taken as an important lever for improving urban carbon neutrality performance, and the institutional supply capacity for green technology innovation should be continuously strengthened. From a policy perspective, the support system for green technology R&D should be further improved, with increased fiscal support, tax incentives, research funding, and assistance for the commercialisation of achievements in key areas related to energy conservation, carbon reduction, and the green economy, thereby enhancing the motivation of enterprises and research institutions to engage in green innovation. At the same time, a more open and efficient regional innovation ecosystem should be built, strengthening collaborative innovation among universities, research institutes, enterprises, and governments to facilitate the transfer of green technologies from the laboratory to the industrial, application, and governance fronts, thereby improving the efficiency of green technology commercialisation.

(3) Industrial structure upgrading should be taken as the core focus for achieving the UNCP, driving a shift in urban development patterns from high-carbon lock-in to green restructuring. When implementing carbon neutrality strategies, local governments should accelerate the green transformation of traditional energy-intensive and high-emission industries, strictly control the

expansion of backward production capacity and high-carbon projects, and promote the growth and development of emerging green industries, modern service sectors, and high-tech industries. Particularly at the city level, industrial structure adjustment should be integrated with low-carbon city construction and innovative city construction to form a modern industrial system dominated by green manufacturing, the digital economy, and low-carbon services, thereby reducing the carbon emission intensity of urban development at the source.

(4) Differentiated dual pilot implementation strategies should be adopted according to the actual conditions of different cities. For resource-based cities, DPP should be combined with energy transition, industrial substitution, ecological restoration, and fiscal compensation policies, prioritising the resolution of structural problems such as high-carbon industry lock-in, weak innovation foundations, and excessive transition costs, so as to enhance their actual capacity to undertake pilot policies. For inland cities, while strengthening infrastructure and the supply of innovation resources, the business environment and factor flow mechanisms should be further improved to enhance the diffusion and absorption capacity of DPP. In contrast, coastal and non-resource-based cities can further leverage their existing demonstration effects and continue to explore pathways for improving the carbon neutrality performance, providing replicable and scalable empirical models for emission reduction actions in other developing countries.

References

Ai, M., Wang, P., & Bu, Y. (2025). Climate policy and inclusive green growth: The role of China's low-carbon city pilot policy. Journal of Cleaner Production, 519, 145959. doi: https://doi.org/10.1016/j.jclepro.2025.145959

Borrás, S., & Edquist, C. (2013). The choice of innovation policy instruments. TECHNOLOGICAL FORECASTING AND SOCIAL CHANGE, 80(8), 1513-1522. doi: 10.1016/j.techfore.2013.03.002

Chen, C., Li, P., & Wang, H. (2022). Research on the synergistic effect of national innovative policy

[In Chinese]. Journal of Finance and Economics, 48(5), 80–94.doi:10.16538/j.cnki.jfe.20220317.101

Chen, C. F., Lin, Y. S., Lv, N., Zhang, W., & Sun, Y. W. (2022). Can government low-carbon regulation stimulate urban green innovation? Quasi-experimental evidence from China's low-carbon city pilot policy. APPLIED ECONOMICS, 54(57), 6559-6579. doi: 10.1080/00036846.2022.2072466

Chernozhukov, V., Chetverikov, D., Demirer, M., Duflo, E., Hansen, C., Newey, W.,... Robins, J. (2018). Double/debiased machine learning for treatment and structural parameters. ECONOMETRICS JOURNAL, 21(1), C1-C68. doi: 10.1111/ectj.12097

Costantini, V., Crespi, F., & Palma, A. (2017). Characterizing the policy mix and its impact on eco-innovation: A patent analysis of energy-efficient technologies. RESEARCH POLICY, 46(4), 799-819. doi: 10.1016/j.respol.2017.02.004

Crespi, F., Ghisetti, C., & Quatraro, F. (2015). Environmental and innovation policies for the evolution of green technologies: A survey and a test. Eurasian Business Review, 5(2), 343–370.doi: 10.1007/s40821-015-0027-z

Dhanshyam, M., & Srivastava, S. K. (2021). Effective policy mix for plastic waste mitigation in India using System Dynamics. RESOURCES CONSERVATION AND RECYCLING, 168. doi: 10.1016/j.resconrec.2021.105455

Dong, X. Y., Wang, Y., Zhu, S. Y., Zhang, J. L., & Tan, Z. F. (2026). Evaluating Carbon Emission Reduction Effect, Transmission Mechanism, and Carbon Market Efficiency of Carbon Emission Trading Policy: Evidence from China. CSEE JOURNAL OF POWER AND ENERGY SYSTEMS, 12(1), 424-436. doi: 10.17775/CSEEJPES.2025.04180

Fan, M. M., Zhang, Z. H., Wei, Y. G., & Sun, S. (2024). Does innovative city pilot policy improve carbon reduction? Quasi-experimental evidence from China. ENVIRONMENTAL RESEARCH, 262. doi: 10.1016/j.envres.2024.119748

Farbmacher, H., Huber, M., Lafférs, L., Langen, H., & Spindler, M. (2022). Causal mediation analysis with double machine learning. The Econometrics Journal, 25(2), 277-300. doi: 10.1093/ectj/utac003

Flanagan, K., Uyarra, E., & Laranja, M. (2011). Reconceptualising the 'policy mix' for innovation. RESEARCH POLICY, 40(5), 702-713. doi: 10.1016/j.respol.2011.02.005

Gao, S., & Wang, S. J. (2024). Carbon Abatement Effect of Low-Carbon City Pilot Policy: Insights from a Time-Varying DID Model. ANNALS OF THE AMERICAN ASSOCIATION OF GEOGRAPHERS, 114(10), 2414-2430. doi: 10.1080/24694452.2024.2388120

Ge, T., Li, J. Y., & Wang, C. (2023). Econometric analysis of the impact of innovative city pilots on CO2 emissions in China. ENVIRONMENT DEVELOPMENT AND SUSTAINABILITY, 25(9), 9359-9386. doi: 10.1007/s10668-022-02439-8

Hou, G. C., & Shi, G. F. (2024). Green finance and innovative cities: Dual-pilot policies and collaborative green innovation. INTERNATIONAL REVIEW OF FINANCIAL ANALYSIS, 96. doi: 10.1016/j.irfa.2024.103673

Hou, Z. P., Wan, J., Wang, Z. Y., & Li, C. G. (2023). How does low-carbon city construction drive enterprise green governance? A complete chain mediation model. INTERNATIONAL JOURNAL OF CLIMATE CHANGE STRATEGIES AND MANAGEMENT, 15(5), 768-789. doi: 10.1108/IJCCSM-04-2023-0050

Huo, W. D., Qi, J., Yang, T., Liu, J. L., Liu, M. M.,... Zhou, Z. Q. (2022). Effects of of China's pilot low-carbon city policy on carbon emission reduction: A quasi-natural experiment based on satellite data. TECHNOLOGICAL FORECASTING AND SOCIAL CHANGE, 175. doi: 10.1016/j.techfore.2021.121422

Lai, M. Y., Fang, J. Y., & Xie, R. (2024). Does regional innovation policy encourage firm indigenous innovation? Evidence from a quasi-natural experiment of the pilot project of innovative cities in China. APPLIED ECONOMICS, 56(15), 1817-1833. doi: 10.1080/00036846.2023.2177601

Lei, X., & Kocoglu, M. (2025). When good intentions meet bad outcomes: Evidence from China's cleaner production mandate. Energy Economics, 152, 109030. doi: https://doi.org/10.1016/j.eneco.2025.109030

Lei, X., & Xu, X. G. (2025). From City Wisdom to Corporate Action: Climate-Adaptive City Construction and Corporate Environmental Responsibility. WEATHER CLIMATE AND SOCIETY, 17(4), 1027-1041. doi: 10.1175/WCAS-D-24-0136.1

Li, X., Hu, J., Lyu, X., & Bhuiyan, M. A. (2025). Are low-carbon city pilot policies conducive to carbon reduction?: An analysis of experiences from China. Environment, Development and Sustainability. doi: 10.1007/s10668-024-05776-y

Li, X. Y., & Yao, X. L. (2020). Can energy supply-side and demand-side policies for energy saving and emission reduction be synergistic?--- A simulated study on China's coal capacity cut and carbon tax. ENERGY POLICY, 138. doi: 10.1016/j.enpol.2019.111232

Li, Y., Yang, X., Ran, Q., Wu, H., Irfan, M., & Ahmad, M. (2021). Energy structure, digital economy, and carbon emissions: evidence from China. Environmental Science and Pollution Research International.doi: 10.1007/s11356-021-15304-4

Liu, X., & Xu, H. (2022). Does low-carbon pilot city policy induce low-carbon choices in residents? living: Holistic and single dual perspective. JOURNAL OF ENVIRONMENTAL MANAGEMENT, 324. doi: 10.1016/j.jenvman.2022.116353

Luo, X., Zhao, C., Dong, C., Yang, P., & Dong, X. (2025). Does innovative city construction boost urban employment? Evidence from China. Applied Economics, 57(49), 8019-8035. doi: 10.1080/00036846.2024.2402576

Qi, Y., Liu, T., Song, Q., Wang, Y., & Lu, J. (2020). Low-carbon city pilot: Leading the carbon emissions peak in the 14th five-year plan period [In Chinese]. Environmental Protection, 48(5), 9–12.

Ren, Y., Yu, J., Zhang, G., & Yu, Y. (2024). Towards low-carbon development through innovation: Empirical evidence from China. Cities, 152, 105197. doi: 10.1016/j.cities.2024.105197

Shu, J. X., Peng, J. J., & Zhang, J. (2025). The impact of low-carbon city pilot policy on carbon emission intensity: evidence from China using a multi-period difference-in-differences model. FRONTIERS IN ENVIRONMENTAL SCIENCE, 12. doi: 10.3389/fenvs.2024.1488526

Sun, H., & Deng, Y. (2022). The effect of “reducing pollution and carbon emissions” in environmental policy: a study based on the perspective of pollution fee collection [In Chinese]. China Economic Studies, (3), 115–129.doi: 10.19365/j.issn1000-4181.2022.03.07

Wang, H., Gu, K. Y., Dong, F., & Sun, H. (2024). Does the low carbon city pilot policy achieve the synergistic effect of pollution and carbon reduction? ENERGY & ENVIRONMENT, 35(2), 569-596. doi: 10.1177/0958305X221127018

Wang, J., Sun, H., & Liao, J. L. (2024). Digital economy empowerment, dual-carbon development performance and regional coordination effect. Inquiry into Economic Issues, (5), 125-148. https://kns.cnki.net/kcms2/article/abstract?v=JRmhR0Lfi27YmIPL1TOtzod3u3C27JjdvnLYh3PWpxteivM9ELh5KCozC5FUcgTPaTmcCCISoPvBCXkbi0dBRfmnYg8c8KNVYlyyR85rNmNslFbxkQjG7n_1UezDs2iW9zMYHEgvc3m5dzWeaaS4rO6kVIt4lArne7Cip5ppd38Je6yvrJT8zg==&uniplatform=NZKPT&language=CHS

Wang, Y., Hou, L., & Zhu, J. (2022). Can urban innovation help the development of low carbon economy? Impact assessment and mechanism analysis of innovative city pilot policy on carbon intensity [In Chinese]. Science & Technology Progress and Policy, 39(18), 39–49.doi: 10.6049/kjjbydc.CZ202107033

Wang, Z., Liang, F., Li, C., Xiong, W., Chen, Y.,... Xie, F. (2023). Does China's low-carbon city pilot policy promote green development? Evidence from the digital industry. Journal of Innovation & Knowledge, 8(2), 100339. doi: https://doi.org/10.1016/j.jik.2023.100339

Wei, Q. (2022). Research on coordination between carbon trading scheme and green&low-carbon policies under “double carbon” targets [In Chinese]. Journal of Hebei University of Science and Technology(Social Sciences), 22(1), 19–26.doi: 10.7535/j.issn.1671-1653.2022.01.003

Xu, Y., Mao, S., & Li, J. (2023). Enterprise green innovation with dual incentives —Synergies effect and mechanism of green loans and fiscal subsidies [In Chinese]. Studies of International Finance, (4), 86–96.

Yang, P. (2023). Whether national innovative city construction can promote carbon emission efficiency—Theoretical construction, mechanism analysis and spatial effect evaluation [In Chinese]. Journal of Guizhou University of Finance and Economics, (2), 93–102.

Yin, L., Jiang, X. L., & Guo, Z. T. (2025). The impact of broadband China and innovative city dual pilot policies on urban carbon productivity. DISCOVER SUSTAINABILITY, 6(1). doi: 10.1007/s43621-025-01809-2

Yu, C. Y., Long, H. Y., Tu, C. L., Tan, Y. F., Zang, C. X.,... Zhou, Y. (2022). Assessing the effectiveness of innovative city pilots in improving urban carbon emission performance: A spatial difference-in-difference approach. FRONTIERS IN ENVIRONMENTAL SCIENCE, 10. doi: 10.3389/fenvs.2022.983711

Zeng, S. B., Jin, G., Tan, K. Y., & Liu, X. (2023). Can low-carbon city construction reduce carbon intensity?Empirical evidence from low-carbon city pilot policy in China. JOURNAL OF ENVIRONMENTAL MANAGEMENT, 332. doi: 10.1016/j.jenvman.2023.117363

Zhang, C., & Liu, L. (2022). Authorized patents and total factor productivity under intensified market competition: Quasi-natural experimental evidence from China. Managerial and Decision Economics, 43(8), 3576-3592. doi: https://doi.org/10.1002/mde.3615

Zhang, Y., Cheng, J., Xu, Z., et al. (2021). Whether green innovation can adapt to climate change: an empirical study of China's patent and GHG emission data [In Chinese]. China Population, Resources and Environment, 31(1), 48–56.doi: 10.12062/cpre.20200921

Zhang, Y., Pi, L., Chen, Y., & Shi, R. (2024). Energy transition policy and Chinese rural revitalization: The roles of industrial upgrading and digital economy. Finance Research Letters, 69, 106100. doi: https://doi.org/10.1016/j.frl.2024.106100

Zhao, K., Gao, Y., & Liu, X. M. (2025). The impact of environmental regulation on industrial structure upgrading: A case study of low carbon city pilot policy. ENERGY POLICY, 197. doi: 10.1016/j.enpol.2024.114432

Zhao, W. Q., & Toh, M. Y. (2023). Impact of Innovative City Pilot Policy on Industrial Structure Upgrading in China. SUSTAINABILITY, 15(9). doi: 10.3390/su15097377

Zhao, X., Ke, X., Jiang, S., & You, X. (2024). Exploring the dynamics of urban energy efficiency in China: A double machine learning analysis of green finance influence. Environmental Technology & Innovation, 35, 103653. doi: https://doi.org/10.1016/j.eti.2024.103653

Zheng, S., He, Y., & Zou, K. (2021). Climate policy synergy: mechanism and effect [In Chinese]. China Population, Resources and Environment, 31(8), 1–12.doi: 10.12062/cpre.20210421

Zhong, Z. Q., Zheng, C. Y., & Chen, Z. G. (2025). Low-carbon cities pilot and industrial structure upgrading: enabling or negative? Evidence from a quasi-natural experiment in China. JOURNAL OF ENVIRONMENTAL PLANNING AND MANAGEMENT, 68(11), 2566-2598. doi: 10.1080/09640568.2024.2319267

Zhou, Y. L., & Li, S. S. (2023). Can the innovative-city-pilot policy promote urban innovation? An empirical analysis from China. JOURNAL OF URBAN AFFAIRS, 45(9), 1679-1697. doi: 10.1080/07352166.2021.1969243

Zhuang, G. (2020). Policy design logic of low-carbon city pilots in China [In Chinese]. China

Population, Resources and Environment, 30(3), 19–28.doi: 10.12062/cpre.20200301

Zou, C., Huang, Y., Wu, S., & Hu, S. (2022). Does “low-carbon city” accelerate urban innovation? Evidence from China. Sustainable Cities and Society, 83, 103954. doi: https://doi.org/10.1016/j.scs.2022.103954