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Article

China's Climate-Adaptive Urban Pilot Policy and Green Total-Factor Energy Efficiency: A Difference-in-Differences Approach

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Abstract

Urban areas, as critical regions that bear the brunt of climate change risks, have drawn significant attention. To enhance urban resilience to climate risks, China launched pilot projects for climate-adaptive city construction in 2017. This study leverages the climate-adaptive city pilot policy as a quasi-natural experiment. Employing a Difference-in-Differences (DID) model based on data from 2008 to 2022, this study examines the impact of the pilot policy on the green total-factor energy efficiency (GTFEE) of Chinese prefecture-level cities. A series of robustness tests confirms that the pilot policy for constructing climate-adaptive cities has a significant positive effect on green total-factor energy efficiency. The transformation and upgrading of industrial structures, as well as green innovation, serve as key mechanisms for improving GTFEE. Heterogeneity analysis reveals that the pilot policy for constructing climate-adaptive cities has a more significant effect on improving GTFEE in non-resource-based cities, cities with high levels of science and technology, and cities designated as dual-control areas. The empirical results enhance the understanding of China's policy implementation for climate-adaptive city construction and provide substantive evidence to support the promotion of climate-adaptive urban construction experiences and the advancement of sustainable urban development.

Keywords: climate-adaptive urban pilot policy; green total-factor energy efficiency; industrial structure; China; green innovation
JEL: Q54, Q48, Q56, O44, R11

1. Introduction

The instability and extremity of climate conditions pose significant challenges to social and economic development. Climate change risks encompass the security threats and resource losses that climate change imposes on human society. The concepts of enhancing adaptability, strengthening climate resilience, and reducing vulnerability have long been central to climate change adaptation research (Adger et al., 2003). Against this background, the Paris Agreement further established these as global climate risk management objectives. China has incorporated the concept of adapting to climate change into its ecological civilization strategy. As human society modernizes, cities have become high-density areas for the global population and production activities, making them key regions for climate change risks (Ng and Ren, 2018). China's urbanization rate reached 67% by the end of 2024. Since urban climate risk management can benefit a larger population, constructing climate-adaptive cities using panel data from prefecture-level cities as the research subject is particularly feasible. Climate-adaptive city construction is an effective initiative for national energy conservation, emission reduction, and sustainable development (Wamsler et al., 2013). In 2017, China issued the "Notice on Pilot Work for Climate-Adaptive Urban Construction", thereby implementing the national climate adaptation strategy in urban development. As major energy consumption centers, cities must integrate energy efficiency into their planning and evaluation systems (Umoh et al., 2024). To more accurately assess energy utilization efficiency, the academic community has introduced green total-factor energy efficiency (GTFEE), which accounts for undesired outputs such as sulfur dioxide, industrial dust, and industrial wastewater emissions during energy use (Zhang et al., 2021). GTFEE has emerged as a core indicator for measuring urban green development quality (Gao et al., 2025b). Enhancing GTFEE aligns closely with the core objectives of climate-adaptive city construction policies, particularly in optimizing resource allocation, applying renewable energy, and improving resource utilization efficiency.

The research results closely related to the theme of this paper can be primarily categorized into two types. The first category involves studies, both domestic and international, on the external manifestations of climate change risks, their causes, and potential solutions. The capacity to adapt to climate change is pivotal to the sustainable development of human societies. Existing research indicates that climate change is closely linked to urbanization (Satterthwaite, 2009). To enhance adaptability to climate change, on the one hand, it is necessary to consider the negative impacts of climate change risks on social and corporate development. Systematic and quantitative assessments of climate change risks at the provincial, city, and corporate levels have been conducted, along with investigations into their causes, to provide data support for climate governance (Gandini et al., 2021). On the other hand, research into various climate governance policies, such as the UK's "Climate Change Act", New Zealand's "National Climate Change Risk Assessment", and China's "National Strategy for Climate Change Adaptation", is being conducted. Specific initiatives such as the "Resilient Cities" program (Hofmann, 2021), sponge cities (Ma and Jiang, 2023), and urban forests (Zhang and Brack, 2021) are being implemented to enhance national and urban capacities to adapt to climate change risks. The pilot policy for building climate-adaptive cities is increasingly demonstrating its positive impact on improving GTFEE.

The second category centers on GTFEE research. Energy efficiency, a key metric for energy conservation, emission reduction, and ecological construction, is significantly influenced by multiple factors. Existing studies highlight that mechanisms such as industrial structure (Yang et al., 2022), internet penetration (Wan et al., 2025b), green technological innovation (Wang et al., 2021a), green finance (Lee and Lee, 2022), and digital technology (Wan et al., 2025a) substantially impact GTFEE. Moreover, heterogeneous factors such as regional conditions, time phases, and technological levels (Zhang and Guo, 2024) lead to diverse effects on GTFEE improvement. Environmental regulation significantly enhances GTFEE (Zhao et al., 2022). It is a broad concept encompassing the systems established and implemented by government agencies to protect the ecological environment and reduce energy consumption. Through mandatory measures and incentive policies, environmental regulations integrate GTFEE into government performance evaluations, thereby improving energy-utilization efficiency (Liu et al., 2022). The pilot policy for constructing climate-adaptive cities is closely associated with environmental regulation and resilience-building (Baker, 2012), climate-governance mechanisms (Satterthwaite, 2008), and climate justice principles (Yang et al., 2021). By constructing green infrastructure and optimizing the urban energy-consumption structure, this pilot policy reduces urban greenhouse gas, carbon, and pollutant emissions (Cuce et al., 2025).

To some extent, the existing literature demonstrates that the fundamental objectives of climate-adaptive pilot policy are consistent with those of GTFEE. These pilot policies provide new policy support for enhancing GTFEE. As a crucial component of environmental regulation, how does the climate-adaptive pilot policy impact GTFEE? Through what mechanisms does this influence operate? Additionally, what heterogeneous factors affect it? These questions merit further exploration. To address them, this article employs the climate-adaptive pilot policy as a quasi-natural experiment, using data on the GTFEE of Chinese prefecture-level cities from 2008 to 2022 as the research sample. A Difference-in-Differences (DID) model is utilized to analyze the impact of the climate-adaptive urban construction pilot policy on GTFEE. The policy effects are evaluated through stability tests, mechanism analysis, and heterogeneity analysis.

The marginal contributions of this paper are threefold. First, in terms of research perspective, this study investigates the impact of the climate-adaptive city pilot policy on GTFEE. Unlike previous studies that predominantly examine GTFEE through the lens of mitigation-oriented policies, such as low-carbon city pilots (Zhou and Qi, 2022) or environmental taxes (Gao et al., 2022), this paper focuses specifically on adaptation-oriented pilots. This distinction enriches the literature on environmental policy evaluation by highlighting the unique role of climate adaptation in driving green development. Second, regarding the research sample, while existing literature on GTFEE often relies on provincial or firm-level data (Chen et al., 2025), this study focuses on Chinese cities. Cities are not only hubs of population and innovation but are also the primary units facing extreme climate risks. Therefore, using city-level data allows for a more rigorous identification of policy effects, capturing the systemic adjustments made by local governments in response to climate challenges. Third, regarding research mechanisms, existing studies have largely attributed the positive effects of climate policies to external factors such as urbanization levels (Liu et al., 2025) and to enhanced economic growth resilience (Wen et al., 2024). In contrast, this paper explores endogenous transmission channels, specifically industrial structure upgrading and green innovation. We provide empirical evidence that the climate-adaptive city pilot policy enhances GTFEE by fundamentally reshaping industrial patterns and incentivizing technological progress, offering a more nuanced understanding of the policy's efficacy. This study, however, specifically investigates the mechanisms of industrial structure and green innovation. The results indicate that the climate-adaptive city pilot policy effectively enhances GTFEE through these channels. The findings reveal that the pilot policy is more effective in non-resource-based cities, cities with advanced science and technology capabilities, and dual-control zone cities. This study provides empirical support for the comprehensive implementation of the climate-adaptive urban construction pilot policy and offers a policy foundation for cities to advance high-quality development through green energy transitions.

2. Institutional Background and Research Hypotheses

2.1 Institutional Background

Historically, climate change has posed numerous risks to human society, representing a global challenge for all of humanity. In response to these risks, countries worldwide have implemented measures and systems to mitigate the effects of climate change. These initiatives aim to reduce the severity of climate change and accommodate its uncertainties, with a concerted effort to enhance adaptive capacities. The "Compilation of Chinese Government White Papers" (2021) emphasizes that "China is a sensitive and significantly affected area of global climate change" (State Council Information Office of the People's Republic of China, 2022). The Chinese government has proactively engaged in adapting to climate change risks, evolving from conceptual acceptance to the establishment of formal systems. Addressing climate change risks has now become an integral part of the national development strategy.

Under the guidance of international climate change agreements, China has developed systems to manage climate change risks according to its national circumstances. This process demonstrates a policy refinement from the national level to provincial and municipal levels, illustrating the progressive application of climate risk management policies from macro-level frameworks to micro-level practices. In 2007, China launched the "National Climate Change Program", initiating governance efforts from the perspective of a developing nation to foster a resource-conserving and environmentally friendly society. In 2013, the "National Strategy for Climate Change Adaptation" was introduced, followed by the "National Climate Change Response Plan (2014–2020)", a medium- to long-term plan mandating effective energy conservation and emission reduction to control greenhouse gas emissions. In 2016, the "Urban Climate Change Adaptation Action Plan" was released, identifying cities as critical areas for climate risk and as practical arenas for implementing the national climate adaptation strategy. In 2017, the National Development and Reform Commission and the Ministry of Housing and Urban-Rural Development issued a notice launching pilot projects for climate-adaptive urban construction, selecting 28 cities as pilot cities. These cities have demonstrated positive results in ecological protection (Fu et al., 2021). In 2023, China's Ministry of Ecology and Environment, along with other agencies, jointly issued the "Notice on Deepening the Pilot Projects for Climate-Adaptive City Construction". By 2035, comprehensive climate-adaptive initiatives are planned for all prefecture-level cities and above. Essentially, addressing climate change risks has become a fundamental requirement for national green transformation development.

2.2 Theoretical Foundations and Research Hypotheses

Human economic and social development is inextricably linked to energy use. As a developing nation, China has predominantly used fossil fuels and other non-renewable energy sources, resulting in high levels of pollution and emissions during the initial phases of industrialization. Consequently, China's rapid economic growth has been accompanied by climate-related disasters and ecological degradation. With deepening urbanization, cities have become the primary spaces for population concentration and the centers of economic production, making them highly sensitive to climate and environmental issues (Xu and Tang, 2021). High pollution and emissions in urban production processes pose significant barriers to sustainable development. GTFEE provides a more scientific measure for accurately assessing and improving urban energy efficiency. The climate-adaptive urban pilot policy requires attention to ten key aspects that can improve urban development resilience, including land planning, waste management, water resources, ecosystems, and technological support (Boyd and Juhola, 2015). The climate-adaptive urban pilot policy emphasizes evaluating the input-output ratio of urban climate adaptation actions. Through cost-efficiency analysis, it advocates formulating climate adaptation plans and action schemes tailored to local conditions, to enhance climate adaptation capacity and the ability to address climate risks. The pilot policy supports urban ecological and environmental protection efforts, including fiscal and tax incentives, financial investments, and talent development. It advocates a collective governance approach led by the government, supported by enterprises, and actively participated in by social organizations and citizens. By fostering cross-sectoral coordination and cooperation in production, the policy aims to reduce the costs of climate governance and energy consumption. The climate-adaptive pilot policy and GTFEE are inherently aligned. Both are based on the principles of cost-efficiency analysis of inputs and outputs, aiming to reduce emissions of various pollutants during production and daily life, thereby enhancing urban green total-factor energy efficiency. Based on this alignment, Hypothesis 1 is proposed:

Hypothesis 1: The climate-adaptive urban pilot policy can effectively enhance GTFEE.

Traditional industrial production activities have released substantial amounts of pollutants, leading to air pollution, soil contamination, and water pollution. These environmental issues have continuously exacerbated the risks associated with global climate change. Climate risks pose direct disruptions to urban ecosystems. As an institutional response, the climate-adaptive city pilot policy drives the optimization of urban industrial structures by steering the transition from energy-intensive, high-pollution industries toward low-carbon and green sectors, thereby strengthening cities' capacity to adapt to climate risks (Tang et al., 2023). Researchers have explored the relationship between the climate-adaptive pilot policy and industrial structure, concluding that the transition from traditional industries to green, low-carbon industries is a critical pathway for climate governance (Mi and Sun, 2021). The transformation of industrial structures specifically trends towards the advancement and rationalization of industrial structures. Advancing industrial structures involves phasing out low-tech, low-added-value industries and transitioning to high-tech, high-added-value industries. Rationalizing industrial structures focuses on achieving rational development through coordinated growth among different industries, enhanced efficiency in resource allocation, and optimization of internal structures (Nurdiawati and Urban, 2021). The optimization and upgrading of industrial structures lead to a significant reduction in energy consumption and pollution emissions, while simultaneously boosting the gross domestic product (GDP) share of low-carbon green industries, knowledge-intensive industries, and high-tech industries. The optimization of industrial structure aims to achieve a balance between economic gains and ecological protection. The climate-adaptive urban pilot policy, as a form of environmental regulation, contributes to improving urban GTFEE by guiding the transformation and upgrading of urban industries and promoting the development of low-carbon, eco-friendly sectors. Based on the above analysis, Hypothesis 2 is proposed:

Hypothesis 2: The climate-adaptive urban pilot policy achieves an increase in GTFEE by guiding the optimization of the industrial structure.

The energy efficiency evaluation system has undergone a progression from single-factor energy efficiency to total factor energy efficiency, and ultimately to GTFEE, thereby augmenting the scientific precision of the assessment framework. GTFEE takes into account the proportion of undesired output factors; hence, it is imperative to diminish the proportion of undesired outputs in order to enhance energy utilization efficiency. While industrial structure, foreign trade, energy consumption structure, and the level of financial development all exert an influence on energy use efficiency, green innovation stands out as one of the most effective means of improving energy efficiency (Li and Ma, 2021). The core of green innovation is to promote technological innovation. Although there is a wealth of research on how technological innovation enhances GTFEE (Wang et al., 2021b), few studies have comprehensively evaluated climate-adaptive pilot policy by integrating pilot policies, technological innovation, and GTFEE. The climate-adaptive city pilot policy guides pilot cities toward green innovation through a combination of positive incentives and punitive measures. The development of green patented technologies and clean energy-saving technologies constitutes a core element in enhancing urban climate adaptability. Through green innovation as a mediating mechanism, cities proactively improve GTFEE (Tang et al., 2025). Under governmental guidance, advanced technologies such as digitalization and intelligence are leveraged, and climate governance concepts are integrated to advance green, low-carbon, and energy-saving technologies (Gao et al., 2025a). For instance, the establishment of a greenhouse gas emission accounting system and a digital carbon emission trading platform is employed to enhance the efficiency of government monitoring and management of corporate production emissions (Wan and Yu, 2025). On the other hand, under the policy incentives of environmental regulations, local governments strongly support green innovation technologies and low-energy-consumption, high-value-added enterprises. In order to obtain policy support and economic benefits in the market competition process, these enterprises consciously engage in green technology innovation and increase the use of clean energy and renewable energy (Jaiswal et al., 2022). This dynamic compels enterprises to continuously innovate and enhance production efficiency, thereby securing a dominant position and reaping economic benefits. The competitive and demonstration effects of technological innovation among enterprises not only bolster urban financial benefits but also reduce atmospheric pollutant emissions, thus achieving the goal of enhancing GTFEE. Based on this rationale, Hypothesis 3 is proposed:

Hypothesis 3: The climate-adaptive urban pilot policy enhances GTFEE by promoting green technological innovation.

The mechanism framework is illustrated in Fig. 1.

3. Study Design

3.1 Model

To investigate the relationship between the climate-adaptive urban pilot policy and GTFEE, this study employs a multi-period DID model and constructs the following empirical model (Eqn. 1):

$$\begin{aligned} GTFEE_{it} &= \alpha_0 + \alpha_1 Treat_i \times Post_t \\ &+ \alpha_2 X_{it} + \phi_i + \mu_t + \epsilon_{it} \end{aligned} \tag{1}$$

In the model, GTFEE is the dependent variable, where i and t denote the city and the year, respectively. Treat is a dummy variable that takes the value of 1 if the city is part of the climate-adaptive urban pilot policy area, and 0 otherwise. Post is a dummy variable that represents the year the policy comes into effect. If city i is selected as a policy pilot area in year t, then Post is assigned a value of 1 for that year and all subsequent years; otherwise, it is assigned a value of 0. X represents a series of control variables; φ denotes fixed city effects; μ represents fixed annual effects; ε denotes the random error term.

3.2 Variable Selection

Dependent Variable: GTFEE. Following the methodology outlined by Wu et al. (2021), this study selects labor, capital, and energy as inputs, while regional gross domestic product (GDP) is chosen as the desirable output. Labor: measured by the number of employed persons at year-end or by total working hours of employed persons. Capital: The Perpetual Inventory Method (PIM) is adopted to estimate the capital stock for each city. Energy: measured by total energy consumption converted into standard coal equivalent. These data are obtained from the statistical yearbooks of each city. GDP: measured using real GDP at constant prices, with data sourced from

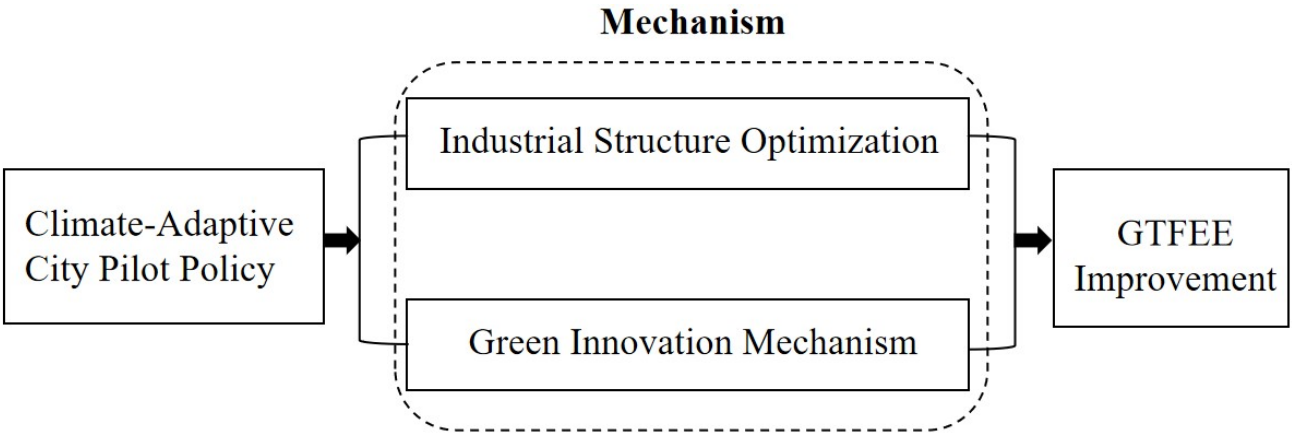

Fig. 1. Mechanism analysis framework. GTFEE, green total-factor energy efficiency.

the National Bureau of Statistics. SO_2, smoke, and effluent emissions are designated as undesirable outputs. The GTFEE of each prefecture-level city is measured using the Slack-Based Measure (SBM) Malmquist-Luenberger index method. Data on SO_2, smoke, and effluents are sourced from environmental statistical yearbooks or the official websites of local environmental protection bureaus. By providing these detailed definitions and measurement methods for the input and output indicators, we aim to clarify the specific variables used in the SBM-Malmquist-Luenberger index method and enhance the interpretability of our research results.

Explanatory Variable: climate-adaptive urban pilot policy (DID). To enhance urban adaptability to climate change risks, China initiated the climate-adaptive pilot cities in 2017. Within the national scope, 28 cities, including Hohhot, Dalian, Chaoyang, Lishui, Hefei, Huaibei, and Jiujiang, were selected to initiate pilot projects. If a city is designated as a pilot city, then in each subsequent year from 2017 onwards, the dummy variable treat × post is assigned a value of 1; otherwise, it is assigned a value of 0.

Control Variables: To comprehensively assess the impact of the climate-adaptive urban pilot on green total-factor energy efficiency, it is necessary to control for other economic and social variables that may influence GTFEE. Drawing on relevant research literature, this study selects the following control variables: Population Size (People), measured by the natural logarithm of the total population of the local city in units of 10,000 persons. Level of Financialization (Finance): Assessed by the ratio of balances of deposits and loans of financial institutions to local GDP. Internet Penetration (Internet): Measured by the percentage of the local population with internet access relative to the total population. Government Spending Level (Gov): Assessed by the proportion of local government fiscal expenditures to fiscal revenues. Number of College Students (Student): Measured by the ratio of enrollment in higher education institutions to the total local population. Market Potential (Market): Assessed by the ratio of total retail sales of consumer goods to regional gross product. Descriptive statistics for these control variables are presented in Table 1.

Table 1. Descriptive statistics.

Variable	SD	*N*	Median	Mean	Min	Max
GTFEE	0.133	4068	0.308	0.335	0.154	1.013
DID	0.185	4068	0	0.035	0	1
People	0.672	4068	5.943	5.897	3.829	7.204
Finance	1.104	4068	2.042	2.355	0.890	6.555
Internet	6.889	4068	0.164	2.037	0.018	46.61
Student	1.369	4068	10.50	10.51	6.841	13.64
Gov	2.019	4068	4.528	4.761	0.807	10.75
Market	0.103	4068	0.362	0.371	0.128	0.679

Note: SD, standard deviation; DID, difference-in-differences; Gov, government spending level.

3.3 Data Description

This study utilizes data on the GTFEE of prefecture-level cities in China from 2008 to 2022 as the initial research sample. This specific timeframe was chosen because, subsequent to the 2007 release of the "National Climate Change Program", China embarked on a proactive national-level exploration to address the risks associated with climate change. In 2017, the "Pilot Work Plan for Climate-Adaptive Urban Construction" was issued, and 28 cities, including Hohhot, were selected as pilot cities. Over the past five years, these pilot cities have achieved significant progress in energy conservation, emissions reduction, and climate adaptation. The primary data sources for this study include the "China City Statistical Yearbook" and the "China Science and Technology Statistical Yearbook", as well as public channels such as official government websites.

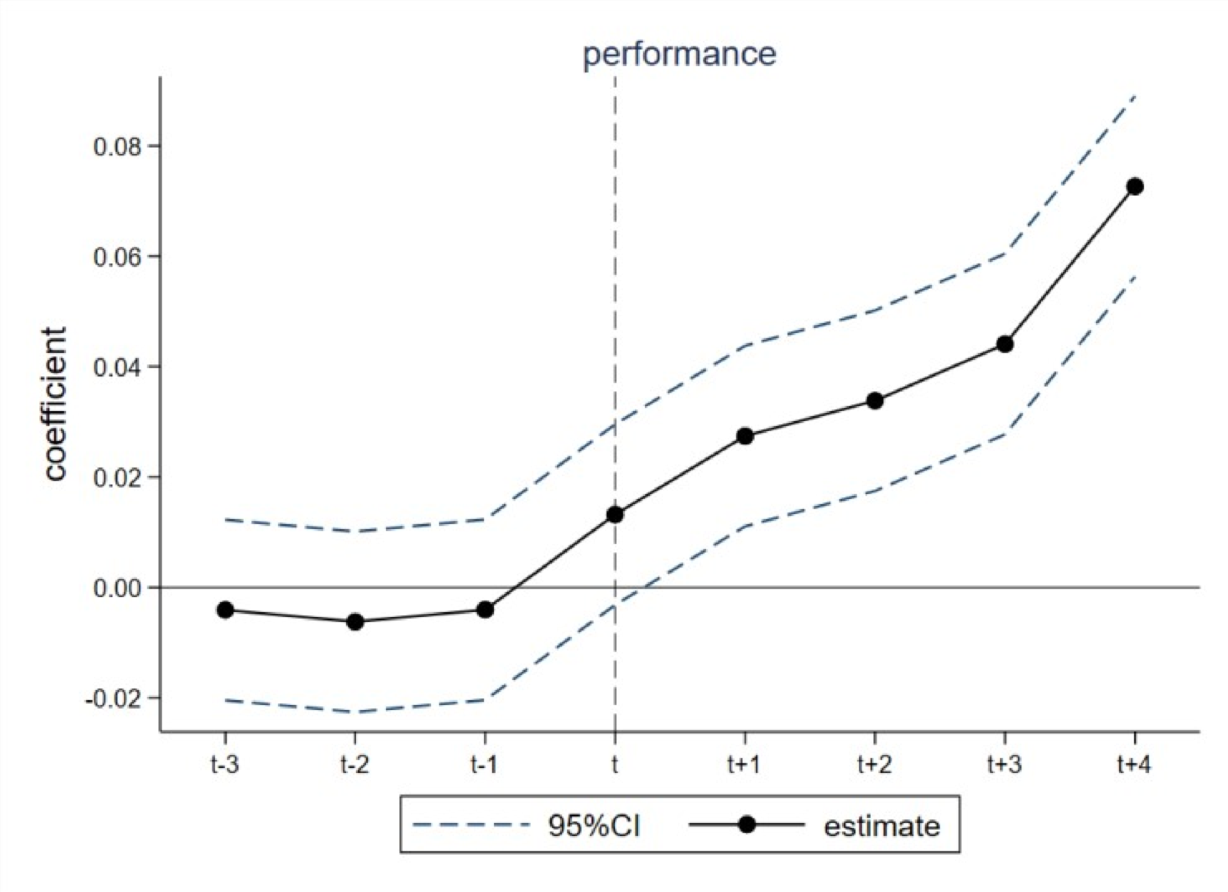

Fig. 2. Event study methodology. CI, confidence interval.

4. Empirical Analysis

4.1 Parallel Trend Test

The event study method is employed to evaluate the impact of the climate-adaptive urban pilot policy. Fig. 2 illustrates the dynamic trend of changes in GTFEE before and after the implementation of the pilot policy. In the three periods prior to the policy implementation (t-3, t-2, t-1), the regression coefficients for pilot and non-pilot cities are insignificant and clustered around zero, indicating that there were no significant differences between the two groups of cities before 2017, satisfying the parallel trend assumption of the event study method. This result lays the foundation for subsequent analysis and ensures the reliability of the estimation results. At the time point (t) when the pilot policy began implementation, the coefficient exhibits a significant upward trend, suggesting that the policy has had a substantial positive impact on GTFEE. As time progresses, the policy effects persist, demonstrating that the climate-adaptive urban pilot policy has a long-term positive influence on enhancing GTFEE. Fig. 2 clearly shows the dynamic changes in GTFEE before and after the policy implementation, supporting the effectiveness of the pilot policy.

4.2 Baseline Regression Results

The baseline regression results are presented in Table 2. The findings suggest that the climate-adaptive urban pilot policy significantly enhances GTFEE, irrespective of whether control variables are included. After incorporating multiple control variables, such as the level of urban economic development, the data in column (2) indicate that the pilot policy has a positive impact on GTFEE, thereby confirming Hypothesis 1. This effect may be attributed to the inclusion of control variables such as the level of urban economic development and government financial support, which provide substantial financial backing and policy assistance for climate risk management, energy conservation, and emission reduction efforts. Higher education provides a talent pool for environmental protection, while the Internet provides a platform for disseminating ecological concepts and knowledge. These control variables directly influence the implementation effectiveness of the climate-adaptive urban pilot policy, which, in turn, affects the policy's efficacy in enhancing GTFEE.

4.3 Mechanism Test

Industrial structure and green innovation are key mechanisms influencing GTFEE in the implementation of the climate-adaptive urban pilot policy. Therefore, in im-

Table 2. Baseline regression results.

	(1) GTFEE	(2) GTFEE
DID	0.036***	0.039***
	(0.009)	(0.009)
People		0.063***
		(0.022)
Finance		0.008***
		(0.003)
Internet		0.001***
		(0.000)
Student		–0.020***
		(0.004)
Gov		–0.005***
		(0.001)
Market		–0.172***
		(0.025)
Constant	0.333***	0.236*
	(0.001)	(0.141)
Year	Yes	Yes
City	Yes	Yes
N	4068	4068
R^2	0.6819	0.6925
adj. R^2	0.6579	0.6687
F	16.926	21.061

Note: Robust standard errors are in parentheses. Yes means the fixed effect is added to the model. Controls indicate a series of control variables. Year indicates time fixed effects, City indicates city fixed effects. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

plementing a climate-adaptive urban pilot policy, transforming and upgrading industrial structures and innovating green technologies are of paramount importance.

(1) Industrial structure optimization. The climate-adaptive urban pilot policy necessitates a comprehensive integration of urban planning, industrial structure, and climate change adaptation efforts. Industrial structure optimization serves as a mediating mechanism, measured by the proportion of the secondary industry in GDP. The secondary industry is primarily led by manufacturing, construction, and other industries. Generally, the higher the proportion of the secondary industry, the higher the level of industrialization and the more advanced the industrial structure. The manufacturing and construction industries within the secondary industry consume large amounts of energy and emit high levels of pollutants. To enhance GTFEE, it is essential to optimize the industrial structure and promote the transition of industries towards renewable energy (Gao et al., 2025c). To empirically examine the mediating role of industrial structure, this study constructs the following model (Eqn. 2):

$$\begin{aligned} Industry_{it} = \alpha_0 + \alpha_1 Treat_i \times Post_t \\ + \alpha_2 X_{it} + \phi_i + \mu_t + \epsilon_{it} \end{aligned} \tag{2}$$

where $Industry_{it}$ denotes the industrial structure of city i in year t, measured by the proportion of the secondary industry in GDP; the remaining variables are defined as in Eqn. 1.

High-quality development necessitates the enhancement of GTFEE, which is primarily achieved through the advanced transformation and upgrading of industrial structures. Cities eliminate large-scale high-energy-consuming industrial clusters, vigorously develop a circular economy, high-tech, knowledge-intensive, and high-value-added emerging industries, and promote the transformation of secondary industries towards efficiency and environmental protection. These measures reduce energy consumption, decrease pollutant emissions, and thereby enhance GTFEE (Xi and Zhai, 2023). In practice, one of the core objectives of the climate-adaptive urban pilot policy is to promote the use of green energy. This is achieved through a government-led approach, competitive enterprise involvement, and public participation. This strategy helps mitigate atmospheric, water, and forest pollution, thereby reducing the risks associated with climate change (Gao et al., 2024b). The emergence of new industries provides fresh impetus for urban development, resolving the conflict between energy consumption and ecological protection, thus facilitating the improvement of GTFEE (Guo et al., 2024). The rationalization of the industrial structure emphasizes the optimal allocation among various industries. However, as China is still in a developmental stage typical of developing countries, the adjustment of the industrial structure remains in a transition from quantitative to qualitative changes. Time lags can limit the immediate positive effects of industrial structure adjustment, meaning that the results may not be readily evident. The test results presented in column (1) of Table 3 demonstrate that the climate-adaptive urban pilot policy has a positive influence on enhancing GTFEE through the transformation and upgrading of the industrial structure, although the effect requires further amplification.

(2) Green innovation mechanisms. The climate-adaptive urban pilot policy can influence energy consumption and pollutant emissions through green innovation mechanisms. Given that green patent data reflect a city's level of green innovation, this paper draws on Wan (2024) and selects the National Intellectual Property Administration's patent database. The database contains filtering information, including patent application number, publication number, invention title, applicant, application date, and international patent classification number. According to the International Patent Classification Green Inventory set by the World Intellectual Property Organization (WIPO), the number of green patents submitted by cities each year is matched, identified, and counted. To examine the mediat-

Table 3. Mechanism effect test.

	(1) Industry	(2) Green innovation
DID	0.046***	0.499***
	(0.010)	(0.087)
People	0.178***	3.898***
	(0.026)	(0.222)
Finance	–0.023***	0.542***
	(0.004)	(0.025)
Internet	0.001***	0.022***
	(0.000)	(0.002)
Student	–0.010**	0.620***
	(0.004)	(0.033)
Gov	0.003**	0.118***
	(0.001)	(0.011)
Market	–0.277***	4.085***
	(0.029)	(0.225)
Constant	–0.426***	–29.407***
	(0.164)	(1.317)
Year	Yes	Yes
City	Yes	Yes
N	4068	4068
R^2	0.6958	0.8343
adj. R^2	0.6722	0.8222
F	37.953	595.792

Note: Robust standard errors are in parentheses. Yes means the fixed effect is added to the model. Year indicates time fixed effects, City indicates city fixed effects. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

ing role of green innovation, this study constructs the following model (Eqn. 3):

$$Green_{it} = \alpha_0 + \alpha_1 Treat_i \times Post_t + \alpha_2 X_{it} + \phi_i + \mu_t + \epsilon_{it} \tag{3}$$

where $Green_{it}$ denotes the level of green innovation of city i in year t, measured by the number of green patents; the remaining variables are defined as in Eqn. 1.

The climate-adaptive urban pilot policy, as a special initiative of the central government, endows pilot cities with enhanced policy resources, financial backing, technical guidance, and human capital compared to non-pilot cities. Climate change risk is essentially an ecological issue stemming from high pollution and high-emission activities in production. To enhance urban adaptation to climate change, the government supports the establishment of a climate change adaptation information-sharing platform through special policies, enabling standardized, intelligent management of pollution monitoring (Pan et al., 2022). Constructing a professional talent pool and enhancing the technical capabilities of practitioners provides think tank resources to support green innovation technologies, such as clean energy and low-carbon technologies. The government initiates green innovation projects and allocates special funding to foster the development of green innovation patents. By adjusting environmental tax policies, businesses are incentivized to actively engage in green innovation research and development and in ecological innovation competitions, thereby enhancing their capacity to manage climate risks (Gao et al., 2024c). Overall, green innovation technologies provide substantial endogenous growth momentum for improving GTFEE. The climate-adaptive urban pilot policy is not a strict environmental regulation; instead, it emphasizes leveraging cities' initiative and local governments' autonomous practices. Local governments develop climate adaptation plans, climate risk management strategies, and construction goals tailored to the city's economic level, resource endowments, and scientific capabilities. They employ technological innovation to offset environmental costs caused by climate change risks. The results of the mechanism effect test, as shown in column (2) of Table 3, indicate that the green innovation mechanism significantly enhances GTFEE, thereby confirming Hypothesis 3.

Although the mechanism tests in this study were conducted independently from the perspectives of industrial structure and green innovation, it is theoretically and practically impossible to completely separate the two when enhancing climate adaptability and GTFEE. The two are strongly correlated. Industrial structure transformation and upgrading stimulate technological innovation in enterprises, which, in turn, accelerates the pace of industrial structure transformation and upgrading.

4.4 Robustness Test

4.4.1 Placebo Test

Given that other random factors might influence the assessment of GTFEE, it is necessary to conduct a placebo test on the estimated results to rule out spurious regression. Specifically, this study uses computer simulations to randomly generate new treatment groups, repeating this process 500 times, and employing a DID regression model. Fig. 3 presents the probability density function of the estimated coefficients from the placebo tests. The bell-shaped, approximately normal distribution, centered around zero, provides strong evidence supporting the robustness of the original DID estimates. The results confirm that the observed treatment effects on GTFEE are not driven by spurious factors but reflect the genuine impact of the policy intervention.

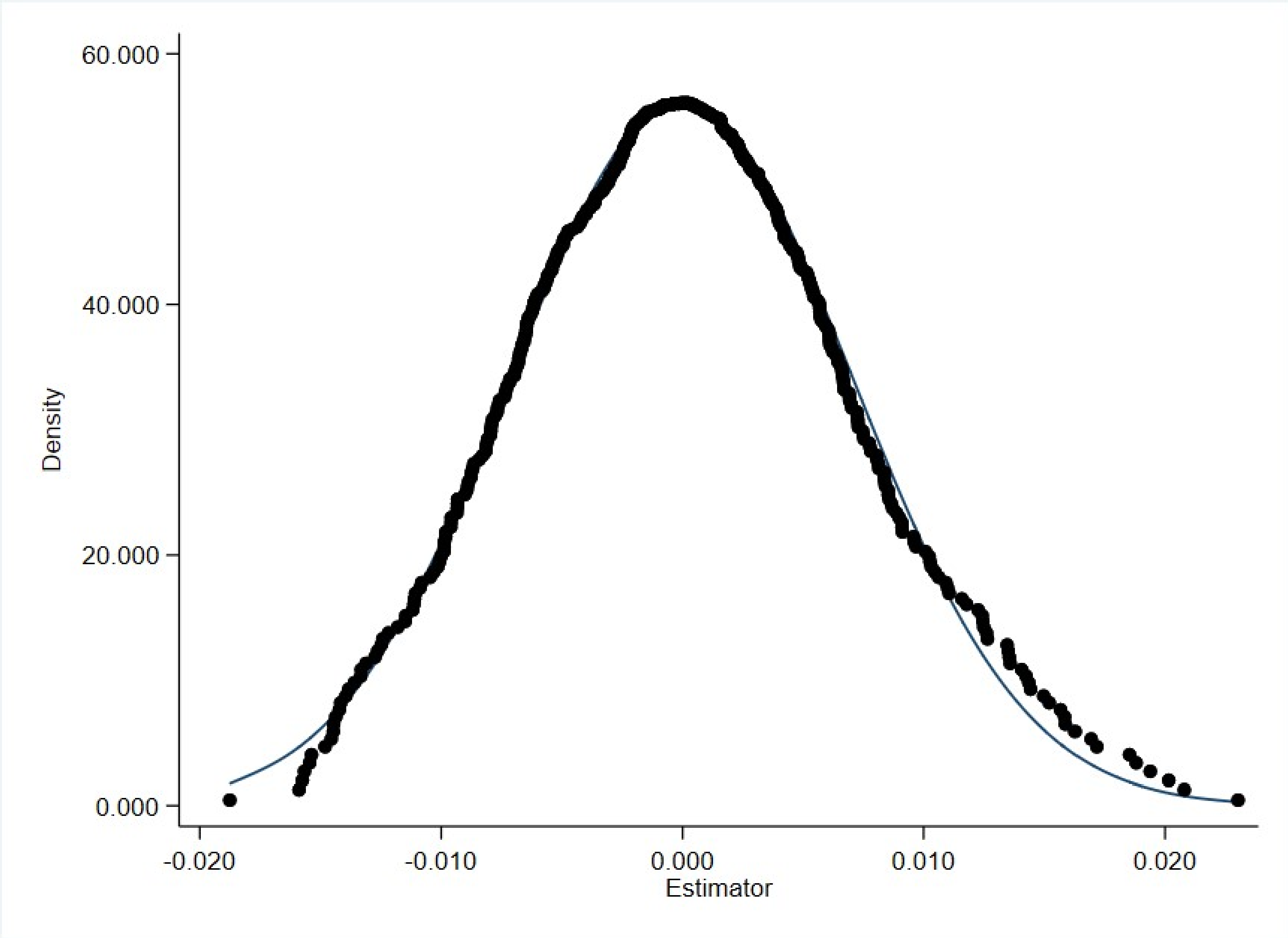

Fig. 3. Placebo test.

4.4.2 Propensity Score Matching (PSM)-Difference-in-Differences (DID)

Given that the Chinese cities selected in this study exhibit substantial differences in geography and economic development, we employ propensity score matching (PSM) to control for sample characteristics and reduce sample selection bias. Following the matching procedure, we further conduct regression analysis using the DID approach on the matched sample. The regression results from the PSM-DID model demonstrate that the climate-adaptive urban pilot policy continues to exert a significant positive impact on urban green total-factor energy efficiency, corroborating the robustness of our study's conclusions. The results of the balance test are presented in Table 4.

4.4.3 Excluding Interference From Other Policies

To achieve energy conservation and emission reduction, China has implemented environmental regulations that affect GTFEE concurrently with the climate-adaptive urban pilot policy. For instance, during the sample period (2008–2022), China promoted several policies, including the Low-Carbon City Pilot Policy (2010), the Ecological Civilization Pilot Demonstration Area Policy (2013), the Air Pollution Prevention and Control Law (2015), the Carbon Emission Trading Pilot Policy (2017), and the Environmental Protection Tax Law (2018). These policies directly facilitated energy conservation and emission reduction, potentially interfering with the baseline results of this study. To prevent the research findings from being influenced by such related environmental policies, the sample was re-analyzed by re-estimating the model, excluding these policy interferences. The empirical results are presented in column (2) of Table 5. According to the data, after excluding other policy interferences, the climate-adaptive urban pilot policy still significantly enhances GTFEE.

4.4.4 Lagged Effect

From the issuance of notifications by the central government to the pilot phase, and then to the specific implementation process, a time lag is required for the process; hence, the effects of policy implementation will exhibit significant latency. To more scientifically assess the impact of the climate-adaptive urban pilot policy on GTFEE, it is necessary to conduct a one-period lagged regression. The empirical results presented in column (3) of Table 5 reveal that the one-period lagged effect of the climate-adaptive urban

Table 4. Balance Test Results for PSM.

Variable	Unmatched / Matched	Mean Treated	Mean Control	%bias	%reduct |bias|	t-test t	t-test $p > t$	V(T)/V(C)
People	U	6.0285	5.8919	22.1	87.1	2.40	0.017	0.67*
	M	6.0285	6.0108	2.9		0.24	0.807	0.69*
Finance	U	3.2073	2.3236	69.9	73.5	9.54	0.000	1.75*
	M	3.2073	2.973	18.5		1.37	0.173	0.92
Internet	U	4.1946	1.9574	27.7	71.9	3.83	0.000	1.83*
	M	4.1946	3.566	7.8		0.56	0.576	0.86
Student	U	11.403	10.473	65.0	76.9	8.06	0.000	1.23
	M	11.403	11.188	15.0		1.26	0.209	1.17
Gov	U	5.1456	4.7467	18.9	60.6	2.33	0.020	1.21
	M	5.1456	4.9884	7.4		0.62	0.533	1.15
Market	U	0.41109	0.36902	41.4	77.9	4.81	0.000	0.94
	M	0.41109	0.40179	9.2		0.78	0.434	0.97

Note: U, Unmatched; M, Matched.* if variance ratio outside [0.72, 1.39] for U and [0.72, 1.39] for M.

Table 5. Robustness test results.

	(1) PSM-DID	(2) Excluding interference from other policies	(3) Lagged effect	(4) Interactive fixed effects test	(5) Replace the dependent variable	(6) Excluding municipalities
	GTFEE	GTFEE	GTFEE	GTFEE	GTFEE	GTFEE
DID	0.042^{***}	0.035^{***}		0.050^{***}	0.049^{***}	0.038^{***}
	(0.009)	(0.009)		(0.009)	(0.011)	(0.009)
DID_{T-1}			0.039^{***}			
			(0.009)			
People	0.059^{**}	0.034	0.071^{***}	0.171^{***}	0.032	0.068^{***}
	(0.024)	(0.024)	(0.024)	(0.025)	(0.030)	(0.022)
Finance	0.007^{**}	0.006^{*}	0.009^{***}	-0.010^{**}	0.011^{***}	0.009^{***}
	(0.003)	(0.003)	(0.003)	(0.004)	(0.004)	(0.003)
Internet	0.001^{***}	0.001^{**}	0.001^{***}	0.001^{***}	0.001^{**}	0.001^{**}
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Student	-0.022^{***}	-0.016^{***}	-0.019^{***}	-0.008^{**}	-0.023^{***}	-0.019^{***}
	(0.005)	(0.004)	(0.004)	(0.004)	(0.005)	(0.004)
Gov	-0.005^{***}	-0.006^{***}	-0.005^{***}	-0.004^{***}	-0.009^{***}	-0.005^{***}
	(0.001)	(0.001)	(0.001)	(0.001)	(0.002)	(0.001)
Market	-0.187^{***}	-0.179^{***}	-0.164^{***}	-0.194^{***}	-0.185^{***}	-0.163^{***}
	(0.026)	(0.026)	(0.026)	(0.030)	(0.032)	(0.024)
Constant	0.296^{*}	0.377^{**}	0.178	-0.479^{***}	0.700^{***}	0.187
	(0.152)	(0.151)	(0.152)	(0.152)	(0.185)	(0.139)
Year	Yes	Yes	Yes	Yes	Yes	Yes
City	Yes	Yes	Yes	Yes	Yes	Yes
Year*city	No	No	No	Yes	No	No
N	3691	3543	3796	3991	4068	4008
R^2	0.6942	0.6845	0.6953	0.7534	0.6680	0.6949
adj. R^2	0.6679	0.6598	0.6700	0.7080	0.6423	0.6713
F	17.869	16.272	17.858	26.324	17.042	18.387

Note: Robust standard errors are in parentheses. Yes means the fixed effect is added to the model. Controls indicate a series of control variables. Year indicates time fixed effects, City indicates city fixed effects. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

pilot policy continues to exert a significant positive influence on GTFEE.

4.4.5 Interactive Fixed Effects Test

The study accounted for the potential impact of interaction effects between cities and years on the evaluation results. The heterogeneous conditions of urban development and the timing of policy implementation can jointly influence the dependent variable. By incorporating interactive fixed effects, the study can more accurately control for these factors. According to the data, the policy effect remains significant. The empirical results are presented in column (4) of Table 5.

4.4.6 Replacing the Dependent Variable

This study replaces the measurement method for the dependent variable from the SBM with the Charnes–Cooper–Rhodes (CCR) model. The new method is used to evaluate changes in urban GTFEE, assuming constant returns to scale. The empirical results are presented in column (5) of Table 5. According to the data, the climate-adaptive urban pilot policy has likely led to a significant improvement in GTFEE through scientific resource allocation, adjustments in industrial structure, and innovations in green low-carbon technologies.

4.4.7 Excluding Municipalities

In China, municipalities directly under the central government possess a higher administrative level than prefecture-level cities. Additionally, these municipalities significantly exceed prefecture-level cities in terms of economic size, population scale, and scientific and technological resources (Zhao and Wang, 2022). The climate change risks and energy consumption issues confronted by these municipalities are more intricate than those faced by ordinary prefecture-level cities. Therefore, disregarding the substantial differences between China's municipalities directly under the central government and prefecture-level cities could introduce bias into the study's results. To mitigate potential bias introduced by samples from these municipalities, the study excluded data samples from the four municipalities and conducted a re-estimation of the model. The empirical results are presented in column (6) of Table 5. According to the data, even after excluding municipalities directly under the central government, the climate-adaptive urban pilot policy continues to positively influence GTFEE. This robustness test underscores that the conclusions of this study are both robust and reliable.

5. Heterogeneity Analysis

5.1 Heterogeneity of Urban Resources

The heterogeneity of urban resource endowments influences the impact of the climate-adaptive urban pilot policy on GTFEE. Resource heterogeneity primarily distinguishes cities as resource-based and non-resource-based cities. In 2013, the National Development and Reform Commission of China released the "National Sustainable Development Plan for Resource-based Cities (2013–2020)", which identified 262 resource-based cities. These cities are characterized by their focus on the development and processing of local minerals, petroleum, and other resources. These natural resources are predominantly non-renewable. Consequently, cities that rely on mineral resources for survival often face dilemmas in which prolonged resource extraction leads to insufficient urban development momentum, ecological damage, and continuous resource depletion (Huang et al., 2018). In contrast, the development of non-resource-based cities does not depend on petroleum. Instead, the use of fossil fuels exacerbates ecological pressures and climate change risks in non-resource-based cities (Li and Liu, 2023). The climate-adaptive urban pilot policy can positively influence non-resource-based cities by promoting the development of green and low-carbon industries, thereby enhancing GTFEE. For resource-based cities, constructing climate-adaptive cities is highly challenging. The production and development of resource-based cities are heavily reliant on oil and coal. Reducing the consumption of these resources can have a significant impact on economic development and living standards (Ruan et al., 2020). Therefore, implementing the climate-adaptive urban pilot policy in resource-based cities is challenging, thereby hindering improvements in GTFEE. The results of the heterogeneity test for specific urban resources are presented in columns (1) and (2) of Table 6.

5.2 Heterogeneity in Technological Levels

The scientific and technological levels of prefecture-level cities in China exhibit uneven development due to differences in economic development, higher education resources, research and development funding, and the level of technological infrastructure. The heterogeneity in scientific and technological levels is primarily determined by the number of technological patents in a city as a measure of its scientific and technological strength. The patent data for each prefecture-level city is obtained from the National Intellectual Property Administration. Overall, cities in the economically developed southeastern coastal regions of China have higher levels of science and technology. In contrast, cities in the northwestern inland areas generally exhibit lower levels of scientific and technological development (Cao et al., 2019). Data from column (3) of Table 6 indicate that a higher level of scientific and technological development can provide technical support for the innovative application of clean and renewable energy sources, offer more green technology patents, and accelerate the development of knowledge-intensive industries. These advancements reduce the climate change risks associated with pollutants and enhance GTFEE (You and Zhang, 2022). Conversely, as shown in column (4) of Table 6, cities with lower levels of scientific and technological development

Table 6. Heterogeneity test results.

	(1) Resource-based cities	(2) Non-resource-based cities	(3) High level of technology	(4) Low level of technology	(5) Dual control zone	(6) Non-dual control zone
	GTFEE	GTFEE	GTFEE	GTFEE	GTFEE	GTFEE
DID	–0.019	0.056***	0.065***	0.007	0.108***	–0.011
	(0.013)	(0.011)	(0.013)	(0.012)	(0.013)	(0.012)
People	–0.071**	0.153***	0.067**	–0.089*	0.080***	–0.006
	(0.028)	(0.033)	(0.027)	(0.052)	(0.027)	(0.041)
Finance	0.016***	0.002	0.020***	0.006	0.009**	0.006
	(0.004)	(0.004)	(0.006)	(0.004)	(0.005)	(0.005)
Internet	0.002***	0.000	0.001**	0.001	0.001***	0.001
	(0.001)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Student	–0.007*	–0.037***	–0.041***	–0.006	–0.029***	–0.010*
	(0.004)	(0.006)	(0.007)	(0.005)	(0.005)	(0.005)
Gov	–0.003**	–0.005***	0.001	–0.010***	–0.006***	–0.004**
	(0.001)	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)
Market	–0.150***	–0.148***	–0.301***	–0.156***	–0.185***	–0.151***
	(0.033)	(0.034)	(0.041)	(0.032)	(0.034)	(0.035)
Constant	0.802***	–0.099	0.453**	0.973***	0.257	0.519**
	(0.163)	(0.216)	(0.177)	(0.308)	(0.173)	(0.249)
Year	Yes	Yes	Yes	Yes	Yes	Yes
City	Yes	Yes	Yes	Yes	Yes	Yes
N	1556	2512	2060	1982	2156	1912
R^2	0.7236	0.6698	0.7119	0.7244	0.7328	0.6534
adj. R^2	0.6997	0.6431	0.6769	0.6921	0.7108	0.6243
F	9.975	16.947	19.667	10.012	25.855	4.363

Note: Robust standard errors are in parentheses. Yes means the fixed effect is added to the model. Controls indicate a series of control variables. Year indicates time fixed effects, City indicates city fixed effects. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$. The sample sizes for patent-based subgroups do not sum to 4068 due to missing data for 26 city-year observations.

tend to have industrial and energy structures that are relatively traditional, relying on high-energy-consuming and heavily polluting fossil fuels for production. These cities often lack a sufficient workforce for technological innovation and have insufficient governmental investment in low-carbon technology research and development. Consequently, these cities have weaker climate adaptation capabilities and infrastructure, and thus fail to enhance GTFEE.

5.3 Heterogeneity of "Dual Control" Areas

The heterogeneity in dual control zones is based on whether a city is listed as an acid rain control zone or a sulfur dioxide pollution control zone under China's "Law on the Prevention and Control of Atmospheric Pollution". China designates regions that have already produced or may produce acid rain, or other regions with severe sulfur dioxide pollution, as dual-control zones (Hao et al., 2001). The primary source of this pollution is sulfur dioxide emissions resulting from the extensive use of fossil fuels in local production processes. The climate-adaptive urban pilot policy applies stricter pollutant-emission standards to industrial production and guides investment and production in low-carbon and renewable energy, effectively reducing ecological pollution in the dual control zones (Hung and Ashner, 2020). The impact of the pilot policy for constructing climate-adaptive cities on GTFEE shows significant heterogeneity between dual-control zones and non-control zones. The pilot policy exerts a significant effect in the dual-control zones. This is attributable to the alignment of objectives between the dual-control zones policy and the climate-adaptive city pilot policy. Given the stringent enforcement of environmental regulations within the dual-control zones, the pilot policy can more effectively leverage its regulatory constraints and guidance functions to achieve synergistic outcomes (Li et al., 2018). The pilot policy negatively affects GTFEE in non-dual-control zones. Due to stringent environmental regulations in dual-control zones, pollution-intensive enterprises tend to relocate to non-dual-control zones where regulatory constraints are less stringent. This industrial transfer results in non-dual-control zones absorbing a greater volume of pollution, thereby suppressing their GTFEE levels (Shen et al., 2017).

The specific test results for the heterogeneity between the dual control zones and non-control zones are presented in columns (5) and (6) of Table 6.

5.4 Regional Heterogeneity Analysis

To further examine the regional differences in the impact of the climate-adaptive city pilot policy on green total-factor energy efficiency, the full sample is divided into three sub-samples—eastern, central, and western regions—for separate regressions. The results are presented in Table 7. The pilot policy has a significant positive effect on GTFEE in the eastern region, whereas its effects in the central and western regions are not statistically significant, indicating pronounced regional heterogeneity in the policy's effectiveness. This finding can be explained from the following three perspectives. First, in terms of economic foundation and fiscal capacity, the eastern region, benefiting from its advantageous geographical location, enjoys a higher level of economic development and can therefore provide sufficient financial support for the infrastructure required by the pilot policy (Hu et al., 2020). In contrast, the central and western regions, with relatively lagging economic development, face difficulties in bearing the substantial upfront costs associated with policy implementation. Second, in terms of human capital and innovation resources, the eastern region has attracted numerous research universities and institutions, providing abundant talent support for green innovation and clean technology development. By contrast, the central and western regions are less competitive in attracting skilled professionals and translating research outputs into practical applications, which constrains the realization of the policy's intended effects (Yu and Zhang, 2019). Third, from the perspective of industrial structure, the eastern region possesses a more balanced industrial composition, with a higher share of the tertiary sector and modern service industries, which lays a solid foundation for green transformation. In contrast, the central and western regions are characterized by a disproportionately large share of traditional energy-intensive and high-emission industries, with resource-dependent cities predominantly concentrated in these areas (Cheng et al., 2019). The resulting structural inertia poses considerable resistance to industrial restructuring, thereby suppressing the policy's capacity to enhance GTFEE and making it difficult for significant effects to materialize in the short term.

Table 7. Regional heterogeneity analysis.

	(1) Eastern GTFEE	(2) Central GTFEE	(3) Western GTFEE
DID	0.111***	0.016	–0.017
	(0.021)	(0.019)	(0.013)
People	0.218***	0.014**	0.026***
	(0.048)	(0.007)	(0.005)
Finance	0.013**	–0.028***	–0.028***
	(0.005)	(0.005)	(0.003)
Internet	0.000	0.001*	0.001
	(0.000)	(0.001)	(0.001)
Student	–0.068***	0.021***	0.009***
	(0.010)	(0.004)	(0.003)
Gov	0.000	–0.018***	0.000
	(0.002)	(0.002)	(0.002)
Market	–0.134***	–0.167***	–0.087**
	(0.042)	(0.044)	(0.037)
Constant	–0.180	0.227***	0.146***
	(0.307)	(0.034)	(0.022)
Year	Yes	Yes	Yes
City	Yes	Yes	Yes
N	1499	1361	1208
R^2	0.6492	0.1679	0.1690
adj. R^2	0.6187	0.1549	0.1543
F	14.511	21.165	27.191

Note: Robust standard errors are in parentheses. Yes means the fixed effect is added to the model. Controls indicate a series of control variables. Year indicates time fixed effects, City indicates city fixed effects. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

6. Conclusions

Enhancing climate adaptability and green total-factor energy efficiency is crucial for the sustainable development of modern cities. This study employs climate-adaptive pilot policy cities as a quasi-natural experiment. Using GTFEE data from Chinese prefecture-level cities from 2008 to 2022, a DID model is applied to examine the impact of the climate-adaptive city pilot policy on GTFEE, its mechanisms of influence, and its heterogeneity. The research concludes that climate-adaptive pilot policy cities significantly enhance GTFEE through mechanisms of industrial restructuring, upgrading, and green innovation. This pilot policy has a more pronounced effect on enhancing GTFEE in non-resource-based cities, cities with high levels of technology, and cities within the dual-control zones. This article enriches the evaluation of the climate-adaptive city pilot policy and provides theoretical support for promoting construction experiences under this policy. It offers policy references for cities to enhance GTFEE and pursue a sustainable development path.

First, it is essential to deepen the work on the climate-adaptive urban pilot policy and leverage the demonstrative role of pilot cities as models for implementation. However, it is important to consider differences in economic conditions, industrial structures, and technological levels among cities when promoting the experiences gained from the climate-adaptive urban pilot policy. Heterogeneity analysis reveals that the effectiveness of the pilot policy is contingent upon three preconditions: economic structural diversification, technological absorptive capacity, and complementary regulatory pressure. Accordingly, a systematic readiness assessment should be conducted prior to extending the policy to new cities. The pilot policy should be tailored to the specific circumstances of each city, a principle consistent with the core rationale of the European Commission's (2021) Climate Change Adaptation Strategy, which mandates that member states develop differentiated national adaptation plans. This approach ensures that context-specific conditions are adequately addressed, enabling the timely formulation of climate adaptation measures aligned with the distinctive characteristics of each city.

Second, it is essential to coordinate differentiated policy portfolios tailored to the specific developmental stage of each city. Resource-based cities should accelerate the optimization and upgrading of their industrial structures by integrating lessons from low-carbon city pilot policies and establishing industrial transition funds, mandatory energy-efficiency retrofitting programs, and workforce retraining initiatives to systematically address the predicament of industrial homogeneity in resource-based cities. Cities with higher technological capacity should leverage their spatial spillover effects to actively disseminate green technologies to surrounding cities, driving their joint participation in green innovation. Cities with lower technological capacity should focus on cultivating specialized teams in science, technology, and environmental protection, advancing patent-driven innovation research and applications, while prioritizing the introduction of mature, applicable energy-saving technologies and increasing investment in digital infrastructure, thereby providing technical support for the implementation of the climate-adaptive city pilot policy. Cities within "dual-control" zones exhibit the most pronounced policy response effects and should further deepen the institutional integration of climate adaptation planning with energy "dual-control" targets, implementing performance-oriented incentive mechanisms to maximize policy synergies. For cities outside the "dual-control" zones, efforts should be directed toward both maintaining sound ecological conditions and strengthening local capacity for climate risk management, establishing publicly disclosed emission reduction targets, and constructing alternative incentive structures.

Third, it is important to actively draw on international experience in urban sustainable development to enhance cities' capacity for climate risk adaptation. Local governments should establish green innovation Research and Development (R&D) programs and cultivate professional talent in fields such as artificial intelligence, clean energy, and environmental science. In terms of resource allocation, a cost-benefit analysis framework should be introduced, prioritizing adaptation investment in city types with strong policy responsiveness to maximize fiscal efficiency, while cities where policy effects are currently insignificant should prioritize investment in building enabling preconditions. It is advisable to systematically benchmark China's climate-adaptive city policies against relevant international experiences in urban climate adaptation, thereby drawing on transferable best practices and adapting them to local contexts.

It is worth noting that, while this study evaluates the actual effects of climate-adaptive city policies, it has certain limitations. While this study primarily focuses on the direct intra-city effects, there remains significant potential to explore the policy's spatial spillovers. Prior evidence on the significant spatial spillover effects of innovative city pilot policies (Gao et al., 2024a) suggests that future research should further examine the potential cross-regional externalities of the climate-adaptive city pilot policy on the GTFEE of neighboring non-pilot cities. Driven by well-developed urban transportation networks and the accelerated mobility of population, capital, and technology, these spatial spillovers may manifest in two distinct directions: positive spillover effects, such as the inter-city diffusion of green technologies, and negative spillover effects, such as the relocation of highly polluting enterprises to neighboring non-pilot cities. Employing a Spatial DID model to accurately measure these bidirectional spillover effects will constitute a key focus of our future research agenda.

Abbreviations

DID, Difference-in-Differences; GTFEE, green total-factor energy efficiency; GOV, government.

Availability of Data and Materials

The datasets generated and analyzed during the current study are available from the corresponding author on reasonable request.

Author Contributions

KW designed the research study. KW and JL performed the research. KW analyzed the data. JL wrote the manuscript. Both authors contributed to editorial changes in the manuscript. Both authors read and approved the final manuscript. Both authors have participated sufficiently in the work and agreed to be accountable for all aspects of the work.

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Conflicts of Interest

The authors declare no conflicts of interest.

Declaration of AI and AI-Assisted Technologies in the Writing Process

During the preparation of this work, the authors used GPT-4 and Grammarly in order to check spelling and grammar. After using these tools, the authors reviewed and edited the content as needed and took full responsibility for the content of the publication.

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