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Does energy transition policy enhance urban green innovation capabilities?–a quasi-natural experiment based on China's new energy demonstration city policy

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As the importance of global climate change and sustainable development issues increases, the enhancement of urban green innovation capabilities is particularly crucial since cities are the main source of energy consumption and carbon emissions. This study focuses on China's New Energy Demonstration City policy to explore how it influences urban green innovation capabilities. By employing a quasi-natural experimental method, combined with data from 282 Chinese cities from 2007 to 2021, this paper provides an in-depth analysis of the impact of the New Energy Demonstration City policy on urban green innovation capabilities. It was found that the policy significantly improves the cities' green innovation capabilities, and this conclusion remains valid after robustness checks. The study also reveals that technological investment and public environmental awareness are two critical mechanisms through which the New Energy Demonstration City policy affects urban green innovation capabilities. Furthermore, this policy has been found to significantly enhance the green innovation capabilities of neighboring cities through spatial spillover effects. The study also examines the interaction between the national-level Big Data Comprehensive Experimental Zone policy and the New Energy Demonstration City policy, discovering that the pilot policy of the national-level Big Data Comprehensive Experimental Zone has to some extent promoted the effectiveness of the New Energy Demonstration City policy in driving urban green transformation. This research provides a new perspective for understanding the dynamics of urban green innovation and points the way for future research and policymaking.

KEYWORDS

new energy demonstration city, urban green innovation, spatial spillover effect, big data comprehensive pilot area, sustainable urban development, investment in science and technology, public environmental awareness, environmental policy of China

1 Introduction

Global climate change has become a significant aspect affecting economic and social development. Controlling the growing consumption of fossil fuels, developing alternative clean energies, and achieving green and sustainable economic and social development represent major policy challenges worldwide (Li et al., 2023). As per the United Nations

Framework Convention on Climate Change and the Paris Agreement, the ongoing global temperature rise is primarily due to increased greenhouse gas emissions from human activities, especially carbon dioxide emissions (Chen and Wang, 2021). Cities, as convergence points for global population and economic activities, are primary sources of energy consumption and carbon emissions. According to World Bank data, cities, though only covering 2% of the global land area, consume about two-thirds of the energy and generate over 70% of greenhouse gas emissions (Dilanchiev et al., 2023). This situation urgently calls for a fundamental transformation of the traditional energy system, i.e., energy transition.

The core goal of energy transition policies is to shift from a high-carbon-emission traditional energy system to a low-carbon, efficient, and sustainable one. This includes actively developing renewable energies (such as solar and wind energy), promoting energy efficiency, implementing carbon pricing and trading mechanisms, aimed at reducing fossil fuel dependency and carbon emissions while ensuring energy security and sustainable economic development (Kabeyi and Olanrewaju, 2022). In rapidly developing countries like China, the implementation of energy transition policies is particularly crucial. The Chinese government has incorporated energy transition into the core of its national development strategy and implemented a series of policies and measures, including the New Energy Demonstration City initiative (Liu et al., 2023). These policies aim not only to address climate change but also to drive economic transformation through technological innovation and industrial upgrading (Sun et al., 2023; Ullah et al., 2023).

The concept of "green innovation" has evolved to become a central topic in environmental economics and policy research. Green innovation encompasses not just technological innovations, such as new renewable energy technologies and energy-saving and emission-reduction technologies, but also management and business model innovations (Tang et al., 2023). These innovations aim to reduce environmental pollution, enhance resource efficiency, and support sustainable economic growth. On the other hand, researchers like Zhang et al. (2022) emphasize the critical role of green innovation in improving environmental quality and achieving low-carbon development. Urban green innovation, as a vital component of energy transition, is a key pathway to sustainable urban development. It includes innovations in urban planning, architectural design, transportation systems, and energy use, aiming to reduce environmental impact, improve quality of life, and promote economic green growth.

Regulatory approaches to the environment, especially energy policies like the New Energy Demonstration Cities (NEDC) policy, have been widely studied and acknowledged as effective tools for promoting urban green innovation. The existing literature reports that such policies play a positive role in enhancing the green innovation efficiency of pilot cities. For example, Chen et al. (2023) explored the significant utility of the NEDC policy in cities in eastern and central China, highlighting the importance of regional differences in assessing the effectiveness of energy policies. Additionally, Yang et al. (2021) detailed the differential impacts arising from structural effects, technology innovation effects, and fiscal support effects across various city types. Furthermore, Nie et al. (2023) found that energy conservation and emission reduction policies have a significant impetus on green technology innovation in western and northern regions of China and cities with lower levels of environmental concern. Recent studies have also emphasized the reciprocal influence between environmental policies and the stages of urban green development, suggesting that dual objectives of environmental management and technological advancement should be integrated into long-term planning (Jiang et al., 2022; Jiang et al., 2023; Guo et al., 2024). These studies underline the necessity of a deep understanding of the geographical heterogeneity of green innovation, the complexity of policies, and the interaction of policies with urban characteristics. As such, the objective of this paper is to explore how energy transition policies, particularly the New Energy Demonstration City policy, affect green innovation capabilities in different urban settings. This research is not only poised to provide a deeper understanding of the mechanisms through which energy policies promote urban green innovation but also to offer critical references and guidance for policymakers in crafting more effective strategies.

The central question explored in this study is the impact of energy transition policies on urban green innovation capabilities. Globally, cities, as major energy consumers and carbon emission sources, play a crucial role in energy transition. China's New Energy Demonstration City policy provides a unique research context, allowing for an analysis of policy effects from a quasi-natural experiment perspective. We focus on how the New Energy Demonstration City policy specifically influences a city's green innovation capabilities, revealing the actual effectiveness of the policy in promoting technological innovation and environmental improvement. Additionally, this study pays particular attention to whether the policy generates spatial spillover effects on neighboring cities. Assessing whether the New Energy Demonstration City policy impacts green innovation in surrounding non-demonstration cities is essential for comprehensively evaluating the overall impact of energy transition policies and guiding future regional policy formulation. Finally, this study also assesses the potential influence of the National-level Big Data Comprehensive Experimental Zone policy on energy transition policies in promoting urban green innovation. We explore whether the big data policy provides technical support and policy incentives for energy transition policies, thus aiding urban green innovation.

The core objective of this research is to delve into the promotion effect of China's New Energy Demonstration City policy on urban green innovation capabilities. Utilizing a quasi-natural experimental research method, this paper aims to provide a thorough analysis and an objective evaluation of the actual effectiveness of the policy. Our study fills the gap in the existing literature regarding the assessment of the impact of energy policies and offers fresh perspectives and data support for the fields of energy transition and urban sustainable development. The contributions of this research are as follows. First, by comparing new energy demonstration cities with non-demonstration cities in terms of green innovation, we provide empirical evidence of the direct impact of new energy policies, which helps gain a deeper understanding of the actual effects of policies in different urban contexts. Second, our study uses a quasi-natural experimental design to offer an effective solution for addressing causal inference problems. This allows us to more accurately discern the relationships between policy effects and

other variables, enhancing the credibility of our research conclusions. Third, we particularly investigate the geographic spillover effects of new energy policies, assessing the potential impact of the demonstration city policy on the green innovation of neighboring cities. This provides a new perspective for understanding the comprehensive regional effects of policies. Fourth, our study uniquely focuses on the interaction between national-level Big Data Comprehensive Experimental Zone policies and New Energy Demonstration City policies. We explore how policy synergy can strengthen urban green innovation, offering more in-depth insights for policymakers. The findings of this research are not only instructive for policymakers and enterprises, helping them to more effectively address the challenges of energy and environmental issues in urban development but also provide beneficial references and practical insights for global efforts to promote sustainable urban development and energy transition.

2 Theoretical analysis

2.1 Impact of new energy demonstration city policy on urban green innovation capability

In examining the influence of energy transition policies on urban green innovation capability, it is essential to recognize the multidimensional nature of these policies, encompassing aspects from the promotion of renewable energy and enhancement of energy efficiency to the development of low-carbon technologies. The implementation of these policies provides the necessary framework and impetus for green innovation in cities. As a key energy transition initiative, China's New Energy Demonstration City policy is designed to accelerate urban green development through the promotion of new energy technologies and improvement of energy efficiency (Yusup, 2016).

Firstly, the policy directly encourages the research and implementation of new energy projects through financial subsidies and policy support. For instance, demonstration cities receive governmental funding support in new energy areas like solar energy, wind energy, and electric vehicles. This not only reduces the R&D risk for enterprises and research institutions in new energy technologies but also enhances their willingness to innovate (Xing, 2022). Secondly, the New Energy Demonstration City policy elevates the urban green innovation environment through establishing a demonstration effect. The successful application of new energy technologies in these cities offers replicable experiences and models, stimulating broader green innovation activities. This demonstration effect extends beyond the technological level to encompass management and policy innovation (Liu et al., 2022). Additionally, the policy facilitates the establishment of public-private partnerships. The collaboration between the government, businesses, and research institutions plays a key role in advancing the R&D and application of new energy technologies. Such cooperation not only accelerates the commercialization of new technologies but also strengthens the overall green innovation capability of cities (Manfren et al., 2011). Lastly, the New Energy Demonstration City policy enhances public awareness of sustainable development and green technologies by improving urban infrastructure and promoting environmentally friendly lifestyles. The widespread adoption of new energy vehicles, smart grids, and energy-efficient buildings gradually increases public acceptance and participation in green living (Kammen and Sunter, 2016).

In summary, China's New Energy Demonstration City policy not only directly drives the R&D and application of green technologies but also comprehensively enhances urban green innovation capabilities through demonstration effects, public-private collaboration, and infrastructure improvement. The implementation of this policy plays a vital role in guiding cities towards a low-carbon, environmentally friendly future. Thus, the following research hypothesis H1 is proposed.

H1: The New Energy Demonstration City policy enhances urban green innovation capabilities.

2.2 New energy demonstration city policy, technological investment, and urban green innovation capability

Against the backdrop of global efforts to promote sustainable development and address climate change, China's New Energy Demonstration City policy, as a key strategic measure, significantly boosts urban green innovation capabilities through strengthened technological investment. The implementation of this policy influences and stimulates technological investments in the following ways, thereby effectively enhancing urban green innovation capabilities (Wang and Yi, 2021).

First, the New Energy Demonstration City policy incentivizes investment in the R&D of new energy technologies by enterprises and research institutions through financial support and policy incentives. Government financial subsidies, tax reliefs, and R&D funding allocations reduce economic risks and costs for new technology development, fueling enthusiasm for innovation in the scientific and business communities. In areas like solar energy, wind energy, and electric vehicles, this support provides a strong impetus for technological innovation (Zhang et al., 2022). Secondly, the demonstration city policy promotes the aggregation and efficient utilization of technological resources by establishing cooperative platforms and demonstration projects. Collaboration between the government, businesses, and academic institutions provides a broad resource base and platform for technological R&D, accelerating the incubation and application of innovative outcomes. The New Energy Demonstration City policy also attracts private capital investments in new energy and green technology sectors, diversifying the sources of technological investment (Yang et al., 2021).

The technological investments fostered by these policies directly drive the enhancement of urban green innovation capabilities. Investments and resource allocations expedite the R&D and optimization of new energy technologies, leading to more efficient and environmentally friendly technological solutions. Technological investments also promote the development and upgrading of related industries, enhancing urban economic competitiveness and driving broader green economic development (Li et al., 2022). Furthermore, as new technologies become widespread and applied, public awareness of sustainable

development is raised, further promoting the overall green transformation of cities.

In conclusion, China's New Energy Demonstration City policy, by increasing investments in technology, comprehensively enhances urban green innovation capabilities in promoting technological innovation, accelerating industrial upgrading, and raising public awareness. These efforts not only drive sustainable development in cities but also provide a powerful example and experience for global green development trends. Therefore, the following research hypothesis H2 is proposed.

H2: The New Energy Demonstration City policy enhances urban green innovation capabilities through increased technological investments.

2.3 New energy demonstration city policy, public environmental awareness, and urban green innovation capability

China's New Energy Demonstration City policy plays a significant role in enhancing public awareness of environmental issues, which in turn fosters an increase in urban green innovation capabilities. On one hand, the policy, by implementing specific green projects and initiatives, has made environmental issues a focal point of public attention (Wang and Yi, 2021). In these cities, tangible projects ranging from the promotion of solar and wind power facilities to the construction of electric vehicle charging stations and green transportation systems allow the public to directly observe the practical effects of sustainable energy solutions (Yang et al., 2021). Government and related organizations further enhance public awareness of these projects through exhibitions, seminars, and media campaigns, strengthening their consciousness of environmental protection and sustainable development.

On the other hand, as public environmental awareness increases, citizens become more actively involved in green lifestyles and environmental activities (Zhang et al., 2022). This involvement is reflected not only in everyday life choices, such as using green energy, reducing waste, and conserving resources, but also in the demand for green innovative products and technologies. Increased public demand for green products and services provides a market impetus for businesses to develop green technologies and products (Yang et al., 2021). Additionally, public support for environmentally friendly policies and practices provides a social foundation for the government to promote green innovation. Moreover, public attention to environmental issues fosters broader societal dialogue and collaboration (Li et al., 2022). When the public, businesses, and governments collectively focus on environmental issues, a synergy is more likely to form, jointly promoting urban green innovation and sustainable development. Such collaboration may include jointly developing new technologies, promoting green lifestyles, and participating in community green projects (Chen et al., 2022). Finally, increased public environmental concern also helps to create a conducive policy and innovation ecosystem. When the public places greater emphasis on environmental protection, governments and businesses are more motivated to invest in green innovation, creating a positive cycle that further accelerates the city's green transformation (Jin et al., 2022).

In summary, the New Energy Demonstration City policy indirectly but effectively promotes urban green innovation capabilities by enhancing public awareness of environmental issues. This change in public consciousness not only influences daily choices but also inspires market and governmental investment and support for green innovation, thereby facilitating sustainable urban development. Thus, the following research hypothesis H3 is proposed.

H3: The New Energy Demonstration City policy enhances urban green innovation capabilities through increased public environmental awareness.

2.4 New energy demonstration city policy, spatial spillover effect, and urban green innovation capability

China's New Energy Demonstration City policy not only has a significant positive impact within the demonstration cities but also enhances the green innovation capabilities of neighboring cities through spatial spillover effects. On one hand, as pioneers in green technology and policy, the successful cases and experiences of New Energy Demonstration Cities are emulated and imitated by neighboring cities (Peng et al., 2021). When a city achieves breakthroughs or significant progress in new energy fields, surrounding cities are often inspired to adopt similar technologies and strategies (Yang et al., 2023). This process of imitation and learning includes not just the replication of technologies but also the adoption of policy-making, market mechanism construction, and public participation methods. On the other hand, new energy projects and technologies in demonstration cities often impact surrounding areas through regional cooperation and resource sharing. For example, advancements in smart grid construction and electric vehicle promotion in demonstration cities may lead to infrastructure and technology application upgrades in neighboring cities (Ma et al., 2022). Through such cooperation and interaction, green technologies and innovative thinking are disseminated more widely.

Moreover, the impact of the New Energy Demonstration City policy on enhancing public environmental consciousness is not confined to the cities themselves. As attention to environmental issues and the promotion of green lifestyles increase, the experiences and achievements of demonstration cities can influence residents in surrounding areas through media and social networks, thereby raising public attention to environmental protection and green innovation in a broader region (Zhu et al., 2022). Notably, the policy and project implementations in New Energy Demonstration Cities also contribute to creating a favorable market environment, encouraging the development of green industries in neighboring cities (Yue et al., 2022). With the growing demand for green products and services, businesses and research institutions in neighboring cities are also motivated to invest more resources in the development and marketing of green technologies.

In conclusion, the New Energy Demonstration City policy, through spatial spillover effects, not only drives green innovation in demonstration cities but also positively influences the green innovation capabilities of surrounding cities. This process

involves not just the direct dissemination of technology and policy but also the formation of public consciousness, market demand, and regional cooperation networks, collectively promoting green transformation and sustainable development in a broader area. Thus, the following research hypothesis H4 is proposed.

H4: The New Energy Demonstration City policy enhances the green innovation capabilities of neighboring cities.

3 Methodology

3.1 Model design

3.1.1 Benchmark model

This study uses research data from 282 Chinese cities from 2007-2021, treating the New Energy Demonstration City policy as a quasi-natural experiment and employing the Difference-in-Differences (DID) method to identify the policy's green innovation effect. The DID method is suitable for evaluating the effects of policies or interventions, especially when the implementation of the policy is heterogeneous in time and space. By comparing before and after policy implementation and by comparing cities that implemented the policy with cities that did not implement the policy, DID can effectively control for city-specific effects and common time trends that do not change over time, thereby accurately identifying policy effects. The study constructs the following two-way fixed effects model to test the specific impact of the New Energy Demonstration City policy on urban green innovation capabilities.

$$GIF_{i,t} = \alpha_0 + \alpha_1 DID_{i,t} + \delta X + \gamma_i + \omega_t + \varepsilon_{i,t} \quad (1)$$

Among them, GIF represents the green innovation capability at the city level, DID represents the virtual variable of new energy demonstration city policy, and X represents each control variable. They are economic development level (edl), financial development level (dfd), opening to the outside world level (lou), infrastructure development situation (inf), government intervention level (dgi), and marketization level (mL). In addition, γ_i and ω_t represent the fixed effect of urban individuals and the fixed effect of time respectively.

3.2 Variable selection

3.2.1 Dependent variable

Urban Green Innovation Capability (GIF). In previous studies, green patent applications are commonly used to measure green innovation. Patents directly reflect the outcomes of R&D and innovation performance and are considered useful in measuring technological innovation (Li et al., 2023). Considering that the number of green patent grants may be influenced by external factors such as administrative approval, and the number of green patent applications is a more direct reflection of green innovation response to policy intervention, this study chooses the number of green patent applications to measure urban green innovation capability. Specifically, using the green international patent classification (IPC) codes provided by the World Intellectual Property Organization (WIPO), the study matches patent types, IPC codes, and the addresses of inventing entities (individuals), and obtains the number of city-level patent applications from the China National Intellectual Property Administration. To standardize the scale, following Fan (2023), the number of green patent applications is divided by the city population (in ten thousand).

3.2.2 Independent variable

New Energy Demonstration City Policy (DID). The Chinese government officially announced 81 new energy demonstration cities and 8 new energy demonstration industrial parks in 2014. If a city is selected as a new energy demonstration city, and the year is 2014 or later, DID is assigned a value of 1, otherwise 0. Additionally, the study excludes new energy demonstration industrial parks, retaining only the list of the first batch of new energy demonstration cities.

3.2.3 Control variables

The study uses the level of economic development (edl), financial development level (dfd), openness level (lou), infrastructure development (inf), degree of government intervention (dgi), and marketization level (mL) as control variables. These variables allow for a more comprehensive consideration of other factors affecting urban green innovation capability, thereby more accurately identifying the green innovation effects of the New Energy Demonstration City policy.

The variable definition table is shown in Table 1.

3.3 Data description

To deeply investigate the impact of China's New Energy Demonstration City policy on urban green innovation capabilities, the study selected balanced panel data of 282 Chinese cities from 2007 to 2021 for empirical analysis. Green patent application data, serving as a significant indicator of urban green innovation capabilities, were directly sourced from the China National Intellectual Property Administration. These data, subject to strict review and certification, ensure authenticity and validity. The pertinent data regarding the New Energy Demonstration City policy were acquired directly from the National Energy Administration of China, ensuring an accurate reflection of the policy variable.

Regarding control variables, data on the level of economic development, the level of financial development, the degree of openness to the outside world, infrastructure development, the extent of government intervention, and the level of marketization were all sourced from the authoritative "China City Statistical Yearbook". The selection of these indicators is based on existing literature and theoretical frameworks, aiming to comprehensively control for external factors that may influence urban green innovation capabilities. Furthermore, linear interpolation was employed to impute certain missing values. Descriptive statistics of the variables are presented in Table 2.

This study is conducted based on the research framework as shown in Figure 1.

TABLE 1 Variable definition.

	Variable name	Variable symbol	Measure of variable
Dependent Variable	Urban Green Innovation Capability	GIF	Number of green patent applications per 10,000 people in the city
Independent Variable	New Energy Demonstration City Policy	DID	Policy dummy variable
Control Variables	The level of economic development	edl	Per capita GDP logarithm
	financial development level	dfd	Balance of deposits and loans of financial institutions as a proportion of regional GDP at year-end
	Openness level	lou	Ratio of actual utilization of foreign capital to regional GDP
	Infrastructure development	inf	Public library books per hundred people
	Industrial Structure Level	dgi	Government general expenditure as a proportion of regional GDP
	Degree of government intervention	ml	The proportion of private and self-employed persons in urban employment

TABLE 2 Descriptive statistics.

VarName	Obs	Mean	SD	Median	Min	Max
GIF	4230	0.956	2.311	0.252	0.000	35.407
DID	4230	0.117	0.322	0.000	0.000	1.000
edl	4230	10.557	0.684	10.569	4.595	13.056
dfd	4230	2.374	1.239	2.035	0.560	21.302
lou	4230	0.018	0.019	0.012	0.000	0.229
inf	4230	71.957	293.172	34.000	2.000	10,426.000
dgi	4230	0.190	0.121	0.163	0.043	2.349
ml	4230	3.460	142.175	0.997	0.013	9247.539

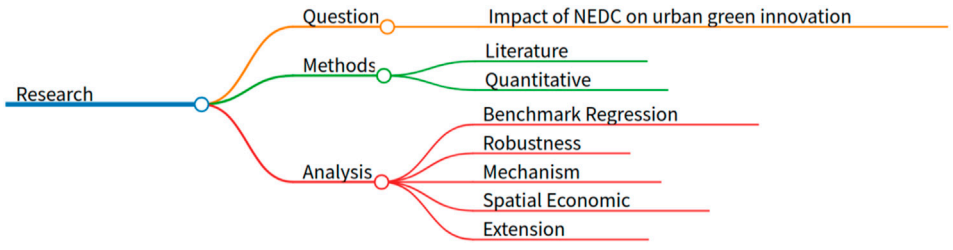

FIGURE 1
Research framework.

4 Results

4.1 Baseline regression results

Table 3 presents the test results of the impact of China's New Energy Demonstration City policy on urban green innovation capability. Column 1) shows the regression results without control variables, while column 2) includes both control variables and fixed effects. It is found that the coefficient of DID is significantly positive in both columns, indicating that the New Energy Demonstration City policy has enhanced urban green innovation capability, thereby validating research hypothesis H1. Specifically, the policy accelerates the R&D and application of new energy technologies through financial support and policy incentives, particularly in areas such as solar energy, wind energy, and electric vehicles. Moreover, the policy implementation has raised public

TABLE 3 Baseline regression results.

	(1)	(2)
	GIF	GIF
DID	0.591***	0.612***
	(0.097)	(0.094)
edl		−1.130***
		(0.123)
dfd		−0.035
		(0.039)
lou		−16.135***
		(1.664)
inf		0.000**
		(0.000)
dgi		−2.221***
		(0.318)
ml		0.000
		(0.000)
Control	No	YES
City_FE	YES	YES
Year_FE	YES	YES
Obs	4230	4230
r2	0.705	0.722

[a]Note: The symbols *, *, *** indicate significance at the 10%, 5%, and 1% levels, respectively.

awareness of sustainable development and environmental protection, promoting the prevalence of environmentally friendly behaviors and green consumption. Additionally, the New Energy Demonstration City policy synergizes with other environmental protection and sustainable development policies, collectively advancing urban green innovation.

These research results provide valuable data support and decision-making reference for policymakers, emphasizing the importance of comprehensively considering policy impacts in urban sustainable development strategies. At the same time, it offers a new perspective for understanding the drivers of urban green innovation, pointing the way for future research and policy formulation.

4.2 Robustness test results

4.2.1 Parallel trend test

To enhance the robustness of the regression results, a series of robustness tests were conducted. First, the effectiveness of the DID model depends on the absence of time trend differences between the treatment and control groups before the policy shock, i.e., before the implementation of the New Energy Demonstration City policy, the trends in green innovation capabilities of the treatment and control group cities should be consistent. To test this, the study uses an event study method proposed by Jacobson et al. (1993), constructing a staggered quasi-natural experiment. The study selects the period immediately before the implementation of the New Energy Demonstration City policy as the base period and tests the parallel trend assumption for the 7 years before and after the policy implementation. Table 4 and Figure 2 show the results of the parallel trend test. From Table 4 and Figure 2, it is observed that before the implementation of the New Energy Demonstration City policy, there are no significant differences between the treatment and control groups, indicating that there are no systematic differences in urban green innovation vitality between the two groups, and the model passes the parallel trend test.

4.2.2 Placebo test

In assessing policy effects using the Difference-in-Differences (DID) method, endogeneity issues such as unobservable omitted variables and reverse causality can affect the estimation results. To alleviate concerns about the impact of unobservable factors and other endogeneity issues on the estimation results, following the approach of Chen et al. (2023), this study conducts a placebo test by randomly fabricating policy pilot scenarios. Specifically, the study conducts 500 random samplings among 282 cities, randomly selecting 62 cities as the treatment group and the remaining 220 as the control group in each sample. The study then performs baseline regression according to Eq. 1 to obtain 500 estimated values. The distribution of p-values of these estimates is shown in Figure 3. As seen in Figure 3, most estimated coefficients are near zero, and the majority of p-values are greater than 0.1. Additionally, the coefficient estimate from the baseline regression is not consistent with the estimates from the placebo tests, suggesting that the estimation results are not obtained by chance and are unlikely to be influenced by other random factors. This further validates the robustness of the baseline regression conclusions.

4.2.3 PSM-DID test

The selection mechanism of the New Energy Demonstration City policy and differences in other variables between the treatment and control groups may lead to selection bias in the DID model. To more robustly estimate the green innovation effect of the New Energy Demonstration City policy, this study employs the Propensity Score Matching (PSM) method to match pilot city samples with non-pilot city samples, effectively controlling for selection bias. The basic idea is to match the treatment and control groups based on certain characteristics to generate matching scores, and then construct new treatment and control groups based on these scores. Specifically, the study uses the control variables as identification features for the sample points to conduct radius matching between pilot cities and non-pilot cities. The balance test results of the propensity score matching show that the matching effect is good. Regression on the matched samples using the DID method is shown in column 1) of Table 5. The results show that the DID coefficient remains significantly positive, consistent with the baseline regression results, further proving the robustness of the study's conclusions.

TABLE 4 Results of parallel trend test.

	(1)
	GIF
pre_7	−0.243
	(0.257)
pre_6	−0.234
	(0.257)
pre_5	−0.295
	(0.257)
pre_4	−0.116
	(0.257)
pre_3	−0.158
	(0.257)
pre_2	−0.144
	(0.257)
current	−0.004
	(0.257)
post_1	0.153
	(0.257)
post_2	0.287
	(0.257)
post_3	0.551**
	(0.257)
post_4	0.751***
	(0.257)
post_5	0.593**
	(0.257)
post_6	0.590**
	(0.257)
post_7	0.613**
	(0.257)
Control	YES
City_FE	YES
Year_FE	YES
Obs	4230
r2	0.724

4.2.4 Other robustness tests

The study also conducts various other robustness tests, including replacing the dependent variable, lagging the core explanatory variable by one period, excluding samples of municipalities, and mitigating omitted variable issues. Specifically, the study first re-measures urban green innovation capability using the number of green patent grants per ten thousand people in a city, with regression results shown in column 2) of Table 5, where the DID coefficient remains significantly positive. Next, considering potential time lags in the impact of the New Energy Demonstration City policy on urban green innovation capability and to reduce reverse causality interference, the study lags the core explanatory and control variables by one period. The results, shown in column 3) of Table 5, indicate that the lagged policy coefficient remains significantly positive. Additionally, considering the specific political status and urban administrative structure of municipalities that may influence the results, the study excludes samples of municipalities and conducts a new regression. The results, shown in column 4) of Table 5, indicate that the DID coefficient remains significantly positive. Finally, to reduce endogeneity issues caused by omitted variables, the study adds three control variables: urban economic density (ued, the ratio of GDP to city land area), population density (dp, the logarithm of the number of people per square kilometer), and urbanization level (ul, the proportion of urban permanent residents in the total population) and conducts a new regression. The introduction of these variables aims to more comprehensively control factors that might affect urban green innovation capability. The results, shown in column 5) of Table 5, indicate that the DID coefficient remains significantly positive, confirming the robustness of the study's conclusions.

4.3 Mechanism test results

To test the mechanisms through which the New Energy Demonstration City policy affects urban green innovation capability, this study uses a mediation effect model to examine the mechanisms from two aspects: technological investment and public environmental awareness.

$$GIF_{i,t} = \alpha_0 + \alpha_1 DID_{i,t} + \delta X + \gamma_i + \omega_t + \varepsilon_{i,t} \quad (2)$$

$$middle_{i,t} = \alpha_0 + \alpha_1 DID_{i,t} + \delta X + \gamma_i + \omega_t + \varepsilon_{i,t} \quad (3)$$

$$GIF_{i,t} = \alpha_0 + \alpha_1 DID_{i,t} + \alpha_2 middle_{i,t} + \delta X + \gamma_i + \omega_t + \varepsilon_{i,t} \quad (4)$$

Where, middle represents science and technology investment (sci) and public environmental concern (car), and Eq. 2 is the same as Eq. 1.

4.3.1 Technological investment mechanism test

This study measures the level of technological investment using the ratio of science and technology expenditure to local government general public budget expenditure, and performs regression on mechanism test models 3) and 4). The regression results are shown in columns 1) and 2) of Table 6. In column 1), the coefficient of DID is significantly positive, indicating that the New Energy Demonstration City policy significantly promotes technological investment. Specifically, this means that cities implementing the New Energy Demonstration City policy have a significantly higher proportion of expenditures in the field of science and technology compared to cities without this policy. This finding is consistent with policy expectations, indicating that the New Energy Demonstration City policy effectively encourages local governments to increase financial

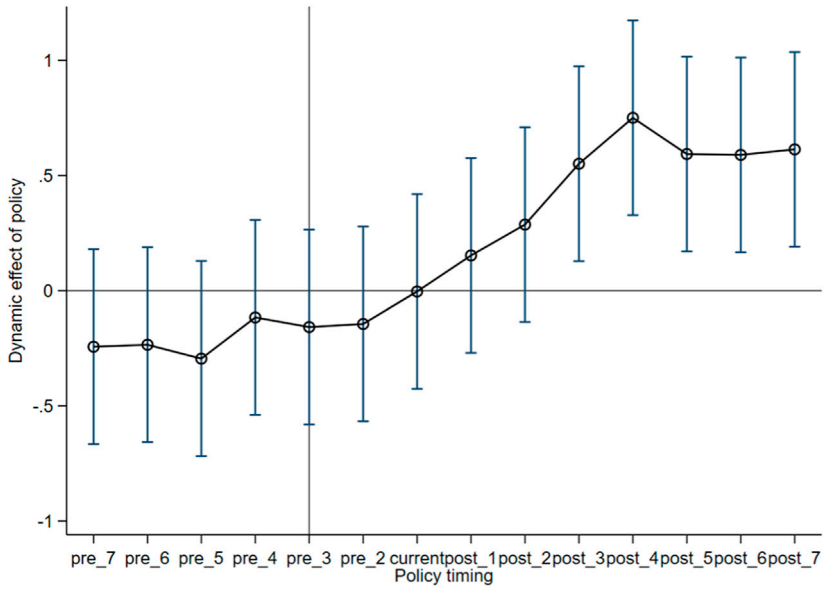

FIGURE 2
Parallel trend test.

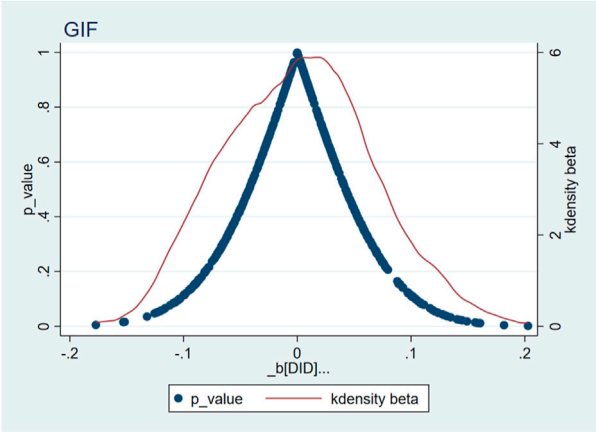

FIGURE 3
Placebo test.

TABLE 5 Robustness test results.

	(1)	(2)	(3)	(4)	(5)
	GIF	GIF2	GIF	GIF	GIF
DID	0.575***	0.325***		0.489***	0.309***
	(0.092)	(0.058)		(0.091)	(0.070)
LDID			0.631***		
			(0.096)		
ued					2.685***
					(0.050)
dp					−0.014
					(0.107)
ul					−2.018***
					(0.339)
Control	YES	YES	YES	YES	YES
City_FE	YES	YES	YES	YES	YES
Year_FE	YES	YES	YES	YES	YES
Obs	4196	4230	3948	4170	4157
r2	0.730	0.704	0.747	0.717	0.850

investments in technological R&D. In column 2), both DID and sci coefficients are significantly positive, suggesting that technological investment significantly promotes the enhancement of urban green innovation capability. In other words, this result not only confirms that the New Energy Demonstration City policy directly promotes technological investment, but also reveals the important pathway of technological investment in positively influencing urban green innovation capability. Research hypothesis H2 is validated.

These results further indicate that the New Energy Demonstration City policy enhances urban green innovation capability by motivating local government's technological investments. This finding aligns with sustainable development theory and innovation-driven development strategies, highlighting the importance of policy in guiding local governments to support technological innovation. This provides empirical evidence for understanding the impact mechanism of the New Energy Demonstration City policy and offers important references for further optimizing related policies.

TABLE 6 Mechanism test results.

	(1)	(2)	(3)	(4)
	sci	GIF	car	GIF
DID	0.002***	0.507***	13.883***	0.496***
	(0.001)	(0.089)	(3.119)	(0.113)
sci		47.631***		
		(2.280)		
car				0.002***
				(0.001)
Control	YES	YES	YES	YES
City_FE	YES	YES	YES	YES
Year_FE	YES	YES	YES	YES
Obs	4230	4230	3102	3102
r2	0.747	0.750	0.788	0.826

4.3.2 Public environmental awareness mechanism test

Drawing on the study by Wu et al. (2022), this paper uses Baidu's smog search index to depict public environmental awareness. With the development of the internet, data based on online search behavior has become a new indicator capable of timely and accurately reflecting public focus and behavioral intent. Baidu, being China's largest Chinese search engine, offers broad coverage and high data availability. By analyzing search frequencies and geographic locations, the study effectively captures and compares public environmental awareness across different regions in China. The Baidu smog search index, divided by 100 for scale standardization, is used to gauge public concern about air quality and environmental pollution. The regression results are shown in columns 3) and 4) of Table 6. In column 3), the DID coefficient is significantly positive, indicating that the New Energy Demonstration City policy significantly promotes public environmental awareness. Specifically, cities implementing the New Energy Demonstration City policy show more frequent public search behavior concerning environmental pollution compared to cities without this policy, reflecting high public concern for environmental protection and desire for improved air quality. These results not only validate the effectiveness of the policy but also reveal its important role in enhancing public environmental consciousness. In column 4), both DID and car coefficients are significantly positive, suggesting that public environmental awareness significantly promotes the enhancement of urban green innovation capability. This further indicates that public attention to environmental issues helps drive more effective environmental protection measures, pushing the entire city towards a more sustainable innovation and development model. Increased public environmental consciousness helps form a more environmentally friendly social atmosphere, thereby stimulating businesses and governments to adopt more green innovation measures and accelerate urban green transformation. Research hypothesis H3 is validated.

These results further emphasize the key role of public environmental awareness in urban green innovation. As society's awareness and concern for environmental issues increase, the momentum for urban green innovation is also expected to strengthen. This is not only reflected in the effective implementation of environmental protection measures but also in the overall innovation vitality and sustainable development strategies of cities. Thus, enhancing public environmental consciousness and participation should be one of the key strategies for promoting urban green transformation.

4.4 Spatial spillover effect results

Moreover, to examine whether the New Energy Demonstration City policy's impact on urban green innovation capability exhibits spatial spillover effects, capturing the economic connections and potential spillover effects between regions, we introduce the commonly used spatial Durbin model in spatial economic analysis. The model, by incorporating a spatial weight matrix, is able to capture and quantify inter-regional economic connections and the potential spillover effects resulting from them. Thus, it provides a comprehensive framework for analyzing the impact of the New Energy Demonstration City policy on urban green innovation capabilities in a spatial dimension. The analysis uses a common spatial geographical distance matrix.

$$GIF_{i,t} = \alpha_0 + \alpha_1 DID_{i,t} + \beta_1 \sum_j w_{ij} DID_{i,t} + \alpha_2 X + \beta_2 \sum_j w_{ij} X + \rho \sum_j w_{ij} GIF_{i,t} + \gamma_i + \omega_t + \varepsilon_{it} \quad (5)$$

Where, ρ represents the spatial lag autoregressive coefficient, w_{ij} is the element of the spatial weight matrix.

To verify the spatial spillover effects of the New Energy Demonstration City policy on urban green innovation capability, it is necessary to perform regression on the spatial spillover effect test model. Before regression, this study conducts a spatial autocorrelation test on the dependent variable. The global Moran's I test for urban green innovation capability is shown in Table 7, where Moran's I values are significantly positive, indicating the presence of spatial autocorrelation, i.e., a clustering phenomenon in spatial distribution, which warrants further analysis. This spatial clustering may be related to similar levels of economic development, environmental policies, or industrial structures, leading to similar spatial distribution characteristics in neighboring regions.

The results of the spatial Durbin model regression are shown in Table 8. The DID coefficient is significantly positive, indicating that the New Energy Demonstration City policy significantly enhances green innovation capability in the implementing cities themselves. More importantly, the coefficients of the spatial Durbin term and the indirect effect term are also significantly positive, meaning that the New Energy Demonstration City policy not only enhances the green innovation capability of the implementing cities but also significantly enhances the green innovation capability of neighboring cities. This finding validates research hypothesis H4 and reveals that the positive impact of the New Energy Demonstration City policy is not limited to the implementing cities themselves but extends to surrounding areas through

TABLE 7 Spatial autocorrelation test results.

year	I	E(I)	Sd(I)	Z	*p*-value
2007	0.0435	−0.0036	0.0040	11.7018	0.0000
2008	0.0465	−0.0036	0.0042	11.9291	0.0000
2009	0.0491	−0.0036	0.0042	12.6232	0.0000
2010	0.0695	−0.0036	0.0045	16.2440	0.0000
2011	0.0689	−0.0036	0.0046	15.8274	0.0000
2012	0.0780	−0.0036	0.0048	17.0497	0.0000
2013	0.0696	−0.0036	0.0048	15.2376	0.0000
2014	0.0773	−0.0036	0.0049	16.5329	0.0000
2015	0.0895	−0.0036	0.0049	18.9337	0.0000
2016	0.0927	−0.0036	0.0049	19.8102	0.0000
2017	0.1022	−0.0036	0.0049	21.6836	0.0000
2018	0.0991	−0.0036	0.0048	21.3835	0.0000
2019	0.0875	−0.0036	0.0049	18.6156	0.0000
2020	0.0916	−0.0036	0.0050	19.1858	0.0000
2021	0.0820	−0.0036	0.0049	17.3413	0.0000

TABLE 8 Regression results of spatial Durbin model.

	(1)
	GIF
DID	0.537***
	(0.076)
Wx*DID	4.712***
	(1.431)
Direct*DID	0.530***
	(0.079)
Indirect*DID	1.177**
	(0.536)
Total*DID	1.707***
	(0.506)
Control	YES
City_FE	YES
Year_FE	YES
Obs	4230
r2	0.000

spatial spillover effects. Specifically, this suggests that the successful experiences and policy measures in green innovation of cities implementing the New Energy Demonstration City policy have a positive impact on neighboring cities through geographical proximity and economic connections. Neighboring cities might enhance their own green innovation capability by learning and emulating these successful experiences or being stimulated by the green innovation activities of the demonstration cities.

This finding provides a new perspective for understanding the green innovation effects of the New Energy Demonstration City policy and offers an empirical basis for formulating more efficient regional coordinated development policies. Especially considering the interdependence of regional economies and the coordination of environmental policies, these findings suggest that regional environmental protection efforts should be viewed as interconnected and mutually influencing systems.

4.5 Extended analysis

As big data technology rapidly evolves and is applied, the Chinese government has established national-level Big Data Comprehensive Experimental Zones to explore innovative applications of big data in various industries and fields, promoting the digital transformation of the economy and society. These experimental zones are not only the forefront of technological innovation but also important experimental fields for exploring how big data can promote economic and social development. The New Energy Demonstration City policy has played a significant role in promoting renewable energy and green technology development, while the national-level Big Data Comprehensive Experimental Zone policy provides data support and an analysis platform for the R&D and application of these technologies. The application of big data technology, such as data analysis and intelligent algorithms, can optimize the operational efficiency of new energy projects and enhance the level of intelligence in energy management. For instance, big data analysis can optimize the power output of solar and wind power generation, improving energy utilization. Additionally, the implementation of the Big Data Comprehensive Experimental Zone policy provides a platform for New Energy Demonstration Cities to better understand and respond to citizens' needs, thus promoting the implementation of green innovation projects. By analyzing residents' data on energy use, city planners and policymakers can more accurately develop and adjust green policies to align better with citizens' actual needs. Therefore, the implementation of the national-level Big Data Comprehensive Experimental Zone policy not only provides data support and analytical tools for the New Energy Demonstration City policy but also enhances the policy's specificity and effectiveness, ultimately promoting the city's green innovation capability. The interaction between these two policies demonstrates the powerful potential of combining technological innovation with environmental policy, providing an effective path to achieving more sustainable urban development.

This study next examines whether the national-level Big Data Comprehensive Experimental Zone pilot policy affects the effectiveness of the New Energy Demonstration City policy in promoting urban green transformation. In 2015 and 2016, China announced two batches of national-level Big Data Comprehensive Experimental Zone provinces, and this study considers these batches as the experimental group and the remaining provinces as the control group. A multi-period DID model is constructed to test the incentive effect of the Big Data Comprehensive Experimental

TABLE 9 Results of extended analysis.

	(1)
	GIF
DID	0.276***
	(0.102)
DID2	−0.005
	(0.099)
DID*DID2	1.593***
	(0.198)
Control	YES
City_FE	YES
Year_FE	YES
Obs	4230
r2	0.728

Zone pilot policy (DID2) on the green innovation process driven by the New Energy Demonstration City policy. The regression results of the interaction term model are shown in Table 9, where the coefficients of DID*DID2 are positive. This result suggests that the national-level Big Data Comprehensive Experimental Zone pilot policy promotes the effectiveness of the New Energy Demonstration City policy in driving urban green transformation, providing a new perspective for understanding the green innovation effects of the New Energy Demonstration City policy and an empirical basis for formulating more efficient regional coordinated development policies.

5 Discussion

The results of this study show that China's New Energy Demonstration City policy significantly enhances urban green innovation capabilities, consistent with the findings of Li et al. (2023). The policy accelerates the R&D and application of new energy technologies, especially in areas such as solar energy, wind energy, and electric vehicles (Peng et al., 2021). These technological developments not only improve energy efficiency but also reduce urban carbon emissions, contributing to environmental sustainability goals. This result is consistent with innovation system theory, which posits that government policies are a key factor in driving technological innovation. In the context of the New Energy Demonstration City policy, the government provides necessary financial support and market incentives. These measures create favorable conditions for the research and development as well as the application of new energy technologies, which in turn promote the enhancement of urban green innovation capabilities. Additionally, the implementation of the New Energy Demonstration City policy also promotes the transformation and upgrading of related industries. Through cooperation between governments and enterprises, an innovation ecosystem has been formed, allowing technology innovations to be more rapidly translated into practical applications (Yang et al., 2022). This ecosystem involves not only technological R&D but also policy planning, market promotion, and public education. The results of this study have significant implications for formulating effective energy transition policies and promoting green development.

This study also reveals that technological investment and public environmental awareness are two important mechanisms through which the New Energy Demonstration City policy affects urban green innovation capabilities. Increased technological investment reflects the government's emphasis on and support for technological innovation, crucial for green innovation activities in cities. Government financial investments and policy incentives create a conducive environment for the R&D of new energy technologies, thus promoting active innovation activities and rapid technological development (Yang et al., 2021). For example, government financial support and tax incentives in the new energy sector not only reduce the R&D costs for enterprises but also enhance the enthusiasm and feasibility of developing new technologies. At the same time, the increase in public environmental awareness plays a key role in enhancing urban green innovation capabilities. As society places greater emphasis on environmental protection issues, public demand for green products and technologies increases, providing market impetus for businesses to develop green technologies and products (Zhu et al., 2022). In addition, public support for environmentally friendly policies also provides a social foundation for governments to promote green innovation. For instance, public acceptance and use of clean energies such as solar and wind power accelerate the popularization and marketization of these technologies. Public participation and support are important forces in driving urban green innovation, especially in terms of public education and involvement in environmental protection and sustainable development activities, contributing to a social atmosphere that fosters green innovation (Yue et al., 2022). These findings are significant for understanding the mechanisms of urban green innovation and provide valuable policy insights for further promoting sustainable urban development.

This study finds that the New Energy Demonstration City policy not only has a significant positive impact in the implementing cities but also significantly enhances the green innovation capabilities of neighboring cities through spatial spillover effects. This process involves not only the direct dissemination of technology and policy but also the formation of public awareness, market demand, and regional cooperation networks, collectively promoting green transformation and sustainable development in a broader area. The successful cases and experiences in green technology and policy of the demonstration cities are emulated and imitated by neighboring cities, especially in terms of new energy technology and policy-making. This sharing of information and experiences accelerates innovation and application in green technology in other cities within the region (Peng et al., 2021). The presence of spatial spillover effects suggests that the formulation of green innovation strategies should possess a spatial perspective. By strengthening connections and coordination between cities, an innovation agglomeration effect within the region can be formed, thereby promoting green development across the entire area. Additionally, new energy projects and technologies in

demonstration cities positively impact surrounding areas through regional cooperation and resource sharing (Ma et al., 2022). For example, advancements in areas such as smart grid construction and electric vehicle promotion provide references for neighboring cities in infrastructure and technology application upgrades. The impact of the New Energy Demonstration City policy on enhancing public environmental awareness is not limited to the cities themselves. As attention to environmental issues and the promotion of green lifestyles increase, the experiences and achievements of demonstration cities can influence residents in surrounding areas through media and social networks, thereby raising public attention to environmental protection and green innovation in a broader region (Zhu et al., 2022). Notably, the policy and project implementations in New Energy Demonstration Cities also contribute to creating a favorable market environment, encouraging the development of green industries in neighboring cities (Yue et al., 2022). As demand for green products and services grows, businesses and research institutions in neighboring cities are also motivated to invest more resources in the development and marketing of green technologies. This finding provides a new perspective for understanding the green innovation effects of the New Energy Demonstration City policy and offers an empirical basis for formulating more efficient regional coordinated development policies.

This study delves into the interaction between the national-level Big Data Comprehensive Experimental Zone policy and the New Energy Demonstration City policy, revealing their synergistic effects. The application of big data technology in urban green development, especially in optimizing energy management and enhancing energy efficiency, has been proven to have a significant impact on urban sustainable development (Wei and Zhang, 2023). The combination of big data and new energy policies provides new perspectives and pathways, accelerating the development and application of new energy technologies through data-driven approaches. Additionally, the introduction of big data technology enhances information sharing and resource optimization among cities, which is crucial for promoting coordinated development within the region (Yang et al., 2021). For instance, the application of big data in monitoring and analyzing environmental data and improving urban management efficiency helps build more effective regional environmental governance mechanisms. Data-driven decision-making can better understand and address complex issues in urban development, thus promoting sustainable development within the region. Therefore, the interaction between the national-level Big Data Comprehensive Experimental Zone policy and the New Energy Demonstration City policy highlights the importance of combining technological innovation with environmental policy. This policy combination not only strengthens the effects of individual policies but also promotes coordinated development within the region, which is significant for achieving urban sustainability goals. The results of the extension analysis highlight the importance of considering the synergistic effects between different policies when formulating policy. When establishing and implementing new energy or big data-related policies, policymakers need to consider how to integrate the resources and advantages of different policies in order to achieve a greater policy effect.

6 Conclusion

With increasing global emphasis on environmental protection and sustainable development, new energy policies have become key tools for driving urban green transformation. This study focused on China's New Energy Demonstration City policy, exploring its impact on enhancing urban green innovation capabilities and the related mechanisms. The results show that the policy significantly promotes the enhancement of urban green innovation capabilities, and this conclusion remains robust after stability testing. The study revealed two main mechanisms through which the New Energy Demonstration City policy affects urban green innovation capabilities: technological investment and public environmental awareness. The increase in technological investment reflects the local government's emphasis on and support for technological innovation, which is crucial for promoting green innovation activities. At the same time, the increase in public environmental awareness reflects society's emphasis on environmental protection, creating a conducive social atmosphere for urban green innovation. The study also found that the New Energy Demonstration City policy significantly enhances the green innovation capabilities of neighboring cities through spatial spillover effects. Furthermore, the study examined the interaction between the national-level Big Data Comprehensive Experimental Zone policy and the New Energy Demonstration City policy. The results show that the Big Data Comprehensive Experimental Zone policy to some extent enhances the effectiveness of the New Energy Demonstration City policy in driving urban green transformation. These findings provide a new perspective for understanding the drivers of urban green innovation and point the way for future research and policy formulation.

Based on the findings of this study, we propose several targeted policy suggestions to optimize China's New Energy Demonstration City policy and promote broader green innovation. Firstly, the government should increase fiscal support and policy incentives for the R&D of new energy technologies, especially in key technological areas such as solar, wind, and electric vehicles, which would include providing funding, tax incentives, and market promotion support. Secondly, strengthening public environmental awareness through education and publicity to enhance societal recognition and support for green innovation is crucial, as it increases the demand for green products and encourages public participation. Additionally, encouraging technical exchanges and cooperation between new energy demonstration cities and other cities can use the experiences of demonstration cities to drive regional green innovation, establishing regional technology exchange platforms and cooperative networks. Moreover, integrating big data with new energy policies can optimize policy formulation and execution by utilizing big data to improve energy management efficiency. Lastly, enhancing policy transparency and public participation through regular policy reports, forums, and hearings encourages the involvement of the public, enterprises, and research institutions in the discussion and evaluation of policies. Implementing these recommendations will enhance the effectiveness of the New Energy Demonstration City policy and promote collaborative green innovation between cities, supporting the achievement of broader sustainable development goals.

While this study reveals the positive effects of China's New Energy Demonstration City policy on urban green innovation capabilities, there are limitations. First, the study's timeline from 2007 to 2021 covers a sufficient period before and after the implementation of new energy policies, but future research could consider extending the time frame to explore the long-term effects of policy impact. Second, this study is primarily based on data from Chinese cities, where cultural and geographical factors may limit the universality of the conclusions. Future research could consider conducting similar studies in different countries or regions to validate the applicability of the findings. Furthermore, due to data availability constraints, this study could not consider all possible factors affecting urban green innovation capabilities, such as education levels and residents' income. Future research should attempt to include more control variables for a more comprehensive understanding.

In terms of future research directions, one path could further explore the interaction between the New Energy Demonstration City policy and other policies (such as environmental protection and scientific innovation policies) on green innovation. Another could investigate differentiated effects of new energy policies across various city sizes and types for more nuanced policy guidance, and a third could utilize diverse research methods such as qualitative studies or case analyses to deeply understand the mechanisms behind policy effects. Through these studies, a more comprehensive understanding of the effects of New Energy Demonstration City policy can be achieved, providing a scientific basis for formulating more effective green innovation policies.

Data availability statement

The raw data supporting the conclusion of this article will be made available by the authors, without undue reservation.

Author contributions

YJ: Conceptualization, Formal Analysis, Investigation, Methodology, Supervision, Writing–original draft, Writing–review and editing. MF: Conceptualization, Data curation, Investigation, Resources, Software, Writing–original draft. YF: Conceptualization, Formal Analysis, Investigation, Methodology, Supervision, Writing–original draft.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

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