Environmental Science and Pollution Research (2023) 30:62376–62396
https://doi.org/10.1007/s11356-023-26402-w

RESEARCH ARTICLE

From pilots to demonstrations: the green economic development effect of low-carbon city pilot policies

Lina Peng[1] · Xiaohan Yan[1] · Zhide Jiang[1] · Zhenyu Yan[1] · Jiapeng Xu[1]

Received: 19 December 2022 / Accepted: 7 March 2023 / Published online: 21 March 2023
© The Author(s), under exclusive licence to Springer-Verlag GmbH Germany, part of Springer Nature 2023

Abstract

Accurately assessing the impact of low-carbon urban construction on green economic development has great significance for achieving economic development with environmental protection, and for building an ecological civilization and a beautiful China. Based on panel data for 271 cities in China from 2004 to 2019, multi-period and spatial difference-in-difference econometric models were used to comprehensively investigate the impact of three batches of low-carbon city pilot policies on green economic development, finding the following: The contribution of low-carbon urban construction on urban green economic development is significant and positive, and still holds under a series of robustness tests. Parallel trend tests also show a lag in the policy effect, and the effect is strengthened over policy implementation time. Green orientation of technological progress, green transformation of industry, and green upgrade of consumption are important channels for the effect of the policies. The promotion effect of low-carbon city construction is stronger in the central and northern cities, and in cities with high green economic development, than in western and southern cities, and those with low green economic development. Construction of low-carbon pilot cities not only promotes their own green economic development, but also that in neighboring cities, exerting a demonstration effect. This effect is greater in urban areas. This study provides empirical support for policy planning to promote low-carbon urban construction across the country.

Keywords Low-carbon city pilot policies · Multi-period difference-in-difference · Dual difference spatial econometric model · Green economic development effect

Responsible Editor: Ilhan Ozturk

✉ Jiapeng Xu
xujp@nwsuaf.edu.cn

Lina Peng
pln@nwsuaf.edu.cn

Xiaohan Yan
yanxiaohan@nwafu.edu.cn

Zhide Jiang
jiangzhide@nwafu.edu.cn

Zhenyu Yan
yanzhenyu@nwsuaf.edu.cn

[1] College of Economics and Management, Northwest A&F University, No. 3 Taicheng Road, Yangling 712100, Shaanxi, People's Republic of China

Introduction

Cities undoubtedly play an important role in addressing the challenges that climate change poses to global human development. They are key vectors of economic growth, and their vast industrial activities and transportation networks, and rich residential life, also make them the largest unit of carbon emissions (Gong et al. 2022). Urban areas accounted for 61–68% of global greenhouse gas emissions in 2015 (Gurney et al. 2022; Moran et al. 2018), and their share of global emissions is expected to increase in the future, exceeding 80% by the end of this century. Urban areas in Asia, the developing Pacific, and developed countries together account for 65.0–73.3% of cumulative urban emissions (Gurney et al. 2022). Therefore, in the face of severe ecological and environmental problems, a low-carbon urban economic development model featuring low energy consumption, low pollution, and low emissions has become an important strategic initiative for countries to promote sustainable social development.

The concept of carbon reduction first came from the concept of the "low-carbon economy" proposed by the UK government in its 2003 Energy White Paper (DTI 2003). Subsequently, in 2007, the Advisory Body to the Minister of the Environment of Japan issued the Japanese Low Carbon Society Model and its Feasibility Study, asserting that a "low-carbon economy" could not be developed without a "low-carbon society" (Duffield and Woodall 2011). Chinese scholars mostly borrow the definition of "low-carbon economy" from the UK and believe that a low-carbon economy is one based on low consumption and pollution which emits the minimal amount of greenhouse gases during development while maximizing output for society (Fu et al. 2008; Xue et al. 2012). There is no uniform delineation of the low-carbon city concept. Existing studies have mainly defined it from the perspectives of urban energy structure (Guo and Liang 2022), carbon emissions (Wang and She 2020), and social and economic activities (Fu et al. 2008). Synthesizing existing views, Xue et al. (2012) comprehensively defined it as "a city that consistently maintains a relatively low level of net regional greenhouse gas emissions resulting from its social and economic activities within the constraints of the sustainable development goals."

China is the country with the largest share of global carbon emissions (BP 2021; Fu et al. 2021). In 2018, 338 of its prefectures consumed 85% of its energy, 39.2% of its water, and 60% of its electricity, and emitted 75% of its CO_2 (Wang et al. 2021). To this end, China has made commitments to reduce carbon intensity and to achieve a carbon peak and carbon neutrality, and places important strategic emphasis on reducing greenhouse gas emissions (Li et al. 2018). In order to explore effective new models of low-carbon urban development that achieve sustainable development goals, the National Development and Reform Commission launched three batches of low-carbon city pilots (LCCPs) in 2010, 2012, and 2017, respectively. In recent years, the emission reduction effect of the LCCPs has begun to appear. Hangzhou, Xiamen, and Shenzhen reduced their annual carbon emissions by 20,000 tons, and the carbon emission intensity of Jingdezhen, Zunyi, and Wuhan is 24.47%, 20.43%, and 19.12% below their respective provincial averages (Qiu et al. 2021). Thus, the LCCP is an inevitable choice for China to achieve its carbon emission reduction targets and develop a green economy. However, China is still in a phase of accelerated urbanization, and its quality of life still needs to be improved. Low-carbon urban construction should not aim for the same total carbon emissions as western cities, but should strive to reduce the carbon footprint of social and economic activities. While achieving sustainable urbanization, it should meet development needs and improve people's living standards to ultimately achieve the goal of green economic development (GED) (Liu et al. 2009). Therefore, the effect of the policy on the goals of green economic development with urban decarbonization is increasingly important to measuring the effectiveness of its implementation and reform. This paper will focus on that question.

The economic impacts of LCCPs go beyond carbon reduction and are multifaceted. The existing literature is rich in research evaluating the policy effects of LCCPs, providing important ideas and insights for this paper, yet there is still some room for improvement. First, it tends to focus on policy effect testing, while neglecting analysis of policy mechanisms. If pilot regions indeed improve their green economic development, only by further digging into the specific initiatives behind that improvement can they use the opportunity of early pilot implementation to play a demonstration and leadership role. Second, assessment of LCCPs mostly focuses on the policy implementation sites, and rarely considers the spatial spillover effects in neighboring regions, which may lead to biased results. Finally, most studies only analyze static policy effects, without further analyzing the dynamic spatial evolution. Therefore, this paper deeply and systematically explores the impact of low-carbon urban construction on green economic development, not only providing theoretical support to promote profound changes in urban economic development models, but also promoting the transformation of urban economic development from crude factor-driven production to green innovation.

Based on this, using multi-period and spatial difference-in-difference (DID) models, this paper will use data on 271 cities in China from 2004 to 2019 to comprehensively examine the impact of three batches of low-carbon urban construction on green economic development. Its main contributions are as follows. First, complementing the existing literature, it analyzes the theoretical mechanisms of urban carbon governance affecting green economic development from three aspects: green orientation of technological progress, green industrial transformation, and green upgrade of consumption. Second, regarding methodology, it applies a spatial econometric model to explore the effect of urban carbon governance on green economic development, using LCCP as a quasi-natural experiment. The results help remedy the shortcomings of existing studies in which the strength and direction of the effect of the policy on the control group are not sufficiently observed. Third, it analyzes the spatial evolution of LCCP cities by measuring their green economy development from 2004 to 2019 using natural breakpoints. The characteristics of the dynamic spatial evolution are of great practical significance for revealing the interactive and coordinated relationships between regions, realizing synergistic regional governance, and jointly achieving high-quality economic development.

The remainder of this study is organized as follows. The "Literature review" section presents a literature review. The

"Policy background and hypotheses" section presents the policy background and an analysis of the mechanisms and, then proposes theoretical hypotheses. The "Methodology" section describes the methodology. The "Empirical results" section analyzes the results of the benchmark regression, robustness test, and instrumental variable method. The "Mechanism analysis" section discusses the influence mechanism. The "Spatial spillover effect analysis" section analyzes the results of spatial spillover effect. The "Conclusions and recommendations" section presents the main conclusions and recommendations.

Literature review

Since the National Development and Reform Commission first implemented the low-carbon pilot city policy in 2010 in China, more and more studies began to pay attention to the pilot policy (Walangitang and Page 2012; Yang and Li 2013). In general, the pilot policy aims to deal with global climate change, reduce the carbon dioxide emission intensity of economic development, improve the energy efficiency of urban system, and solve the dilemma between economic development and transformation. Evaluation of the LCCPs has attracted extensive attention from many scholars. Some have examined its effects from the perspectives of industrial structure upgrade (Chen and Wang 2022), foreign direct investment (Duan and Shi 2021), pollution control (Song et al. 2019), corporate green technology innovation (Yu et al. 2022), and energy usage efficiency (Dong et al. 2022). Others have analyzed and assessed its carbon reduction effects. Although most studies support the positive effects of the LCCPs, points of contention still exist. Specifically, it has been argued that low-carbon urban construction fails to reduce carbon emissions and ultimately leads to poor environmental performance due to a lack of clear development goals (Lo 2014). This finding is largely consistent with Sinn's (2008) conclusion that poorly designed low-carbon policies are less effective. However, despite the institutional shortcomings of the LCCPs, the carbon governance of the pilot cities has still laid a solid foundation for sustainable local economic development (Du et al. 2022; Qiu et al. 2021).

Existing studies on the level of green economy development have focused on the measurement of the level of green economy development and the analysis of influencing factors. Most of the existing literature is based on panel data of provincial or prefecture-level cities, and the super-efficient SBM model, Malmquist index, and DEA model are used to measure and analyze the level of green economic development in China (Huang et al. 2021; Luo and Wang 2017). The results of the study indicate that pollutant emissions from the "the three-high" industries (Dinga and Wen 2022), environmental regulations, tax policies (Fernández et al. 2011), geographical location (Qiu et al. 2021), energy structure and efficiency (Fang et al. 2022), trade development and foreign direct investment (Qamri et al. 2022), and production supply chain efficiency (Zhang et al. 2018) are important factors affecting the level of green economy development. In addition, there are also studies in the literature on spatial and temporal differences, which suggest that the overall level of green economic development in China shows a steady upward trend (Qiu et al. 2021), and that the eastern coastal cities and large cities have the highest level of green economic development (Du et al. 2022).

Studies have come to different conclusions on whether LCCPs improve the level of green economic development (Lo 2014; Sinn 2008; Song et al. 2019). Some show that low-carbon urban construction not only improves the environment by optimizing energy efficiency and consumption structure (Fang et al. 2022) but also may have positive externalities through industry transformation and upgrade and technological progress (Chen and Wang 2022; Yu et al. 2022), promoting agglomeration of new industries, and transformation and upgrade of high-energy-consumption industries. In general, LCCP exerts an impact on the development level of urban green economy from the aspects of economic, environmental, and social. In terms of the economic effects, at the micro level, LCCP can alleviate the financing constraints of enterprises, and improve the efficiency of capital allocation and total factor productivity of enterprises (Zhao et al. 2021). At the macro level, the reallocation efficiency and scale efficiency of urban production factors can be improved through the implementation of energy-saving and emission reduction measures (Zeng et al. 2023), and ultimately achieve urban green economic growth. In terms of environmental effects, LCCP can achieve sustained energy conservation and emission reduction effects by establishing a low-carbon industrial system as well as by promoting the optimization and upgrading of industrial structure (Song et al. 2019). In terms of social effects, on the one hand, the construction of low-carbon cities will improve the city's ecological infrastructure system, provide green public goods for urban residents, and significantly increase the level of green consumption (Cao and Gao 2021; Zeng et al. 2023). On the other hand, LCCP induces green technology innovation effects by stimulating enterprises to apply for energy-saving and alternative energy patents (Qu et al. 2023). Green technology advances induced by LCCP will diffuse and spill over through innovation networks locally and between cities due to the existence of network spaces (Zhu and Lee 2022). However, the hypothesis that low-carbon urban construction positively impacts the green economy remains controversial. Although the sustainable energy industry develops rapidly during the process, cities with this industry are not "strongly decoupled" from CO_2

emissions; 89% are still "weakly decoupled" or "not decoupled." This result indicates that the current urban economic development model is still dependent on energy production and consumption (Shan et al. 2021; Shi et al. 2022), which is not conducive to green economic development.

As far as we know, there are several limitations in the existing literature on low-carbon pilot city policies and green economic development. On the one hand, few studies have emphasized the spatial spillover effects of environmental policies on green economic development, especially the low-carbon pilot city policy. The implementation of low-carbon policies could not have a consistent impact on other regions, but have a decaying effect as a certain spatial relationship weakens. On the other hand, few studies have simultaneously integrated technological progress, industrial transformation, and green consumption to comprehensively analyze the theoretical mechanisms of urban low-carbon governance affecting green economic development. As far as these are concerned, using multi-period and spatial difference-in-difference (DID) models, this paper will use data on 271 cities in China from 2004 to 2019 to comprehensively examine the impact of three batches of low-carbon urban construction on green economic development.

Policy background and hypotheses

Policy background

Since 2006, China has been the largest contributor to global carbon emissions (Fu et al. 2021; Ortega-Ruiz et al. 2022), and emissions have been increasing year by year as its economy expands. Its emissions reached 9894 MT in 2020, accounting for 30.7% of the world's total (BP 2021), with urban emissions accounting for 75% of that total (Wang et al. 2021). This reality has put China under tremendous social and international pressure to address the trade-offs and coordination between carbon emissions and economic growth. In response, the Chinese government has developed a series of carbon emission reduction policies, as shown in Fig. 1.

At the Copenhagen Climate Conference in 2009, the Chinese government set a carbon intensity target to reduce its emissions per unit of GDP in 2020 by 40–45% from 2005. In order to achieve that target, it began to gradually implement the LCCPs (Fig. 2). In January 2010, the Ministry of Housing and Urban–Rural Development established national low-carbon eco-demonstration city in Shenzhen, and in July of that year in Wuxi. That same July, the National Development and Reform Commission (NDRC) also identified five provinces and eight cities as the first batch of low-carbon pilots. In 2011, in the 12th Five-Year Plan to Control Greenhouse Gas Emissions, the State Council proposed LCCPs to control greenhouse gas emissions. Specifically, the pilot cities should not only promote research, demonstration, and industrialization of low-carbon technology, but also actively use it to transform and upgrade their traditional industries. The second and third groups were identified in 2012 and 2017, respectively, with a total of 81 pilot cities, accounting for a quarter of all prefecture-level cities. These two groups had higher requirements than the first group of pilots for setting emission reduction targets

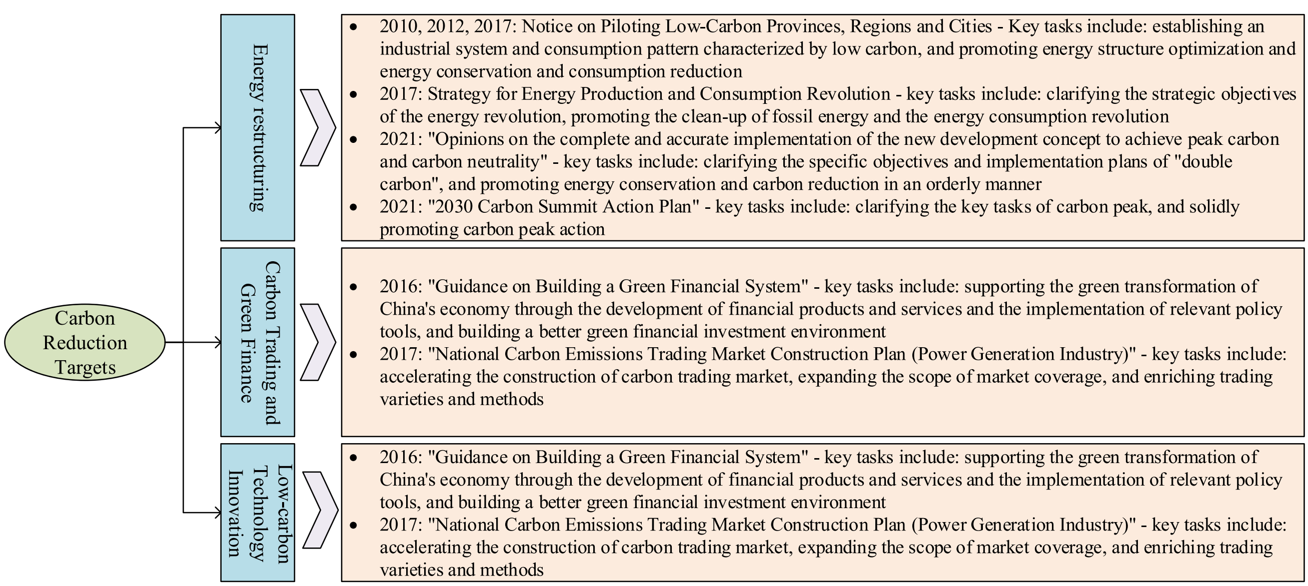

Fig. 1 Major policies related to carbon reduction in China

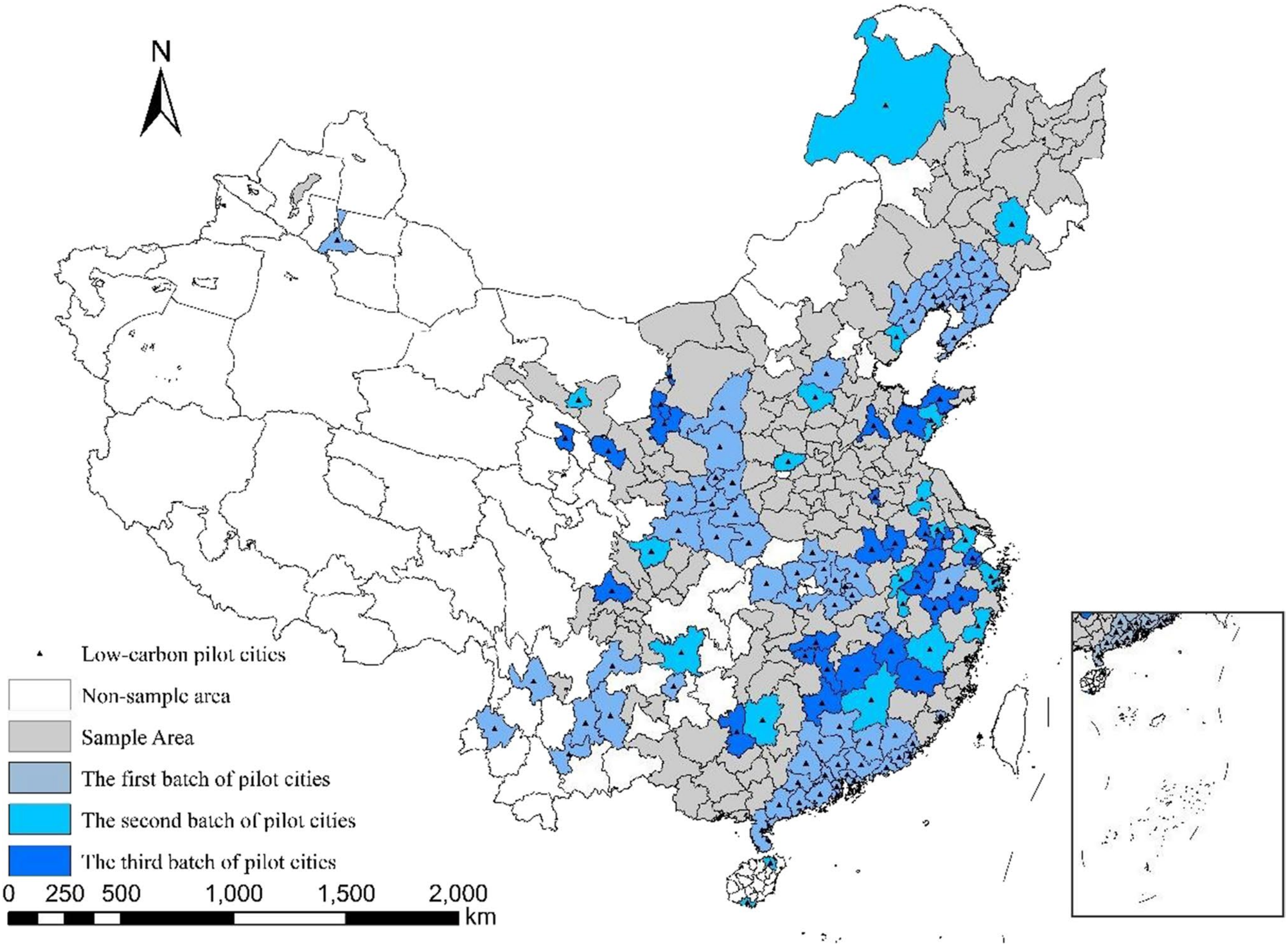

Fig. 2 Distribution of the three batches of low-carbon pilot cities

and implementing the Target Responsibility System (TRS) for emission control (Li et al. 2018).

Basic assumptions

The influence mechanisms of LCCPs on green economic development

Environmental regulation is an important way to achieve green economic development (Mahmood et al. 2022; Zhao et al. 2022). As a comprehensive environmental regulation tool, LCCPs can achieve green economic development through command-and-control, public participation, and market incentive roles (Wang and She 2020). The influence mechanism of LCCPs on green economic development is shown in Fig. 3. Specifically, the pilot cities can obtain financial and institutional support from the central and local governments during the implementation period, stimulating business to carry out green technological innovation, making breakthroughs in low-carbon industries, and accelerating green technological progress (Chen and Wang 2022). These steps can promote industry transformation and energy structure optimization and adjustment in the pilot cities, indirectly enhancing their green economic development (Du et al. 2021; Pan et al. 2022). At the same time, the carbon reduction targets impose hard constraints, increasing the operating costs of energy-intense and highly-polluting businesses, forcing them to improve their development and application of green technologies, shift to cleaner production models, or exit from the industry (Porter and Linde 1999). Meanwhile, incentive-based policy support such as subsidies and low-interest loans to businesses with low energy consumption and low pollution production helps accelerate factor flow and absorb high-quality factor resources, thus bringing their comparative advantages into play. By helping rationalize industry structure in the pilot cities, the policy supports the formation of efficient industrial chains and specialized green

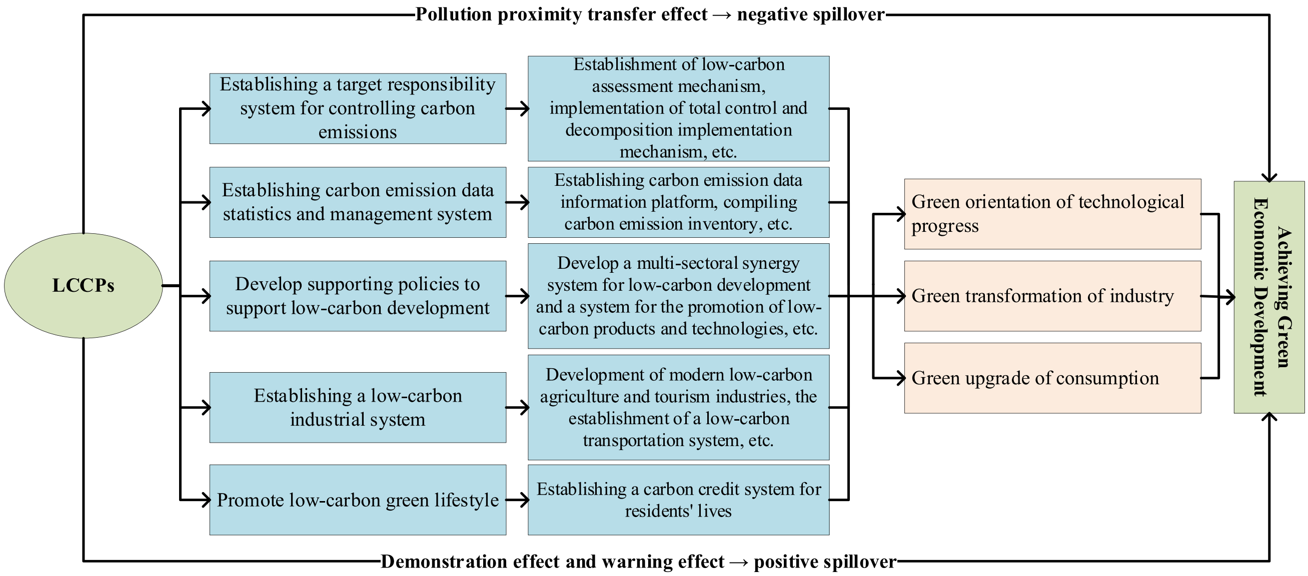

Fig. 3 Influence mechanism of LCCPs on urban green economic development

industrial systems (Chen and Wang 2022), helping cities eventually transform their production and operating models from crude to intensive, thus promoting the green economy. Accordingly, the following hypothesis is proposed.

H1: LCCPs promote green urban economic development.

According to Porter's hypothesis, reasonable and strict environmental regulations can stimulate the "innovation compensation" effect, helping promote low-carbon technology upgrade, compensating for the "environmental regulation compliance cost," improving the competitiveness of businesses, and promoting their sustainable development. Under the rigid constraint of carbon reduction and growing demand for green living in the pilot cities, on the one hand, the traditional bottom-up competition of crude development will not be accepted by the market or the government. The market vacancy for green products will attract more foreign investment related to clean technology, and stimulate local businesses to carry out low-carbon technological innovation and clean production, thus promoting development of a regional green economy (Duan and Shi 2021). On the other hand, LCCPs provide more market information for businesses to reduce the uncertainty of technological innovation by establishing low-carbon innovation mechanisms (Qiu et al. 2021). The substantial government support greatly enhances the willingness of market innovation agents to produce green products, thus improving innovation capacity and overall green economic urban development. Accordingly, the following hypothesis is proposed.

H2a: LCCPs promote green economic development through development of green production processes and enhancement of green orientation of technological progress.

Under low-carbon governance, local governments minimize use of non-renewable energy, and businesses implement cleaner production models and improve energy efficiency. Specifically, from the perspective of long-term economic efficiency, LCCPs improve businesses' factor allocation, reducing factor inputs to inefficient sectors, increasing them to efficient sectors, and increasing output per unit of energy (Qiu et al. 2021). From the perspective of overall social benefits, they improve resource utilization efficiency through direct guidance of production factors from low-productivity to high-productivity businesses (Qian et al. 2018). At the same time, local governments can encourage development of renewable clean energy industries such as solar, wind, and hydropower energy, and coordinate ecological civilization construction and economic growth. In other words, society can accelerate green industrial transformation by reducing the energy consumption per unit of output value, or increasing the output value per unit of energy, to promote energy usage efficiency to ultimately achieve green economic development (Cao and Gao 2021). Accordingly, the following hypothesis is proposed.

H2b: LCCPs promote green economic development by optimizing energy use efficiency and accelerating green transformation of industry.

The concept of carbon conservation in China has changed from government leadership to universal participation, and awareness of low-carbon consumption has increased. All of society is increasingly advocating for the values of economic, green, and low-carbon consumption, and the public is gradually discarding the values of extravagant, wasteful, and high-energy consumption (Mao and Xie 2019). In 2010, the NDRC issued a notice proposing to "promote the use of low-carbon products and the concept of low-carbon life." At the same time, against the background of huge losses brought by crude development at the expense of the environment, demand for a green life is increasing as people's living conditions improve and the concept of sustainable development becomes more popular. Implementation of LCCPs may further enhance awareness of green consumption, such as by advocating low-carbon dining, curbing food waste, advocating low-carbon living, popularizing water-saving appliances, and advocating for green and low-carbon travel methods. These steps will help promote green upgrade of consumption, reduce the intensity of lifestyle pollution, and promote the green urban economy (Cao and Gao 2021). Accordingly, the following hypothesis is proposed.

H2c: LCCPs promote green economic development through the concepts of low-carbon life and green upgrade of consumption.

Spatial spillover effects

Low-carbon pilots and similar policies tend to have spatial spillover effects due to technological spillover and interregional economic linkages (Jia et al. 2021). In the context of rapid development of the digital economy, businesses or industries with relative comparative advantages will absorb high-quality production factors between regions (such as high-level human resources, innovation, and entrepreneurial capital) (Xu and Sun 2020), which is also known as the "siphon effect." At the same time, efficient industry chains and specialized green industry systems will be formed within the region (Chen and Wang 2022), not only improving its green economic development, but also bringing significant impact to neighboring cities. Specifically, on the one hand, the policy will certainly promote upgrade of the local industrial structure and eliminate industries with high investment, energy consumption, and pollution, or transfer them to surrounding areas, resulting in a so-called pollution paradise effect (Cole et al. 2017). The relocation of polluting industries not only expands their scale in neighboring cities, but also deepens the pollution level of local industry structures, thus producing negative spillover effects. In other words, even though local green economic development is improved, it may be to the detriment of neighboring cities. On the other hand, by promoting local industrial structure upgrade and technological innovation, the pilot policy also has a "demonstration effect" and "warning effect" on neighboring cities (Du et al. 2022). In other words, those cities will strengthen their investment in innovative energy-saving technologies through learning and imitation, and use regulatory tools to improve their green economic development. The interactions between neighboring cities lead to a convergence effect on green economic development. Accordingly, the following hypothesis is proposed.

H3: LCCPs have spatial spillover effects on green economic development in neighboring cities.

Methodology

Econometric models

Multi-period double difference model

Since three batches of LCCPs have been implemented since 2010, the inconsistent timing of the treatment group's acceptance of the policy pilot made it difficult to apply traditional DID. With reference to Beck et al. (2010) and Cao and Gao (2021), this paper constructs the following multi-period double difference model to assess the impact of successive LCCPs on urban green economic development.

$$GED_{it} = \alpha + \beta LCCP_{it} + \delta X_{it} + \upsilon_t + \gamma_i + \varepsilon_{it} \tag{1}$$

In the above Eq. (1), i indicates city and t denotes year; GED_{it} is the outcome variable and refers to the green economy growth of city i in year t; the key variable $LCCP_{it}$ is a dummy variable used to identify the pilot policies of low-carbon cities. Specifically, $LCCP_{it}$ is the product of the dummy variable $treat_{it}$ and the dummy variable $reform_{it}$. If city i implements the LCCP, the value of $treat_{it}$ is 1, and 0 otherwise. $reform_{it}$ is the dummy variable and is assigned the value of 1 if the LCCP has been implemented, and 0 otherwise. In order to control the influence of time-varying factor characteristics of cities on the green economy development of cities, a series of control variables X_{it} are selected. υ_t is the year fixed effect, γ_i represents city fixed effects, and ε_{it} denotes the random error term. The multi-period double difference model allows the differences in characteristics and temporal trends between pilot and non-pilot cities to be effectively controlled.

Our DID framework can address the endogeneity problem caused by measurement error and omitted variable bias. The coefficient of interest, β, captures the net impact of China's $LCCP_{it}$ on GED_{it}. Specifically, a negative and significant β denotes that the $LCCP_{it}$ reduces GED_{it}, which confirms the green economic development effect of the $LCCP_{it}$. Contrastingly, a positive and significant β implies that the $LCCP_{it}$ is effective in enhancing GED_{it}. Furthermore, an insignificant β suggests that the $LCCP_{it}$ fails to affect GED_{it}.

Dual difference spatial econometric model

Since urban economic activities often have spatial and temporal effects such as "siphoning" and "spillover," it is assumed that urban green economic development has similar effects. Given this, this paper will further use a dual difference spatial econometric model to evaluate the effect of LCCPs. The advantage of using the dual difference spatial econometric model is that it can explore the effect of LCCPs from a new perspective. It also enables to decompose the direct and indirect effects of the policy and discuss and assess the spatial spillover effects of the policy (Cao and Gao 2021; Sunak and Madlener 2016).

In this paper, drawing on the treatment of related literature (Chagas et al. 2016), a spatial weight matrix is introduced on the traditional DID model to construct a dual difference spatial econometric model, and the model form is set as follows.

$$\begin{aligned} GED_{it} &= \beta LCCP_{it} + \rho\omega_i' GED_{it} \\ &+ \theta\omega_i' LCCP_{it} + \delta_1 X_{it} + \delta_2 \omega_i' X_{it} \\ &+ \upsilon_t + \gamma_i + (1-\lambda\omega_i')^{-1}\varepsilon_{it} \end{aligned} \tag{2}$$

In the above Eq. (2), $\rho\omega_i' GED_{it}$ is the spatial lag term of the dependent variable to test whether there is a spillover effect of "promoting or inhibiting" the level of green economic development among cities. Then, for the consideration of economic exchanges and factor flows among provinces, the spatial cross-multiplication term $\theta\omega_i' LCCP_{it}$ of the key variable $LCCP_{it}$ is added to test how the LCCPs of one city affect the green economic development of other cities. Among them, ρ is the spatial autocorrelation coefficient of the dependent variable, θ is the policy spillover effect, ω_i' is the spatial weight matrix, and this paper adopts two spatial weight matrices generated based on the geographical distance of cities and gravity model, δ_2 is the spillover effect of the control variable, λ is the spatial autocorrelation coefficient of the random error, and the rest of variables have the same meaning as Eq. (1).

Variable selection

Explained variable: green economic development

GED is an important criterion in the new normal economy to measure regional economic development. Considering the increasing rigidity of environmental constraints on economic development, the efficiency of green development based on an input-output perspective has become the key to GED. Based on the relevant literature (Dong et al. 2022; Guo and Liang 2022), this paper determines input-output indicators for evaluating urban green economic development by combining urban economic activity in urban areas with data availability. The super-efficient non-radial and non-angle SBM model is then used to measure GED. The GED output indicator measures the total value added by economic activity. Therefore, GDP is chosen as the desired output. To eliminate the effect of price factors, GDP was adjusted to constant 2000 prices using the GDP deflator. Three major urban pollutants were selected as undesired outputs of GED: urban industrial wastewater, industrial sulfur dioxide, and industrial soot emissions. According to the relevant theories, the main input indicators for urban economic activity are as follows: (1) labor input, measured by employee count (expressed as the sum of public sector, private, and self-employed employees). (2) Energy input, which mainly includes natural gas and LPG for direct energy consumption, and electricity consumption for indirect consumption. Due to non-uniformity in units, energy consumption was converted into standard coal units. (3) Capital input, measured by fixed asset investments in the current year. Specifically, borrowing from Han and Cheng (2020), 2004 was chosen as the historical base period, and the perpetual inventory method was used to measure the capital stock using the following formula.

$$K_{it} = (1-\varphi)K_{i(t-1)} + I_{it}/P_{it} \tag{3}$$

where K_{it} denotes the capital stock of city i in period t, φ is the depreciation rate, I_{it} denotes the nominal fixed asset investments in city i in period t, and P_{it} denotes the fixed asset investment price index in city i in period i. Price indices of each city were used as fixed asset investment deflators. Regarding the depreciation rate φ, this paper refers to Zhang's measurement of 9.6% (2004). Assuming that the average rates of fixed asset capital stock growth and fixed asset depreciation are equal, the formula for measuring the capital stock, with 2004 as the base period, is as follows.

$$K_{2004} = \frac{I_{2004}}{g_i + \varphi} \tag{4}$$

where I_{2004} and φ are the nominal fixed asset investment amount and depreciation rate in 2004, respectively. g_i is the average annual growth rate of fixed asset investment amount in constant prices in city i during the period under examination.

Core explanatory variable: the low-carbon city pilot policy

The list of the three batches of pilot cities was obtained from successive Circulars on National Low-Carbon City Pilot Work issued by the NDRC, as follows. The first batch was in 2010 and covered five provinces and eight cities; the second was in 2012 and covered Hainan Province and 28 cities; and the third was in 2017 and covered 45 cities. This paper does not consider counties and regions of municipalities directly under central government administration, nor non-prefecture-level cities. At the same time, for the case of duplication among the three batches of pilot cities, this paper draws on the approach of Song et al. (2019). If a province is a low-carbon pilot province, the cities under its jurisdiction are also pilot cities. The earliest time of policy approval is used as the time of pilot implementation time for that city. Therefore, for pilot cities, LCCP takes the value of 1 from the year of policy implementation on, otherwise, it is 0; for non-pilot, it is always 0.

Control variables

With reference to relevant literature (Dong et al. 2022; Li and Wang 2019), the following controls are selected. ① The degree of fiscal decentralization (Fiscal), expressed as the ratio of revenue to expenditure within the general local budget, which may affect the strength of policy implementation, and thus indirectly affect GED. ② Infrastructure development (Infras), which is the basis of urban economic activity. Sound infrastructure, expressed in terms of road area per capita, improves the operational efficiency of urban systems, reduces social and economic operating costs, facilitates the efficient allocation, and use of urban resources, and enhances green economic development. ③ Foreign investment (FDI), expressed as the ratio of actual foreign investment used in the year to GDP, may improve the investment structure of cities, increase the efficiency of factor use, and promote green development. ④ Education level (EDU), expressed as the ratio of the number of secondary school students to the area's total population, reflects public environmental literacy and a city's ability to cultivate talent. More education is conducive to conscious improvement of low-carbon concepts and behaviors, which increases public participation and enthusiasm for green and low-carbon environmental protection, thereby improving a city's GED. ⑤ Urbanization level (Urban), expressed as the logarithm of population density, on the one hand will increase total energy consumption and pollution, but on the other, will improve the efficiency of the urban sector through the population agglomeration effect, which is conducive to GED. ⑥ Social security level (Security), expressed as the number of hospital beds per capita, which reflects public demand for a healthy life. Security can motivate people to actively pursue a better environment and actively participate in environmental construction.

Mediating variables

① Green orientation of technological progress (Tech), expressed by the number of green patent applications in each city, with reference to Bendig et al. (2023), Fan et al. (2023), and Acemoglu et al. (2001). ② Green industrial transformation (Industry), expressed as total added value of output per unit energy consumed, considering that the more output per unit of energy consumption, the higher the degree of product greening (Wei et al. 2011). ③ Green upgrade of consumption (Consumption), expressed by the ratio of carbon emissions of urban residents' living[1] to gross domestic product (i.e., the carbon emission intensity of urban residents' living), considering that the carbon emission intensity of urban residents' living reflects the green upgrading of consumption, with reference to Cao and Gao (2021), Lenzen et al. (2004), and Liu and Xu (2022).

Data sources

The sample of this paper is panel data on 271 prefecture-level cities in China from 2004 to 2019. Considering the administrative level of some cities and the problem of missing data, the sample does not include municipalities directly under central government administration (Beijing, Tianjin, Shanghai, and Chongqing) or regions such as Hong Kong, Macao, Taiwan, or Tibet. The relevant data are obtained from the China City Statistical Yearbooks, China City Construction Statistical Yearbooks, China Regional Economic Statistical Yearbooks, statistical yearbook of each city, and national economic and social development statistical bulletins. City-level data related to carbon dioxide emissions are obtained from China Carbon Accounting Databases (CEADs). Drawing on Yu et al. (2019), data on green patents are obtained from the National Intellectual Property Database, and are matched with the international patent classification green list of WIPO. Linear interpolation was for missing individual data points. The descriptive statistics of the variables are shown in Table 1.

[1] Considering the availability of data, the carbon emissions of urban residents' living mainly include electricity consumption, gas consumption, transportation, and heating. The detailed calculation is shown in the Appendix Table 9.

Table 1 Descriptive statistics of the variables

Variable	Obs	Mean	Std. Dev	Min	Max
GED	4336	0.3301	0.1303	0.0100	1.0902
LCCP	4336	0.2103	0.4002	0.0000	1.0000
Fiscal	4336	0.4701	0.2301	0.0600	1.5402
Infras	4336	2.6204	0.4702	0.0214	4.1003
FDI	4336	0.0200	0.0200	0.0151	0.2003
EDU	4336	0.0600	0.0200	0.0100	0.3902
Urban	4336	5.7401	0.8803	1.3902	7.8802
Security	4336	38.8113	17.6325	3.5103	141.0000
Tech	4336	407.1251	1293.2671	12.0148	26,243.4613
Industry	4336	1.3201	0.6302	0.2302	3.1502
Consumption	4336	0.4312	0.2354	0.0423	4.6820

Empirical results

Spatial pattern analysis of GED

The years following the implementation of the first and third batches of policies were selected as time nodes, with comparable time intervals. Using the natural breakpoint method, the ArcGIS 10.8 software classified the GED of the 271 cities into high, medium, and low categories (shown in Fig. 4). As shown in Fig. 4, Chinese cities were basically at a low level of GED in 2004. The distribution of high values was scattered, mainly in Sanya, Haikou, Zhongwei, Tianshui, Jiayuguan, and Lijiang. Other cities such as Hefei (ranked 201st), Zhuhai (ranked 216th), Yancheng (ranked 187th), and Zhuzhou (ranked 264th) were ranked low. A reasonable explanation is that those cities mostly emphasized economic development in the early days, yet due to their relatively rapid economic development at the time, problems such as insufficient coordination of industrial structure, a heavy-duty internal structure in the secondary industry, and slow pace of industrial structure upgrade kept appearing, hindering upgrade of GED (Zhong 2004). The high-GED cities in 2011 and 2018 were still scattered, but the number of medium-level cities increased significantly, concentrated on the east and southeast coast, which is related to each city's natural resource endowment and economic growth bias. In recent years, under policy guidance for industry transformation and upgrade, the eastern and southeastern coastal cities became more economically developed and technologically advanced. The increasing maturity of their development model also synchronized and coordinated their economic environment. The central region has also been significantly improved its GED, but its industry structure is less diversified than the eastern cities, and it is more dependent on coal and other resources (Luo and Wang 2017). The sloppy resource-based development model is not conducive to improvement of GED. In the western region, the fragile environment, coupled with lagging low-carbon technology, has led to decreasing rather than increasing GED trend.

Baseline estimation result

The command-based and incentive-based instruments in LCCPs have helped reduce urban pollution, but their effects on economic growth are still debatable. To evaluate their effects, this paper compares GED before and after the policies based on a quasi-natural experiment method. Furthermore, the estimation bias arising from individual heterogeneity is mitigated using multi-period LCCPs. The results are shown in Table 2. Column (1), with no controls, shows that the estimated coefficient of LCCPs was significantly positive, indicating that the LCCPs significantly improve GED. Columns (2) to (7) of Table 2, adding control variables in turn, show that the coefficient of LCCP remained significantly positive, indicating that the LCCPs increase GED effectively. This result is consistent with Porter's hypothesis and Chen and Wang's (2022) findings, verifying hypothesis H1.

The regression coefficients show that compared to the non-pilot cities, GED in the pilot cities increased by about 1% over the policy implementation period. Since this paper captures the policy effect over 10 years, this result implies that LCCPs increased GED by about 0.1% per year. This further demonstrates that the performance of the national pilot low-carbon policy is evident, largely achieving the expected economic and environmental objectives, significantly contributing to the development of the city in a green and high-quality direction. In addition, the regression coefficients containing control variables all decrease to different degrees, which indicates reasonable selection of control variables. The coefficients of Fiscal, EDU, Urban, and Security were significantly positive, and FDI was significantly negative. These results indicate that moderate government intervention, high-quality educational resources, urbanization, and more social security are all conducive to GED. However, while foreign investment improves investment structure and technological level, it may also cause technological dependence and a "pollution paradise" effect, which is detrimental to green development. The effect of infrastructure construction was not significant.

Robustness tests

Expected effect test

The premise of the approved low-carbon city pilot as a quasi-natural experiment is the randomness of the low-carbon pilot policy, to prevent biased assessment of the quasi-natural experiment due to excessive subjectivity.

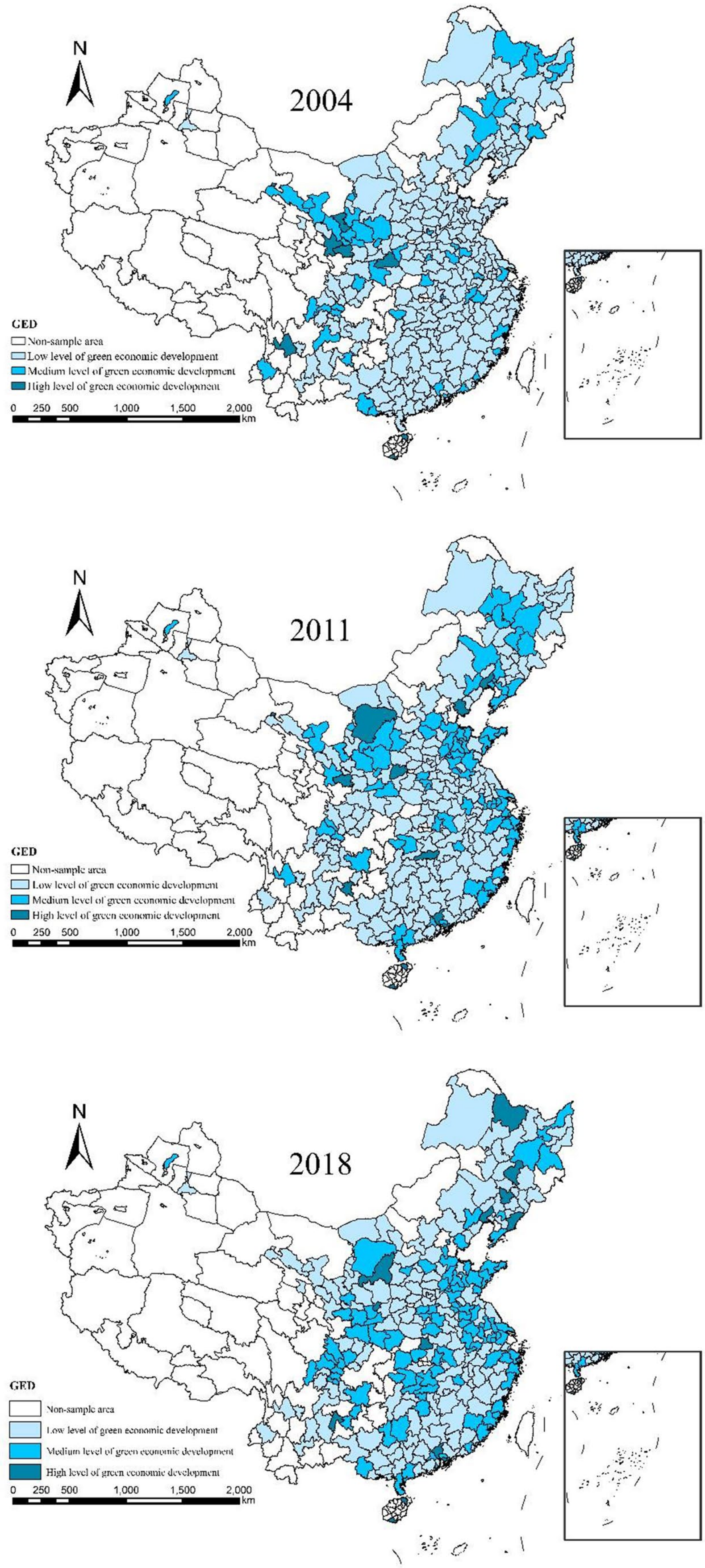

Fig. 4 Spatial evolution of urban GED in 2004, 2011, and 2018

Table 2 Baseline regression

Variable	GED						
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
LCCP	0.0171***	0.0173***	0.0162***	0.0142***	0.0154***	0.0141***	0.0101**
	(3.60)	(3.53)	(3.39)	(3.05)	(3.06)	(3.04)	(2.06)
Fiscal		0.0593***	0.0610***	0.0653***	0.0662***	0.0664***	0.0564***
	–	(3.36)	(3.44)	(3.67)	(3.70)	(3.72)	(3.24)
Infras			0.0121**	0.0113**	0.0122**	0.0110**	0.0052
	–	–	(2.35)	(2.20)	(2.30)	(2.17)	(1.05)
FDI				−0.2551**	−0.2603**	−0.2392**	−0.2371**
	–	–	–	(−2.45)	(−2.50)	(−2.30)	(−2.63)
EDU					0.1900	0.2202*	0.5634***
	–	–	–	–	(1.60)	(1.85)	(4.67)
Urban						0.0541***	0.0522***
	–	–	–	–	–	(4.14)	(4.11)
Security							0.0034***
	–	–	–	–	–	–	(11.97)
Constant	0.3231***	0.2951***	0.3264***	0.3272***	0.3390***	0.0304	−0.0551
	(210.96)	(34.66)	(20.70)	(20.77)	(19.46)	(0.39)	(−0.73)
City effect	YES	YES	YES	YES	YES	YES	YES
Time effect	YES	YES	YES	YES	YES	YES	YES
N	4336	4336	4336	4336	4336	4336	4336
Adj. R^2	0.6702	0.6711	0.6713	0.6724	0.6722	0.6732	0.6841

*, **, and *** denote 10%, 5%, and 1% significance levels, respectively, and *t* values are in parentheses

Table 3 Robustness tests

Variables	Expected effect test	Mitigating serial correlation test	Controlling for the impact of disturbance policies	One-period lag of control variables	PSM-DID	Intensity-based DID
	(1)	(2)	(3)	(4)	(5)	(6)
LCCP	0.0112** (2.30)	0.0260*** (70.05)	0.0094** (20.02)	0.0101** (2.13)	0.0119** (2.56)	0.0140*** (3.05)
Expected effect test	−0.0018 (−0.21)	–	–	–	–	–
ICPP	–	–	0.0399*** (6.88)	–	–	–
Control variables	YES	YES	YES	YES	YES	YES
City effect	YES	YES	YES	YES	YES	YES
Time effect	YES	YES	YES	YES	YES	YES
N	4285	4288	4285	4018	4280	4285
Adj. R^2	0.687	0.857	0.691	0.699	0.688	0.687

*, **, and *** denote 10%, 5%, and 1% significance levels, respectively, and *t* values are in parentheses

Therefore, this paper refers to Lu and Yu (2015) to test for the expected effects of the policy shock of approval. Specifically, an expected effect test is conducted by introducing a dummy variable for the year prior to the policy shock into the baseline model. The results in column (1) of Table 3 show that the estimated coefficient of the key variable LCCP is still significantly positive, but the coefficient of the expected effect test is not significant, indicating no significant expected effect before the policy shock of being approved as a low-carbon pilot city.

Mitigating serial correlation

Although the multi-period DID above effectively identifies the average effects generated by multiple policy shocks using multi-period data, it may also generate serial correlation as a result, causing overestimation of the policy implementation effect (Cao and Gao 2021). Therefore, drawing on the existing literature, this paper divides the study sample into two intervals using the time of the first batch of approvals in 2010 as the cut-off point. The averages of the variables in the intervals are then taken for two-period DID to mitigate the estimation bias arising from serial correlation. The results in column (2) of Table 3 show that the estimated coefficients of the key variable LCCP are still significantly positive, indicating that the findings of the benchmark regression are robust.

Controlling for the impact of disturbance policies

Drawing on Cao and Gao (2021), interfering policy dummy variables are introduced into the benchmark model to control for the impact on GED. Yu et al. (2022) showed that Innovative Cities Pilot Policies (ICPPs) significantly improved urban energy efficiency and promoted GED, both economically and statistically. ICPPs were conducted four times during the sample interval of this paper. Therefore, a new policy variable was constructed for ICPP, assigned a value of 1 for the year in which the city was first approved for the ICCP and after, otherwise 0, then the variable was added to the baseline regression model. Column (3) of Table 3 shows that ICCPs contributed to GED, indicating that ignoring the policy role of ICPPs when assessing the effect of LCCPs would lead to overestimating the effect of the latter. However, it is worth noting that the policy effect—the coefficient of LCCP—remains significantly positive, which still supports the baseline conclusion.

One-period lag of control variables

The control variables selected in the baseline regression model were lagged by one period to mitigate the estimation bias caused by a possible inverse relationship between them and LCCP approval. Column (4) of Table 3 shows that the coefficients of the key variable LCCP remain significantly positive, indicating that the findings of the baseline regression are robust.

PSM-DID method

In order to reduce model endogeneity and policy assessment bias, this paper also used propensity score matching (PSM) to verify the robustness of the results of the DID method. The main steps of PSM are as follows. First, OLS regression was used to calculate the scores, where GED is the independent variable and Fiscal, Infras, FDI, EDU, Urban, and Security were used as covariates. Second,

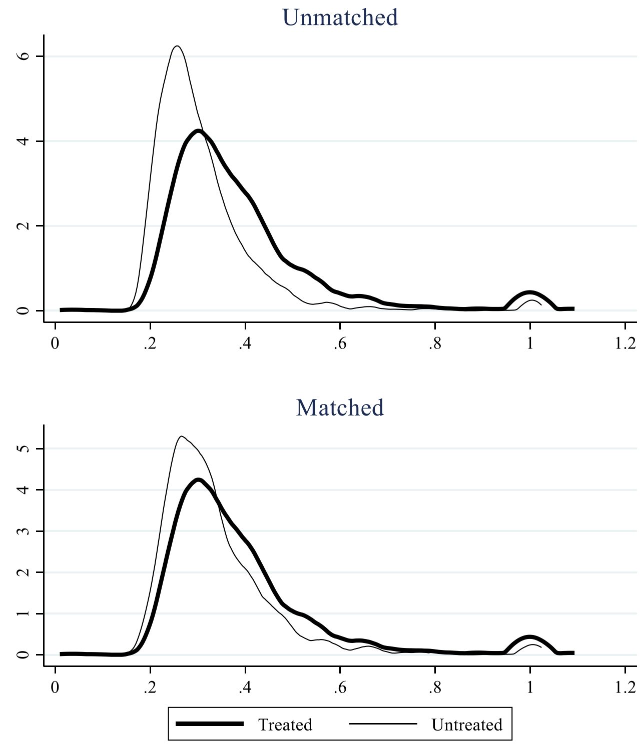

Fig. 5 Kernel density distribution before and after PSM between the experimental and control group

kernel density matching was used, and data points that failed to match the experimental group were excluded. As shown by the kernel density distribution before and after matching the experimental and control groups (Fig. 5), the matched samples passed the multicollinearity test, satisfying the premise of the PSM-DID model, and indicating no significant difference between the matched samples. Column (5) of Table 3 demonstrates the estimated PSM-DID results, indicating that the estimated coefficient of LCCP remains significantly positive, further supporting the baseline results.

Intensity-based DID

Some cities were approved repeatedly between the three batches of LCCPs. The previous section only aligned cities' years of repeated approvals with their provinces. Specifically, in the first and subsequent years of approval, LCCP was assigned 1, without considering the differences in policy implementation intensity between repeatedly approved cities and others. Therefore, intensity DID was further used, reassigning the value of the key variable LCCP according to the total number of approvals. The results in column (6) of Table 3 show that its coefficient remained significantly positive.

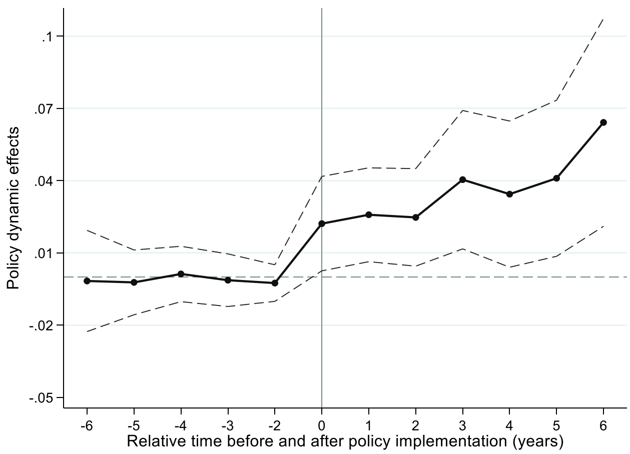

Fig. 6 Parallel trend test

Parallel trend test

A parallel trend test was used to confirm the applicability of DID in policy analysis (Beck et al. 2010). Another possible reason for the significant contribution of LCCPs to GED is it was improving in the pilot cities before the policies were implemented, which would bias the assessment of policy effects.

Therefore, this paper will conduct a parallel trend test through the following model to obtain a purer treatment effect. The policy effects of the pilots are obtained using changes in the coefficients of the core explanatory variables.

$$GED_{it} = \alpha + \sum_{n=-6}^{6} \beta_n LCCP_{it} + \delta \sum X_{it} + \upsilon_t + \gamma_i + \varepsilon_{it} \quad (5)$$

where n denotes the number of years from the policy implementation year (2010, 2012, or 2017). This test examines the dynamic treatment effect in the year of policy implementation and the 6 years before and after. The core explanatory variable is $LCCP_{it}$, and the other variables have the same meaning as in Eq. (1).

The results of the test are shown in Fig. 6. The regression coefficients of the policy dummy variables for each year before the policy implementation did not deviate significantly from 0, indicating no significant difference in GED between pilots and non-pilot cities. Furthermore, after the policy implementation, the coefficients of most years are significantly greater than 0, indicating that the DID model in this paper is consistent with the parallel trend hypothesis and can be used in subsequent studies. It is worth emphasizing that the coefficients do not have a significant upward trend in the 2 years after the policy implementation, but do after 2 years, indicating a certain lag in the effect (Song et al. 2019). The promotion effect is strengthened over time (Fig. 6). From this, it can be inferred that the LCCP is an important cause of the divergence in green economic development dynamics between pilot and non-pilot cities, i.e., the LCCP has contributed to the development of urban green economy.

Placebo test

To explore whether the baseline regression results are affected by the change in pilot time and pilot city selection bias, a placebo test is conducted by randomly setting pseudo-treatment groups and pseudo-policy timing. Based on Cao and Gao (2021) and Zeng et al. (2023), the specific approach is as follows. Firstly, the cities with the same number of samples as the actual pilot sample were randomly and non-repeatedly selected from the 271 samples as the treatment group, and the remaining cities were the

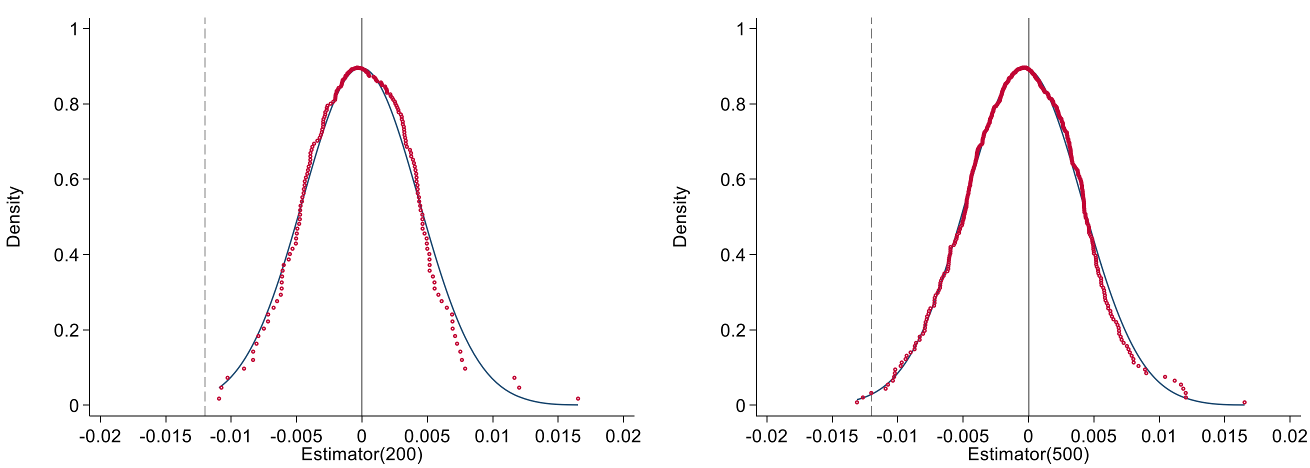

Fig. 7 Placebo test

Table 4 Heterogeneity test

Variables	East (1)	Central (2)	West (3)	South (4)	North (5)	Q10 (6)	Q25 (7)	Q50 (8)	Q75 (9)	Q90 (10)
LCCP	0.0283* (1.98)	0.0762* (5.33)	0.0013 (0.23)	0.0133*** (11.08)	0.0193*** (2.43)	0.0128* (1.71)	0.0184*** (2.74)	0.0192** (2.30)	0.0332** (2.27)	0.0513* (1.78)
Constant	−0.2944 (−1.40)	0.5638*** (3.97)	−0.1448 (−0.74)	0.4116*** (3.50)	0.1118 (1.25)	0.0369 (0.54)	−0.0342 (−0.36)	0.0819 (0.67)	−0.085 (−0.33)	0.4789 (0.91)
Control variables	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES
City effect	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES
Time effect	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES
N	1536	1902	847	2384	1952	4336	4336	4336	4336	4336
Adj. R^2	0.853	0.586	0.554	0.742	0.549	0.154	0.270	0.323	0.227	0.1212

① *, **, and *** denote 10%, 5%, and 1% significance levels, respectively, and *t* values are in parentheses

② Quantile estimation was implemented using the xtrifreg command of the Stata software. q10, q25, q50, q75, and q90 are five representative quartiles

control group. Second, the randomly selected treatment groups are corresponded to the years of pilot policy implementation to obtain the dummy policy variable $LCCP_r$. Finally, the variable $LCCP_r$ is substituted into Eq. (1) for regression. The probability distributions of the estimated coefficients of the $LCCP_r$ for the treatment groups based on 200 and 500 random sampling settings are shown in Fig. 7.

After 200 and 500 random samples, in terms of the magnitude of the regression coefficients, the mean values of the estimated coefficients of the $LCCP_r$ are much smaller than the absolute value of the benchmark regression − 0.0101 ($P<0.01$). The mean sign of the regression coefficients of the $LCCP_r$ shifts to positive with the increasing number of regressions, and the distribution pattern of regression coefficients shows that the estimated coefficients of the false-policy variable are distributed around 0, and approximating to a normal distribution (Fig. 7). Therefore, the benchmark results pass the placebo test, indicating that no serious variables are omitted in the benchmark model setting, and the benchmark estimation results are robust and reliable with little influence from the time series and pilot city selection bias.

Analysis of heterogeneity

Heterogeneity of urban location In order to prevent overall analysis of the sample from ignoring spatial heterogeneity, affecting the analysis of LCCP effect, this paper will examine the effects of policy pilots in eastern, central, and western cities. Regional comparisons and heterogeneity tests are also conducted for southern and northern cities. Columns (1)-(3) of Table 4 show results of the heterogeneity tests for the eastern, central, and western cities. The estimated LCCP coefficient is significantly positive in the eastern and central cities. The coefficient value is higher for central cities and insignificant in the west. Meanwhile, a test based on the seemingly unrelated regression (SUR) model is used for coefficient difference analysis. The results show that the *p* value of the coefficient difference test between the eastern and central regions is $0.0780<0.1$, the central and western regions is $0.0657<0.1$, and the eastern and west regions is $0.0140<0.1$, all of which are significant at the 10% level. These results indicate that the effect of LCCPs on GED differs significantly between the eastern, central, and western regions (specifically, central > eastern > western)—indicating that the central region has received more dividends from the policy. A reasonable explanation is that the early economic growth in the eastern region gave it stronger political status or economic influence, which caused early release of GED dividends through green technology advancement and improvement of factor usage efficiency. The central region, on the other hand, had a late-stage advantage, giving LCCPs more potential to promote GED. The policies were ineffective in western cities, which are more backward in economic growth and environmentally fragile.

Columns (4)-(5) of Table 4 show the heterogeneity test results for southern and northern cities. The coefficients of LCCP are significantly positive for both, and the values are larger for northern cities. Meanwhile, the SUR model is used for coefficient difference analysis. The results show that the *p* value of the coefficient difference test between the southern and northern regions is $0.0886<0.1$, which is significant at the 10% level. These results show that the effect of pilot policies on GED differs significantly between the northern and southern regions, indicating that LCCPs have a stronger contribution to green economic development in northern cities. On the one hand, this effect may arise from differences in residents' lifestyles. Northern cities have four distinct seasons, and demand for heating in winter makes pollution more serious there, causing the public and the government to demand environmental

Table 5 Instrumental variable regression results

Variables	First-stage return (1) LCCP	Second-stage return (2) GED
IV	0.0390*** (3.36)	–
LCCP	–	0.6066*** (2.94)
Control variables	YES	YES
City effect	YES	YES
Time effect	YES	YES
N	4336	4336
Adj. R^2	0.6224	–
Kleibergen-Paap rk LM	0.0044***	–
Kleibergen-Paap rk F	11.27	–

*, **, and *** denote 10%, 5%, and 1% significance levels, respectively, and t values are in parentheses

improvement more strongly. Thus, northern cities respond more actively to the policy, making its effect more significant. On the other hand, from the perspective of social production structure, the north has a more industrial economic structure than southern cities, and economic growth is often accompanied by high-energy consumption and high pollution, especially in areas richer in resources such as coal and oil (Luo and Wang 2017). Therefore, there is more room to enhance green development in the northern cities, and the effect of pilot policies is more significant.

Heterogeneity of GED stratification levels An unconditional fixed effects panel quantile regression was conducted for the specified variables, borrowing from Borgen (2016). The results (columns (6)-(7) of Table 4) show the significantly positive estimated coefficients of LCCP at different quartiles, with an increasing trend as the quantiles increased, indicating that the promotion effect of LCCPs shows an increasing marginal trend with increasing GED. Therefore, low quantile cities should pay more attention to developing environmentally friendly economic models in the pilot city construction process in order to release dividends from the policy.

Instrumental variable method

In order to avoid possible endogeneity caused by the bidirectional causality between pilot city selection and GED, the instrumental variable approach was further employed to check the robustness of the baseline regression model (Table 5). The basic criterion for an instrumental variable is that it is related to the explanatory variable (pilot policies) but has no direct and explicit effect on the explained variable (GED). Based on those principles, as well as data availability, this paper selects green space in urban parks as an instrumental variable. On the one hand, green area in parks can show that a city has a strong level of green demand and awareness. To a certain extent, this indicates that the city has stronger political status and economic influence than the neighboring cities, so the probability of being approved as a pilot is higher, satisfying the correlation. On the other hand, green space in parks is mainly planned by the government, and is related to natural conditions such as urban geology and topography, which do not directly affect GED, satisfying the exogeneity condition. The results in Table 5 show that the IV is significantly and positively associated with the critical policy variable LCCP in the first-stage regression. The value of the F statistic is greater than the critical value of 10, indicating no weak identifiability problem. The Kleibergen-Paap rk LM statistic corresponds to a p value of $0.0044 < 0.01$, passing the under-identification test. In the second-stage results, the coefficient of LCCP is significantly positive, which indicates that the positive effect of LCCP policies on GED remains robust after alleviating the endogeneity problem.

Mechanism analysis

Given that LCCPs significantly improve GED, how is this effect achieved? In order to examine the mechanism of the effect, this paper adds two recursive models to Eq. (1) to build a mediating effect model.

$$M_{it} = \alpha + \beta LCCP_{it} + \delta X_{it} + \upsilon_t + \gamma_i + \varepsilon_{it} \tag{6}$$

$$GED_{it} = \alpha + \beta LCCP_{it} + \sigma M_{it} + \delta X_{it} + \upsilon_t + \gamma_i + \varepsilon_{it} \tag{7}$$

where M_{it} denotes the mediating variables, specifically including green orientation of technological progress (Tech), green transformation of industry (Industry), and green upgrade of consumption (Consumption); the rest of the variables have the same meaning as in Eq. (1). The β in Eq. (1) indicates the total effect of LCCP policy on GED, while in Eq. (6) it indicates the effect of LCCPs on the mediating variables. In Eq. (7) it denotes the direct effect of LCCPs on GED after controlling for the effects of the mediating variables, while σ denotes the effect of the mediating variables after controlling for the effects of the other variables.

The mediating effects were tested and analyzed using the Sobel test and bootstrap method, shown respectively in Tables 6 and 7. The results all show that the effect of the three mediating variables is significant—that is, the mediating effect holds. Specifically, as shown in columns (1), (3), and (5) of Table 6, LCCP has a significant positive effect on Tech, Industry, and Consumption, indicating that it significantly enhances green orientation of technological progress, accelerates green industrial transformation, and promotes

Table 6 Sobel test for influence mechanisms

Variables	Tech (1)	GED (2)	Industry (3)	GED (4)	Consumption (5)	GED (6)
LCCP	0.5105*** (11.35)	0.0395*** (8.33)	0.4405*** (22.90)	0.0201*** (4.11)	0.0612*** (10.32)	0.0547*** (10.27)
Tech	–	0.0119*** (7.51)	–	–	–	–
Industry	–	–	–	0.0558*** (15.29)	–	–
Consumption	–	–	–	–	–	0.0413** (2.34)
Control variables	YES	YES	YES	YES	YES	YES
City effect	YES	YES	YES	YES	YES	YES
Time effect	YES	YES	YES	YES	YES	YES
N	4249	4249	4285	4285	4285	4285
Adj. R^2	0.6501	0.1964	0.4029	0.2202	0.2765	0.1973
Percentage of intermediary effect	13.36%		55.01%		2.35%	

*, **, and *** denote 10%, 5%, and 1% significance levels, respectively, and *t* values are in parentheses

Table 7 Bootstrap test of impact mechanism

Variables		Intermediary effect	Estimated coefficient	Standard error	95% confidence interval	Intermediary effect
(1)	Tech	Indirect	0.0064615***	0.0012405	(0.0040302, 0.0088928)	13.50%
		Direct	0.0413997***	0.0054921	(0.0306355, 0.0521639)	
(2)	Industry	Indirect	0.0253412***	0.002048	(0.0213272, 0.0293552)	53.36%
		Direct	0.0221526***	0.0054992	(0.0113744, 0.0329308)	
(3)	Consumption	Indirect	0.0017112**	0.000742	(0.0003115, 0.0028766)	3.55%
		Direct	0.0464273***	0.005565	(0.034517, 0.0569841)	

** and *** indicate 5% and 1% significance levels, respectively; bootstrap sampling number is 1000

green consumption upgrade. Columns (2), (4), and (6) of Table 6 show the results of the policy variables and mediating variables on the GED, showing significantly positive coefficients of both—indicating that LCCPs improved GED through green transformation of industry and green consumption upgrade. Meanwhile, the Sobel and bootstrap tests show the same results for proportion of mediating effects in the total effect, about 13%, 55%, and 3%, respectively for Tech, Industry, and Consumption—thereby verifying hypotheses H2a, H2b, and H2c.

Spatial spillover effect analysis

The global Moran's *I* index was used to test the spatial correlation of GED. The results are shown in Fig. 8. The Moran indices are all greater than zero, and the *p* values are significant in most years, which initially indicates the existence of spatial correlation. Therefore, it is necessary to use the spatial econometric model to further analyze spatial dependence. Meanwhile, the *p* values of both the LM and LR tests in Eq. (2) were less than 0.05, rejecting the original hypothesis. Finally, a mixed fixed effect spatial Durbin model (SDM) was used, while the results of the spatial autoregressive (SAR) model were added to Table 8 for comparison. Since the SDM model is more realistic and has a high degree of fit, this paper will focus on its results.

The explained variable in Table 8 is GED, and the main explanatory variable is LCCP. The geographic distance spatial weight matrix (W1) and gravitational spatial distance weight matrix (W2) were selected as spatial weight matrices. The following conclusions can be drawn based on the results in Table 8. First, the LCCPs significantly promote regional GED. The coefficients of LCCPs are significantly positive at the 1% level in the estimations of columns (1)-(4) in Table 8. Furthermore, the absolute magnitudes are consistent with the baseline regression findings, generally between 0.012 and 0.017, further verifying the robustness of the findings. Second, LCCPs significantly

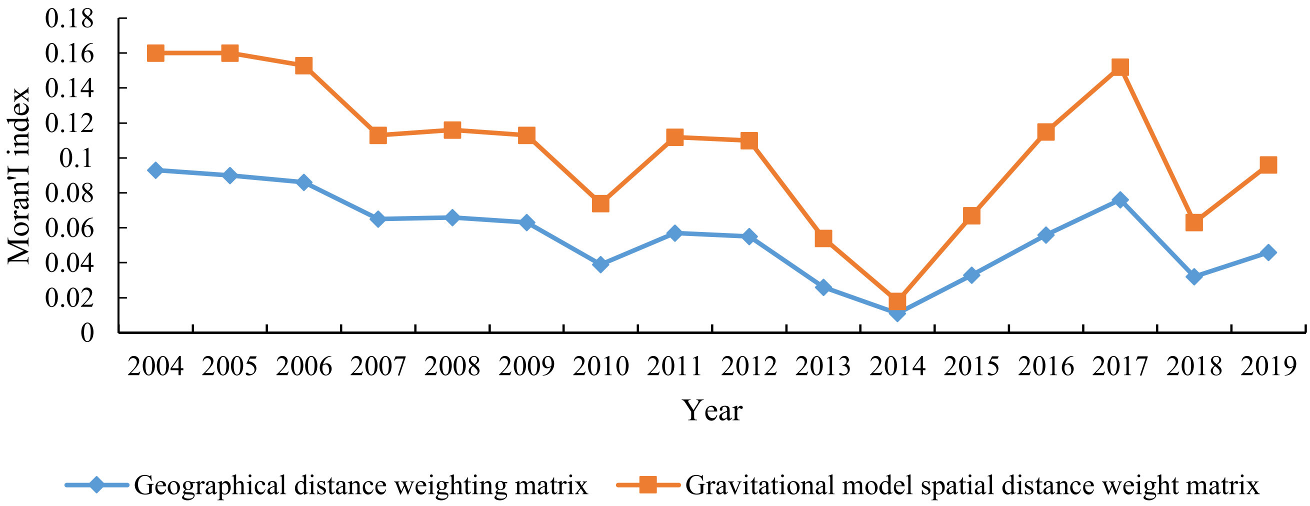

Fig. 8 Moran index distribution of green economic development (GED)

Table 8 Spatial DID regression results

Variables	SAR-DID (W1) (1)	SAR-DID (W2) (2)	SDM-DID (W1) (3)	SDM-DID (W2) (4)
LCCP	0.0162*** (3.47)	0.0201*** (4.44)	0.0124*** (2.60)	0.0174*** (3.71)
W* LCCP	–	–	0.0533*** (4.54)	0.0331*** (3.39)
Direct effect	–	–	0.0142*** (3.09)	0.0194*** (4.03)
Indirect effects	–	–	0.0962*** (5.75)	0.0522*** (4.37)
Total effect	–	–	0.1110*** (6.34)	0.0721*** (5.57)
Control variables	YES	YES	YES	YES
W* control variables	YES	YES	YES	YES
rho	0.4620***	0.3203***	0.4141***	0.2964***
sigma2_e	0.0061***	0.0062***	0.0060***	0.0063***
Log-likelihood	4435.2419	4369.7291	4445.5647	4375.4733
N	4336	4336	4336	4336
Adj. R^2	0.3179	0.3145	0.3455	0.3373

① *, **, and *** denote 10%, 5%, and 1% significance levels, respectively, and *z* values are in parentheses

contribute to GED in surrounding areas. The regression coefficient W*LCCP for the spatial spillover effect of LCCPs is significantly positive at the 1% level in columns (1)-(4) of Table 8, indicating that the impact of the policy on green economic development is reflected not only in the intra-city promotion effect, but also in the dimension of inter-city interaction. In other words, pilot policies have a positive externality effect on neighboring cities' green economic development, initially verifying hypothesis H3. Third, there is a significant positive spatial spillover effect. In columns (1)-(4) of Table 8, the spatial autoregressive coefficient rho of GED is significantly positive at the 1% level, indicating that green economy growth in neighboring cities positively contributes to regional growth, which further indicates a significant positive spatial dependence for green economic development, and verifies the necessity of spatial analysis. This conclusion verifies the findings of Chen and Wang (2022) and Du et al. (2022) on spatial green economic development spillover.

Further drawing on Elhorst (2010), the spatial spillover effect of LCCPs is decomposed by partial differential decomposition, specifically into direct and indirect effects. The direct effect is the impact of the policy in the city. The indirect effect is the spatial spillover effect, which is the impact of the policy in the surrounding areas, which this section focuses on. The indirect results show that LCCPs have a significant positive impact on neighboring cities' GED, further verifying hypothesis H3. This implies that pilot cities encourage their neighbors to improve their green development through a demonstration effect, such as by imitating and learning from pilot cities regarding technological innovation and eliminating inefficient production capacity. In addition, from the overall effect decomposition, the indirect effects of the policies are larger than their direct effects. This may be related to the sample's clustering of pilot cities in the spatial dimension. In other words, the city cluster effect makes the spatial policy spillover more significant. At the same time, urban agglomeration accelerates the flow of factors between cities, causing a phenomenon of free-riding between cities, and further deepening spatial dependence between them. This result also suggests that regional synergistic governance may be somewhat better than implementation of a single pilot policy, which is consistent with findings such as Zhang and Cao (2022).

Appendix

Table 9

Table 9 The calculation method of carbon emissions from urban residential life and the related explanation

Classification of carbon emission sources	Calculation formula	Instruction
Electricity consumption	$CE_i = AC_{1i} \times EF_{1\alpha}$	AC_{1i} represents the residential electricity consumption of city i, $EF_{1\alpha}$ represents the carbon emission factor of the city's grid. α takes a value range of 1–6 to represent the six regional grids in China
Gas consumption	$CG_i = AC_{2i} \times NVI_2 \times EF_2$ $+AC_{3i} \times NVI_3 \times EF_3 \times M_3$	AC_{2i} and AC_{3i} represent the household LPG and gas consumption in city i, respectively. NVI_2 and NVI_3 correspond to their calorific values respectively (0.06307 kg/MJ, 0.0561 kg/MJ). M_3 represents the density of gas (0.45 kg/m^3)
Transportation	$CT_i = \sum_n \times B_{ni} \times L_n \times \lambda_n \times \rho_n$	B_{ni} represents the number of buses ($n=1$), taxis ($n=2$), and private cars ($n=3$) in city i. L_n, λ_n, and ρ_n correspond to their annual travel miles, oil (gas) consumption coefficient, and CO_2 emission coefficient, respectively (2.314 kg/L)
Heating	$CH_i = S_i \times N_i \times EF_4$	S_i represents the heating space for the homes in city i (m^2). N_i represents the coal consumption of heating per unit area in city i (kg/m^2). EF_4 represents the carbon emission factor of standard coal (2.46 kg COz/kg)
Total	$C_i = CE_i + CG_i + CT_i + CH_i$	C_i represents the estimated value of carbon emissions from energy consumption of residents in city i

Conclusions and recommendations

In order to explore a new model of green urban development, the Chinese government organized three batches of low-carbon city pilots in 2010, 2012, and 2017. An accurate assessment of the impact of low-carbon city construction on green economic development has great significance for achieving economic growth with environmental protection, and building an ecological civilization and a beautiful China. Based on data on 271 cities in China from 2004 to 2019, multi-period and spatial difference-in-difference models were used to investigate the impact of the three batches of pilot policies on green economic development. The findings are as follows. (1) The LCCPs significantly improved green economic development in their respective cities, which remained significant under a series of robustness tests. Parallel trend tests also indicated that the boosting effect continued to strengthen over the policy implementation period. (2) Channel tests showed that low-carbon city construction mainly promoted green economic development through green technological innovation and green bias in product supply, and by enhancing residents' awareness of green consumption. (3) Heterogeneity tests showed that the promotion effect varied according to geographical location and the sub-level of green economic development. Specifically, it is stronger in central and northern cities, and those with high green economic development, than in western and southern cities, and those with low development. (4) The analysis of spatial spillover effects showed that low-carbon construction not only promoted green economic development in the pilot cities, but also exerted a demonstration effect on neighboring cities; this effect is greater in urban areas.

Accordingly, this paper makes the following recommendations. First, summarize the positive experiences of low-carbon cities and expand the scope of pilots. The construction of low-carbon cities improves the green economic development, and demonstrates that carbon governance is in line with the policy direction of high-quality national economic development. More cities should be encouraged to implement carbon governance and contribute to early realization of the strategic goal to reduce carbon emissions in developing countries. Second, the specific implementation path of low-carbon city construction is to promote green technological innovation and green bias in product supply, and enhance residents' awareness of green consumption. China should continue to strengthen support for green finance, introduce talent, and promote green technology to support research on innovative low-carbon technology, form a green industrial system, and deepen awareness of green consumption. Third, it should develop differentiated implementation programs based on cities' geographical location and economic development. Western and northern cities should focus on introducing technological innovation and green investment, and actively cultivate public awareness of environmental protection. Cities with less green development should accelerate the efficiency of their green low-carbon industrial development, narrow their gaps with high-level cities, and release the green economic development dividends of low-carbon city construction. Fourth, China should vigorously promote inter-city factor flow and sharing mechanisms to give full play to the spatial effect of low-carbon city construction and form green synergy between regions.

Author contribution Lina Peng: conceptualization, methodology, software, data curation, writing—original draft. Xiaohan Yan: methodology, software, Zhide Jiang: writing—review and editing. Zhenyu Yan: data curation, writing—original draft. Jiapeng Xu: supervision.

Funding This study is supported by Soft Science Research Project of Shaanxi Province (No: 2022KRM032), Soft Science Research Project of Shaanxi Province (No: 2023-CX-RKX-103), Social Science Foundation of Shaanxi Province (No: 2021D058), and Social Science Foundation of Shaanxi Province (No: 2022D022).

Data availability All data needed to evaluate the conclusions in the paper are present in the paper. Additional data related to this paper may be requested from the authors.

Declarations

Ethical approval "Not applicable" for that section.

Consent to participate "Not applicable" for that section.

Consent for publication "Not applicable" for that section.

Competing interests The authors declare no competing interests.

References

Acemoglu D, Aghion P, Violante GL (2001) Deunionization, technical change and inequality. Carn-Roch Conf Ser Public Policy 55:229–264

Beck T, Levine R, Levkov A (2010) Big bad banks? The winners and losers from bank deregulation in the United States. J Financ 65:1637–1667

Bendig D, Schulz C, Theis L et al (2023) Digital orientation and environmental performance in times of technological change. Technol Forecast Soc Chang 188:122272

Borgen NT (2016) Fixed effects in unconditional quantile regression. Stand Genomic Sci 16:403–415

BP (2021) BP Statistical Review of World Energy. London, June, 2021

Cao X, Gao Y (2021) Has the policy of low-carbon city pilot led to a green life? China Popul Resour Environ 31:93–103 (in Chinese)

Chagas ALS, Azzoni CR, Almeida AN (2016) A spatial difference-in-differences analysis of the impact of sugarcane production on respiratory diseases. Reg Sci Urban Econ 59:24–36

Chen L, Wang K (2022) The spatial spillover effect of low-carbon city pilot scheme on green efficiency in China's cities: evidence from a quasi-natural experiment. Energy Econ 110:106018

Cole MA, Elliott R, Toshihiro O et al (2017) The Pollution outsourcing hypothesis: an empirical test for Japan. Discussion papers

Dinga CD, Wen Z (2022) China's green deal: can China's cement industry achieve carbon neutral emissions by 2060? Renew Sustain Energy Rev 155:111931

Dong F, Li Y, Li K et al (2022) Can smart city construction improve urban ecological total factor energy efficiency in China? Fresh evidence from generalized synthetic control method. Energy 241:122909

DTI DoTaI (2003) UK Energy White Paper: our energy future-creating a low carbon economy, London: TSO

Du K, Cheng Y, Yao X (2021) Environmental regulation, green technology innovation, and industrial structure upgrading: the road to the green transformation of Chinese cities. Energy Econ 98:105247

Du M, Feng R, Chen Z (2022) Blue sky defense in low-carbon pilot cities: a spatial spillover perspective of carbon emission efficiency. Sci Total Environ 846:157509

Duan L, Shi D (2021) Technological innovation, market proximity, and China's industrial green development. Chin J Popul Resour Environ 19:1–11 (in Chinese)

Duffield JS, Woodall B (2011) Japan's new basic energy plan. Energy Policy 39:3741–3749

Elhorst JP (2010) Applied spatial econometrics: raising the bar. Spat Econ Anal 5:9–28

Fan F, Dai S, Yang B et al (2023) Urban density, directed technological change, and carbon intensity: an empirical study based on Chinese cities. Technol Soc 72:102151

Fang W, Liu Z, Surya Putra AR (2022) Role of research and development in green economic growth through renewable energy development: empirical evidence from South Asia. Renew Energy 194:1142–1152

Fernández E, Pérez R, Ruiz J (2011) Optimal green tax reforms yielding double dividend. Energy Policy 39:4253–4263

Fu Y, Ma Y, Liu Y et al (2008) Development patterns of low carbon economy. China Popul Resour Environ 3:14–19 (in Chinese)

Fu Y, He C, Luo L (2021) Does the low-carbon city policy make a difference? Empirical evidence of the pilot scheme in China with DEA and PSM-DID. Ecol Ind 122:107238

Gong X, Jiang L, Yu J (2022) More than reducing carbon emissions: low-carbon city construction and green economic growth. Financ Econ 5:90–104 (in Chinese)

Guo P, Liang D (2022) Does the low-carbon pilot policy improve the efficiency of urban carbon emissions: quasi-natural experimental research based on low-carbon pilot cities. J Nat Resour 37:1876–1892 (in Chinese)

Gurney KR, Kılkış Ş, Seto KC et al (2022) Greenhouse gas emissions from global cities under SSP/RCP scenarios, 1990 to 2100. Glob Environ Chang 73:102478

Han Z, Cheng X (2020) Measurement and analysis of R&D investment and innovation efficiency in China. Journal of Quantitative & Technical Economics 37:98–117 (in Chinese)

Huang H, Mo R, Chen X (2021) New patterns in China's regional green development: an interval Malmquist-Luenberger productivity analysis. Struct Chang Econ Dyn 58:161–173

Jia R, Shao S, Yang L (2021) High-speed rail and CO2 emissions in urban China: A spatial difference-in-differences approach. Energy Economics 99:105271

Lenzen M, Dey C, Foran B (2004) Energy requirements of Sydney households. Ecol Econ 49:375–399

Li S, Wang S (2019) Examining the effects of socioeconomic development on China's carbon productivity: a panel data analysis. Sci Total Environ 659:681–690

Li H, Wang J, Yang X et al (2018) A holistic overview of the progress of China's low-carbon city pilots. Sustain Cities Soc 42:289–300

Liu X, Xu H (2022) Does low-carbon pilot city policy induce low-carbon choices in residents' living: holistic and single dual perspective. J Environ Manage 324:116353

Liu Z, Dai Y, Dong C et al (2009) Low-carbon city: concepts, international practice and implications for China. Urban Dev Stud 16:1–7+12 (in Chinese)

Lo K (2014) China's low-carbon city initiatives: the implementation gap and the limits of the target responsibility system. Habitat Int 42:236–244

Lu Y, Yu L (2015) Trade liberalization and markup dispersion: evidence from China's WTO accession. Am Econ J Appl Econ 7:221–253

Luo N, Wang Y (2017) Fiscal decentralization. environmental regulation and regional eco-efficiency: based on the dynamic spatial Durbin mode. China Popul Resour Environ 27:110–118 (in Chinese)

Mahmood N, Zhao Y, Lou Q et al (2022) Role of environmental regulations and eco-innovation in energy structure transition for green growth: evidence from OECD. Technol Forecast Soc Chang 183:121890

Mao Z, Xie C (2019) Xi Jinping's important exposition on consumption economy: realistic basis, theoretical basis and main contents. Consum Econ 35:3–11 (in Chinese)

Moran D, Kanemoto K, Jiborn M et al (2018) Carbon footprints of 13 000 cities. Environ Res Lett 13:064041

Ortega-Ruiz G, Mena-Nieto A, Golpe AA et al (2022) CO2 emissions and causal relationships in the six largest world emitters. Renew Sustain Energy Rev 162:112435

Pan A, Zhang W, Shi X et al (2022) Climate policy and low-carbon innovation: evidence from low-carbon city pilots in China. Energy Econ 112:106129

Porter ME, Linde C (1999) Green and competitive: ending the stalemate. Harvard Bus Rev 28:128–129 (2)

Qamri GM, Sheng B, Adeel-Farooq RM et al (2022) The criticality of FDI in Environmental Degradation through financial development and economic growth: implications for promoting the green sector. Resour Policy 78:102765

Qian XS, Kang J, Tang YL et al (2018) Industrial policy, efficiency of capital allocation and firm's total factor productivity——evidence from a natural experiment in China. China Ind Econ 8:42–59 (in Chinese)

Qiu S, Wang Z, Liu S (2021) The policy outcomes of low-carbon city construction on urban green development: evidence from a quasi-natural experiment conducted in China. Sustain Cities Soc 66:102699

Qu F, Xu L, He C (2023) Leverage effect or crowding out effect? Evidence from low-carbon city pilot and energy technology innovation in China. Sustain Cities Soc 91:104423

Shan Y, Fang S, Cai B et al (2021) Chinese cities exhibit varying degrees of decoupling of economic growth and CO2 emissions between 2005 and 2015. One Earth 4:124–134

Shi B, Xiang W, Bai X et al (2022) District level decoupling analysis of energy-related carbon dioxide emissions from economic growth in Beijing, China. Energy Rep 8:2045–2051

Sinn HW (2008) Public policies against global warming: a supply side approach. Int Tax Public Finance 15:360–394

Song H, Sun Y, Chen D (2019) Assessment for the effect of government air pollution control policy: empirical evidence from "low-carbon city" construction in China. J Manag World 35:95–108+195 (in Chinese)

Sunak Y, Madlener R (2016) The impact of wind farm visibility on property values: a spatial difference-in-differences analysis. Energy Econ 55:79–91

Walangitang D, Page J (2012) A low carbon city action plan for one of China's low carbon pilot cities. EPJ Web Conf 33:05002

Wang Q, She S (2020) Green growth effect assessment of Chinese low-carbon pilot from the perspective of urban heterogeneity. Soft Sci 34:1–8 (in Chinese)

Wang Y, Fang X, Yin S et al (2021) Low-carbon development quality of cities in China: evaluation and obstacle analysis. Sustain Cities Soc 64:102553

Wei Y, Sun G, Li J (2011) Energy consumption and economic growth in China due to technological progress: a comparison of two phases (1953–1977 and 1978–2009). Resour Sci 33:1338–1345(in Chinese)

Xu Z, Sun T (2020) The Siphon effects of transportation infrastructure on internal migration: evidence from China's HSR network. Appl Econ Lett 28:1–5

Xue B, Lu C, Geng Y et al (2012) Practice and prospect of low carbon city development in China. Econ Geogr 32:51–56 (in Chinese)

Yang L, Li Y (2013) Low-carbon City in China. Sustain Cities Soc 9:62–66

Yu L, Zhang W, Bi Q (2019) Can environmental taxes force corporate green innovation? J Audit Econ 34:79–90

Yu Y, Chen X, Zhang N (2022) Innovation and energy productivity: an empirical study of the innovative city pilot policy in China☆. Technol Forecast Soc Chang 176:121430

Zeng S, Jin G, Tan K et al (2023) Can low-carbon city construction reduce carbon intensity?Empirical evidence from low-carbon city pilot policy in China. J Environ Manage 332:117363

Zhang Z, Cao H (2022) Quantitative assessment of the effects of the air pollution control policy in the '2+26' cities. China Popul Resour Environ 32:26–36 (in Chinese)

Zhang J, Wu G, Zhang J (2004) The estimation of China's provincial capital stock: 1952–2000. Econ Res J 10:35–44 (in Chinese)

Zhang J, Chang Y, Wang C et al (2018) The green efficiency of industrial sectors in China: a comparative analysis based on sectoral and supply-chain quantifications. Resour Conserv Recycl 132:269–277

Zhao Z, Cheng Z, Lv D (2021) Has the national low-carbon strategy increased companies' total factor productivity? A quasi-natural experiment based on the low-carbon city pilot. Ind Econ Res 6:101–115 (in Chinese)

Zhao X, Mahendru M, Ma X et al (2022) Impacts of environmental regulations on green economic growth in China: new guidelines regarding renewable energy and energy efficiency. Renew Energy 187:728–742

Zhong X (2004) The present situation and adjustment strategy of industrial structure distribution in Chinese central region are studied. Shanghai J Econ 11:14–22 (in Chinese)

Zhu C, Lee C-C (2022) The effects of low-carbon pilot policy on technological innovation: evidence from prefecture-level data in China. Technol Forecast Soc Chang 183:121955

Publisher's note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Springer Nature or its licensor (e.g. a society or other partner) holds exclusive rights to this article under a publishing agreement with the author(s) or other rightsholder(s); author self-archiving of the accepted manuscript version of this article is solely governed by the terms of such publishing agreement and applicable law.