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RESEARCH ARTICLE

Carbon emission reduction effect of innovative city pilot policies in China: based on the staggered difference-in-difference model

Yongchun Huang[1,2] · **Chen Zou**[1] · **Zi Ye**[1]

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Abstract

Environmental economics theory suggests that the technological effects of increased innovation capacity can drive stable economic growth and act as a major means to mitigate regional environmental pollution levels. Therefore, science and technology innovation is the key to achieving low-carbon and green development. This study examined the influence of China's Pilot Policy for Innovative Cities on greenhouse gas emissions and its operational mechanism. By employing both quantitative and qualitative approaches, we successfully examined the impact of the policy on the nation's carbon emissions peaks. The findings indicated that adopting an urban pilot policy can effectively decelerate the increase of carbon emissions in cities. Additionally, the policy had a more pronounced impact on emission reduction in major urban areas and provinces. A mechanism test revealed that the policy could help reduce urban carbon emissions by implementing various technological innovations and spatial intensification. The results of this research offer significant theoretical support for adopting urban pilot policies and encourage the advancement of eco-friendly growth in Chinese urban areas.

Keywords Innovative City Pilot Policy · Carbon emission reduction · Policy evaluation · Staggered DID method

Introduction

A report released by British Petroleum shows that China's carbon dioxide (CO_2) emissions increased from 7.7 billion tons to 9.8 billion tons between 2009 and 2019, with an average annual growth rate of approximately 2.4%. In 2020, China's carbon emissions increased by only 0.6% due to the pandemic; however, China is still one of the few regions in the world where carbon emissions are increasing. By 2020, China's share of total global carbon emissions had increased to 31%. The Chinese government has been pushing hard to develop a low-carbon economy under the dual pressures of a difficult domestic situation and international climate negotiations. Therefore, how to form a "production, life, and ecology" pattern that conserves resources, protects the environment, and achieves low-carbon and high-quality development has now become the top priority of President Xi Jinping's "ecological civilization construction."

The environmental economics theory suggests that technological innovation can reduce factor inputs per unit of output and lower costs per unit of output, leading to reduced pollutant emissions and higher levels of green development. At the same time, technological innovation may also stimulate economic growth while increasing the demand for energy-related products and services, leading to an increase in pollutants and a decline in environmental quality. However, both empirical studies and real-life situations suggest that science and technological innovation, especially green innovation, significantly impact the ecological environment (Cheng et al. 2023; Hu et al. 2023). The concept of ecological civilization proposes that science and technological innovation is an important driver of economic transformation and green development (Huang and Westman 2021). Therefore, science and technological innovation, as an important means of enhancing carbon emissions performance, provides a new impetus and direction for carbon emission reduction in China (Zhang et al. 2017).

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✉ Zi Ye
yezixuyi@hhu.edu.cn

[1] School of Business, Hohai University, No. 8 Focheng West Road, Jiangning District, Nanjing 211100, Jiangsu Province, China

[2] Institute of Social Sciences, Hohai University, Nanjing 210098, China

As a vital part of the development of a region or country, cities are the central vehicles for economic growth. Although the total area of cities only accounts for approximately 3% of the global land area, they are responsible for over a quarter of the world's greenhouse gas emissions. It is therefore important that scientific and technological innovation in cities is increased to achieve the "dual-carbon" goal in China (reaching peak carbon emissions before 2030 and achieving carbon neutrality before 2060) (Li et al. 2021). In response to the increasing importance of technological and scientific innovation in cities, the Chinese government promoted the development of an Innovative City Pilot Policy (ICPP). This aims to improve a city's innovation capacity and promote low-carbon technologies. The ICPP is a typical spatial example for studying the impact of urban innovation on the rate of carbon emissions. It is worth considering whether the ICPP is conducive to achieving carbon peaking. What are the main mechanisms by which they work? Despite the various initiatives launched, the mechanisms in place for developing scientific and technological innovations in cities are not fully understood. The objective of this study was to offer a thorough examination of the ecological impacts of the ICPP, the correlation between technological and scientific advancements, and the resulting decrease in carbon emissions in urban areas. This analysis can provide valuable guidance for expediting the attainment of peak carbon goals and establishing an innovative nation.

To assess the effects of the pilot policy on innovative cities, existing studies have focused on its innovation, economic, and ecological effects. First, many researchers have found that innovative cities can promote the concentration of scientific and technological expertise (Wang and Wu 2021). The ICPP can improve the efficiency of knowledge research, development, and transformation in cities (Zhang and Wang 2022), which, in turn, can effectively improve innovation (Li et al. 2022a; Guo and Zhong 2022). However, this innovation effect shows a marginally decreasing trend over time (Zhang et al. 2022). Other researchers found that ICPP can significantly and consistently improve firm innovation from a microfirm perspective (Gao and Yuan 2022). This enhancement effect mainly focuses on the quantity of firm innovation, whereas a positive impact on the quality of firm innovation is lacking (Wen et al. 2022).

Second, scientific and technological innovations are the primary driving forces of economic development. Related studies have found that the economic effects of the ICPP are mainly reflected in the fact that the policy can significantly promote factor mobility in cities (Caloghirou et al. 2021) and strengthen the quality of foreign direct investment (Feng et al. 2019). In addition, the ICPP can promote industrial structure upgrading (Rodríguez-Pose et al. 2021), accelerate green transformation (Wang et al. 2021), and ultimately achieve high-quality economic development (Feng et al. 2022).

Finally, with the continuous enrichment of Xi Jinping's ecological civilization, optimizing the ecological environment has gradually become a critical project for China's urban development (Liu et al. 2023a, 2023b; Zhou et al. 2023). As a national-level innovation policy, ICPP has attracted increasing attention from scholars owing to its ecological and environmental effects (Ding et al. 2022; Hu 2023). According to the theory of environmental economics, the technological effect of improvements in innovation capacity can drive stable economic growth and is the primary approach to alleviating regional environmental pollution (Chen et al. 2023; Hu et al. 2023). Studies have also confirmed that ICPP not only improves the level of innovation in cities but also contributes to enhancing green development. Li et al. (2021) showed that China's ICPP can reasonably promote urbanization and effectively mitigate the adverse effects on urban green development, especially by reducing environmental pollutants, such as PM2.5, making a significant impact. Yang et al. (2022) also suggested that innovative cities are more inclined to change toward a green economy, which can not only effectively reduce energy consumption, but also help promote urban green development.

The implementation of ICPP has been shown to significantly affect urban environmental improvement. This is also expected to contribute to a reduction in carbon emissions. Unfortunately, current literature does not provide sufficient information on the various mechanisms that influence the reduction of carbon emissions. The objective of this study was to analyze the effects of the ICPP on the carbon emission rate in 268 Chinese cities from 2002 to 2019. Using a staggered difference-in-difference (DID; also called double-difference) model, we identified various mechanisms that contribute to reducing carbon emissions. The innovations and contributions of this study are as follows. First, we constructed an intra-city production model, incorporated innovation policies into the city production function, and derived an analytical framework to assess the impact of innovation policies on carbon emissions. Second, the research viewpoint integrated the "dual-carbon" goal and ICPP to assess the carbon reduction impact of this experimental strategy and enhance the investigation of the environmental consequences of ICPP. Furthermore, this study employed a staggered DID approach to evaluate the overall impact of forward-thinking cities on reducing carbon emissions. It also examines the influence of ICPP on the rate of urban carbon emissions by considering factors such as energy conservation, technological advancement, industrial development, and population concentration.

Theoretical analysis and research hypotheses

The impact of innovative cities on carbon peaking

Drawing on a related study conducted by Zou et al. (2022), we constructed an intra-city production model, incorporated innovation policies into the city production function, and derived an analytical framework to assess the impact of innovation policies on carbon emissions. It was assumed that the production sector of city A mainly produces *a* products and requires input capital *K* and labor *L* in its production process, which are priced at *r* and *w*, respectively. The production process emits a certain amount of carbon dioxide, and the *a* product production function can be expressed as:

$$F_a\left(K_a, L_a\right) = K_a^{\gamma} L_a^{\delta},\ \ \text{s.t.}\gamma + \delta = 1 \tag{1}$$

This production segment is concerned only with the production costs in the production process. The constraint for minimizing the production cost of the *a* product under the given production conditions is

$$\begin{aligned} &\min c^a(r,w) = rK_a + wL_a \\ &s.t.F_a\left(K_a, L_a\right) = K_a^{\gamma}, L_a^{\delta} \end{aligned} \tag{2}$$

By constructing the first-order condition after the Lagrange equation, we obtain

$$\frac{K_a}{L_a} = \frac{\gamma w}{\delta r} \tag{3}$$

Combining the above three equations, the total production cost of product *a* can be calculated as

$$c^a(r,w) = K_a^{\gamma} L_a^{\delta}\left(\frac{\gamma w}{\delta} w\right)\left(\frac{\delta r}{\gamma w}\right)^{\gamma}, \text{s.t.}\gamma + \delta = 1 \tag{4}$$

assuming that the marginal cost of production of product *a* can be expressed as

$$mc^a(r,w) = \frac{\delta^{-\delta}}{\gamma^{\gamma}} r^{\gamma} w^{\delta} \tag{5}$$

To limit carbon dioxide emissions from the production of *a* products, city A must incorporate new technologies into its production process. It was assumed that the new technology increases production efficiency by scaling down capital and labor inputs in equal proportions, thus reducing CO_2 emissions per unit of product. If the proportional reduction in both capital and labor inputs after the introduction of the new technology is θ, city A's production function is transformed into the following equation:

$$A\left(K_a, L_a\right) == (1-\theta) K_a^{\gamma} L_a^{\delta}, \text{s.t.}\gamma + \delta = 1 \tag{6}$$

If we assume that the amount of carbon dioxide emitted when producing a unit of the *a* product in city A is fixed and is denoted as *e*, carbon dioxide emissions after the new technology is introduced can be expressed as

$$e = (1-\theta)^{1/\sigma} K_a^{\gamma} L_a^{\delta} \tag{7}$$

where σ denotes the coefficient of the relationship between the proportion of factor inputs and CO_2 emissions after the addition of the new technology, and satisfies $\sigma \in (0,1)$. Equation (7) can then be transformed into

$$1-\theta = e^{\sigma}\left(K_a^{\gamma} L_a^{\delta}\right)^{-\sigma} \tag{8}$$

Substituting Eq. (8) into Eq. (6), we get

$$A\left(K_a, L_a\right) == e^{\sigma}\left(K_a^{\gamma} L_a^{\delta}\right)^{1-\sigma}, \text{s.t.}\gamma + \delta = 1 \tag{9}$$

Governments should vigorously promote technological innovation to achieve low-carbon development. Green, low-carbon innovation may be essential for city A to use carbon-reducing technologies in the production process. However, investments in new technologies inevitably increase production costs. It was assumed that the increased technology input cost was proportional to the carbon emissions. To a certain extent, an enterprise's increased share of inputs can be regarded as the intensity generated by the government's technological innovation policy.

Therefore, assuming that the intensity of the government's policy to promote technological innovation is α, city A must increase the cost input of αe during the production process of product *a*. The constraint for minimizing the production cost of product *a* can then be adjusted as follows:

$$\begin{aligned} &\min c^a(r,w,\alpha) = rK_a + wLe_a + \alpha e \\ &s.t.F_a\left(K_a, L_a\right) = e^{\sigma}\left(K_a^{\gamma} L_a^{\delta}\right)^{1-\sigma}, \text{s.t.}\gamma + \delta = 1 \end{aligned} \tag{10}$$

By constructing the first-order condition after the Lagrange equation, we obtain

$$\frac{\sigma}{1-\sigma} \times \frac{a}{e} = \frac{\tau}{mc^a} \tag{11}$$

Assuming City A is in a perfectly competitive market, its total production cost would be equal to its total revenue. When the revenue coefficient of a unit product *a* is β, the following equation is obtained:

$$\beta a = mc^a a + \tau e \tag{12}$$

Average CO_2 emissions of city A (η) can be expressed as

$$\eta = \frac{e}{a} \tag{13}$$

By combining Eqs. (11), (12), and (13), the following equation is obtained:

$$\eta = \frac{\beta\sigma}{\alpha} \tag{14}$$

Among the variables, σ and β satisfy the following conditions: $\sigma \in (0,1)$ and $\beta > 0$. Therefore, from Eq. (14), we find that innovation policy intensity is negatively related to CO_2 emissions. The more certain the coefficient of product returns and the coefficient of the relationship between the proportion of production factors due to low-carbon technological inputs and CO_2 emissions are, the stronger the technological innovation policy pursued by the government, and the lower the CO_2 emissions. The results derived from the above model were consistent with this concept.

In a profit-oriented production sector, innovation captures more market share and maximizes profit. In the event of a market failure, market forces are not sufficient to motivate firms to invest in innovation. This manifests in two main ways. The first is knowledge market failure, which results from the inherent public nature of innovative knowledge (Zou et al. 2022). The public's favorable view of innovation knowledge (Aghion et al. 2016) may lead to more innovation and replicas of current innovations, inevitably inhibiting firms' incentives to innovate (Howell 2017). The second is the issue of externalities: when the market fails, appropriate external policies can stimulate incentives for low-carbon innovation and help firms reduce carbon emissions. Policies that address knowledge market failures are often referred to as low-carbon technology-push policies, whereas policies that address environmental externalities are often referred to as technology-demand-pull policies (Popp 2019).

Public resources and ambiguous property rights regarding the environment, especially carbon emissions, often induce cities to develop in a substandard or piecemeal manner during science and technology innovation. The ICPP plays a crucial role in guiding urban innovation development and is a significant aspect of the central government's top-down innovation policy. ICPP requires pilot cities to follow the principles of green and low carbon in promoting innovation development (Li et al. 2021). At present, both the national and regional authorities consider environmentally friendly and low-emission growth a crucial catalyst and guiding principle for advancing superior-quality urban areas (Du and Li 2022). For example, the relevant documents of ICPP explicitly include two indicators related to ecology and the environment: the percentage of days with air quality that meets or exceeds Grade 2 throughout the year and the comprehensive energy consumption per 10,000 Yuan GDP, which are used as assessment requirements.

However, from the viewpoint of the goals of innovative city construction, the construction of innovative cities is oriented toward realizing innovation-driven development and creating a friendly environment as a breakthrough to build a number of regional innovation centers with high innovation performance, good economic benefits, and excellent environmental quality. Pilot cities should consider the development of economic, social, and ecological environments simultaneously when enhancing their scientific and technological innovation capacities, particularly focusing on promoting an excellent human living environment and urban ecological construction through scientific and technological innovation. Examples include actively innovating in low-carbon technologies and strengthening the role of technological innovation in urban green production, transportation, building, and consumption.

Hypothesis 1: ICPP is conducive to reducing urban carbon emissions, thereby accelerating the achievement of carbon peaking.

Mechanisms inherent in innovative cities that influence carbon peaking

The ultimate goal of ICPP implementation is to improve the innovation capacity of cities and create innovative cities with global competitiveness, pushing China to the forefront of innovative countries (Li et al. 2022a, 2022b; Guo and Zhong 2022). Environmental economics theory suggests that the technological effect of increased innovation capacity is the main driver for mitigating regional environmental pollution levels (Lin and Ma 2022). On the one hand, the establishment of innovative cities will inevitably increase governmental pressure to regulate the green development of enterprises and, at the same time, strengthen incentive policies for green technology research and development (Borghesi et al. 2015). The resulting technological innovations and upgrades can enhance resource and energy utilization, optimize the production factor input structure, and decrease resource consumption per output unit, consequently reducing carbon emissions. On the other hand, end-of-pipe treatment of environmental pollutants is becoming increasingly effective as the technological level of "pollution control" in cities. In particular, advances in adsorption and decomposition technologies for industrial CO_2 emissions have enabled end-of-pipe defense against carbon emissions (Zhang et al. 2022).

Hypothesis 2a: ICPP can take advantage of the technological innovation effect and reduce carbon emissions during production.

Currently, approximately 70% of China's total carbon emissions are from industrial sources. According to Zeng and Zhao (2009), enhanced ecological quality can be achieved by optimizing industrial structure. Hence, the crucial role of enhancing the industrial framework through ICPP cannot be overstated when promoting environmentally friendly and sustainable urban development. The phased elimination and transfer of industries characterized by high pollution and high energy consumption can be achieved by vigorously developing new sectors prioritizing low energy consumption and low pollution, such as high-tech and contemporary productive service industries. However, carbon emissions from industrial production processes can be reduced through technological upgrades and transformation of the original polluting enterprises. Additionally, industrial structure upgrades have significant regional spillover effects and a double-positive effect on local and external environmental improvements (Zhang and Liu 2021).

Hypothesis 2b: ICPP can have an industrial upgrading effect and reduce carbon emissions in the industrialization process.

As a large developing country with a heavy industrial structure, coal-based energy consumption, and high-risk oil and gas supplies, the share of fossil fuels in China's primary energy consumption structure exceeds 80%. Therefore, the proposed dual-carbon target has a profound impact on China's existing energy structure. The construction of innovative cities can promote a gradual shift in the focus of urban technological innovation from technological transformation to technological creation and transfer. Energy savings and consumption reduction can be achieved through the technological transformation of energy-consuming equipment. Establishing innovative cities can also enhance the efficiency of producing, storing, and utilizing eco-friendly renewable energy sources like wind, hydrogen, and solar power. This can promote the diversification of the urban energy mix, improve the overreliance on fossil fuels in urban development, and continuously optimize the energy consumption structure.

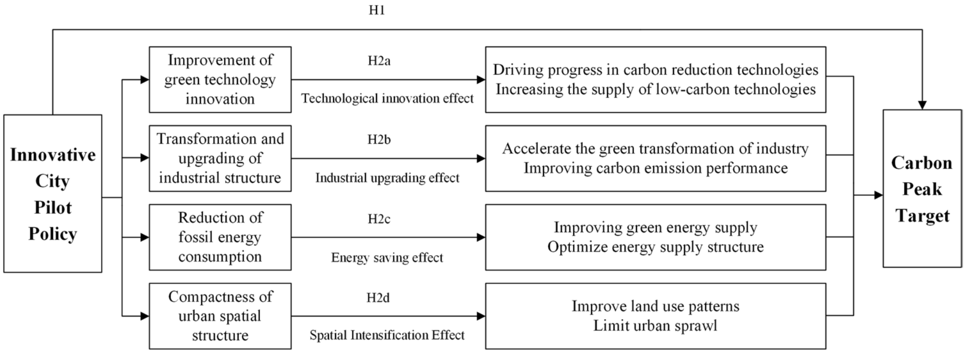
Hypothesis 2c: ICPP can have an energy-saving effect and reduce carbon emissions from fossil fuel consumption.

Numerous studies have shown that land use change is the second-largest source of carbon globally (Zhang et al. 2020). Improving land use and alleviating the current mismatch between land supply and demand must be addressed to achieve the dual-carbon goal. Among the various land-use types, urban construction has the most significant influence on carbon emission intensity (Milesi et al. 2003). Urban sprawl, which is mainly characterized by the expansion of urban construction land, increases the emissions of carbon and sulfur oxides, thus aggravating environmental pollution such as smog (Yuan et al. 2018; Feng and Wang 2020). As key organizational units for science and technology innovation, cities are the best implementation units for low-carbon projects (Florida et al. 2017), and their development patterns are particularly important for achieving carbon peak targets.

The concept of the construction of innovative cities clearly proposes relying on scientific and technological innovation to promote urban development and realize the shift from extensible expansion with an emphasis on quantity to connotative development with an emphasis on quality. The compact city form created by innovative cities can improve the efficiency of urban construction land use. This can not only give full play to the energy-saving effect of the agglomeration economy, but can also avoid the phenomenon of "double-high" enterprises moving to the edge of the city due to urban sprawl (MacDonald and Rudel 2005). Furthermore, innovative cities can not only promote a rational layout of the city's functional areas and avoid excessive separation of living, working, and other retail areas, but can also change the way people travel. This can reduce dependence on private cars by shortening commuting distances (Bento et al. 2006), thus reducing CO_2 emissions (Fig. 1).

Hypothesis 2d: ICPP can exert spatial intensification effects and reduce carbon emissions from over dispersed urban populations and industries.

Fig. 1 Analytical framework of the impact of ICPP on carbon peaking



Research design

As of 2020, China had established 74 innovative pilot cities. These cities created over 80% of the country's patent applications and developed more than 80% of its high-tech enterprises. Pilot cities have significantly improved their innovation capacity compared to those that did not implement the policy. Implementing ICPP provides a good quasi-experimental framework for examining the relationship between urban innovation development and a country's carbon emissions. This study was conducted in 268 Chinese cities between 2002 and 2019. The data collected during this period were used to analyze various aspects of China's innovation policy. Relevant municipal districts involved in ICPP and prefecture-level cities with missing data were excluded from the study, leaving 59 innovative pilot cities (Fig. 2). Based on this, we applied a staggered DID model to quantitatively assess the impacts of ICPP on carbon emission rates, explore the underlying impact mechanisms, and define the regional and city-type heterogeneity of these impacts.

Method design

Considering the implementation of ICPP as a quasi-natural experiment, this study estimated the impact of innovative city building on carbon emissions performance using staggered DID methods, taking advantage of the variation across cities in the timing of pilot program initiation (see Fig. 2). The staggered DID method is commonly used for policy evaluation (Zhou et al. 2021; Chen 2023). In this approach, the treatment group consisted of forward-thinking pilot cities selected based on the timing of policy implementation, whereas the control group comprised prefecture-level cities that had yet to adopt pilot policies. To assess the impact of ICPP on the rate of carbon emissions, the disparity between the pilot and control groups was analyzed before and after the policy implementation. Therefore, the double-difference in this study comes from the city and temporal levels, comparing the carbon emission performances of innovative pilot and non-pilot cities before and after policy implementation. According to a study conducted by Chen et al. (2023), this model can be described as follows.

$$RCO_{2it} = \alpha_0 + \alpha_1 Pilot_i{}^{*} Post_t + \rho X_{it} + \delta_i + \mu_t + \varepsilon_{it} \quad (15)$$

where RCO_{2it} is the carbon emission growth rate of city i in year t, and $Pilot_i$ is a dummy variable for the ICPP. Combined with the characteristics of batch-wise innovation city piloting, if a prefecture-level city becomes an innovation city pilot, it takes a value of one; otherwise, it takes a value of zero. $Post_t$ is a time dummy variable for the pilot innovation cities. If a city is piloted as an innovative city in a certain year, the city takes the value of 1 in that year and thereafter, and 0 before. X_{it} is the control variable; δ and μ are the city and time fixed effects, respectively; and ε_{it} is the random error term.

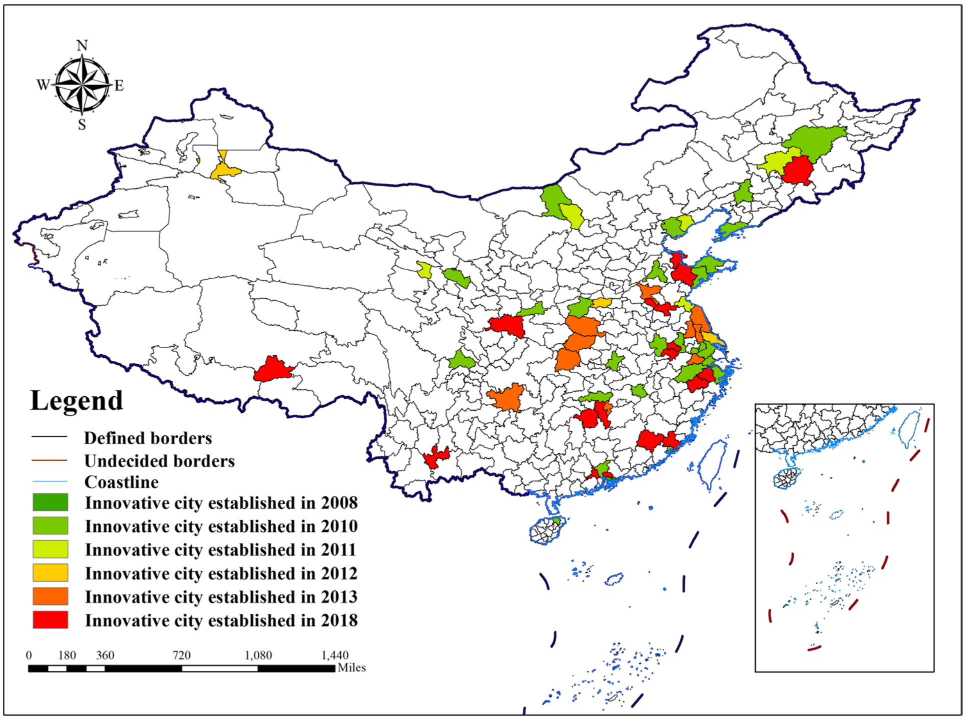


Fig. 2 Map showing the 59 innovative pilot cities used for this study. The color-coding shows the year of establishment as a pilot city, in accordance with China's pilot policy of implementing innovative cities in batches

Variable selection and data description

Dependent variables

Because national data on CO_2 emissions at the prefectural level have not been published, most previous studies have estimated carbon emissions based on different sectors or fossil fuels. However, these methods only measure carbon emissions from fossil fuel energy consumption, which may result in large deviations from the actual values. To avoid this problem, the carbon emission data used in this study were obtained from the Emissions Database for Global Atmospheric Research (EDGAR), jointly published by the Joint Research Centre of the European Union and the Netherlands Environmental Assessment Agency. EDGAR data account for emissions based on different energy types, and it not only calculates emissions from different energy sources, but also quantifies the end-of-pipe processes. EDGAR accounts for carbon emissions from 214 countries and regions worldwide (including China), including carbon emissions from energy activities, industrial carbon emissions, non-energy carbon emissions, and fuel combustion emissions. Our study drew on a processing method for night-time lighting data. First, the NetCDF data file for global CO_2 emissions from 2001 to 2019 was extracted from EDGAR. Second, ArcGIS 10.4 software is used to transform and read the data, and the CO_2 emissions data of 268 cities in China from 2001 to 2019 were extracted using relevant spatial analysis tools. Finally, the growth rate of carbon dioxide emissions for each city during 2002–2019 was calculated.

Control variables

(1) Regions with high economic development should focus on improving ecological and environmental governance. Therefore, they are more likely to invest in government financing to promote low-carbon development (Wang et al. 2022b). Our study assessed the urban economic development (GDP) by calculating the overall GDP per capita. (2) An increase in fixed asset investment is conducive to alleviating factor resource distortions, promoting green industrial transformation and upgrading, and improving carbon emissions performance (Li and Li 2020). We assessed the urban investment level (Inv) by measuring fixed asset investments. (3) The endogenous growth theory considers human capital as a core element in achieving endogenous economic growth and is a key subject in realizing green and low-carbon development, which can effectively reduce regional carbon emission levels (Huang et al. 2021). Our study measured the extent of human capital (Edu) by calculating the ratio of students enrolled in tertiary education to the general population. (4) The level of urban financial development can effectively alleviate financing constraints and motivate enterprises to focus on green research and development, thus contributing to corporate carbon emissions reduction (Shahbaz et al. 2021). We measured the financial development (Ser) based on the year-end loan balances of financial institutions. (5) Digital development has changed traditional production and lifestyles, which can promote both green living and consumption upgrades to achieve a low-carbon lifestyle, as well as facilitate the transformation of industrial intensification to reduce energy and resource consumption (Wang et al. 2022a). The present study assessed the degree of digitalization (Net) by calculating the ratio of households with Internet access to the total population. (6) Improvements in the level of infrastructure construction not only reduce production cost inputs and ensure that enterprises focus on innovation, they also improve the efficiency of interregional factor allocation and accelerate the spillover of low-carbon technological achievements (Fisch-Romito and Guivarch 2019). Our study assessed the extent of infrastructure (Inf) by measuring the per capita urban road area.

The data on innovative pilot cities used in this study came from notices and announcements issued by the Ministry of Science and Technology and the National Development and Reform Commission in previous years. The data on control variables and other basic indicators came mainly from the China Urban Statistical Yearbook, the China Regional Economic Statistical Yearbook, and statistical yearbooks of provinces and cities. The data on patent applications and authorizations involved in the robustness test came mainly from the National Intellectual Property Patent and Google Patent Databases. To objectively reflect the changes in the quality of economic growth at the city level in China, nominal variables, such as GDP and per capita GDP, were converted to real variables with 2002 as the base period using the corresponding price indices. Individual missing values were supplemented by interpolation. The statistical descriptions of the variables of interest are presented in Table 1.

Table 1 Statistical description of the variables

Variable	*Obs*	*Mean*	*Std.Dev.*	*Min*	*Max*
RCO_2	4824	7.44	7.91	− 14.05	56.29
GP	4824	2.75	1.35	0	5.68
IND	4824	0.25	0.08	0	1.62
ELE	4824	0.83	0.44	0	5.89
DEN	4824	5.73	0.88	1.74	7.9
GDP	4824	15.84	1.06	12.39	19.23
Inv	4824	15.33	1.28	11.15	18.4
Edu	4824	0.65	0.45	0.02	3.06
Ser	4824	3.51	0.46	0.68	5.31
Net	4824	1.41	0.31	0	2.06
Inf	4824	1.17	0.18	0	1.74

Empirical results

Baseline results

Based on the regression model constructed above, we tested the effect of the ICPP on carbon emission rate change (Table 2). Column (1) in Table 2 only controlled for city and time-fixed effects without adding control variables, and the coefficient of $Pilot_i*Post_t$ was negative and significant at the 1% level.

The coefficient of $Pilot_i*Post_t$ in column (2) was still significantly positive at the 5% level when the relevant control variables were added, indicating that the ICPP limited to some extent the growth of the carbon emissions rate in pilot cities. This result indicated that the ICPP sets clear low-carbon development goals that are more conducive to promoting the low-carbon development of industries related to high pollution, high energy consumption, and high emissions in pilot cities than in non-pilot cities. The implementation of an innovation city pilot policy is conducive to research and development, and innovation of green and low-carbon technologies in cities, accelerating the transformation of the urban development model from factor- or investment-driven to innovation-driven.

As for the control variables, fixed-asset investment, financial development level, and infrastructure levels significantly contributed to carbon emissions. This finding differed from those of Fisch-Romito and Guivarch (2019) and Shahbaz et al. (2021). Their findings suggested that financial and infrastructure development can effectively reduce regional carbon emissions. A possible reason for this difference is that fixed-asset investment and infrastructure development, both of which require an increase in the level of construction (mainly urban roads), inevitably lead to an increase in urban construction land and the production and use of construction materials, increasing CO_2 emissions. An increase in the level of regional financial development may likewise accelerate the expansion behavior of enterprises, increasing their demand for energy, thus leading to an increase in emissions. An increase in the level of digitization was beneficial for reducing urban carbon emissions. In addition, the effects of the levels of economic development and human capital on urban carbon emission reduction were not significant.

Table 2 Benchmark regression results

Variable	(1)	(2)
$Pilot_i*Post_t$	– 1.196***	– 1.418**
	(– 2.96)	(– 2.32)
GDP		0.309
		(0.77)
Inv		3.609***
		(11.63)
Edu		– 0.660
		(– 1.52)
Ser		0.819***
		(2.65)
Net		– 2.614**
		(– 3.92)
Inf		0.229**
		(2.27)
Year fixed	Yes	Yes
City fixed	Yes	Yes
_cons	8.749***	– 46.620***
	(19.68)	(– 6.92)

T-statistics are in parentheses

***, **, and * represent the 1%, 5%, and 10% significance levels, respectively

Robustness tests

Parallel trend test

Drawing on the study by Beck et al. (2010), the implementation time of the different low-carbon pilot cities was subtracted from the current time when calculating the values of pre- and post-ICPP times. Figure 3 presents the results of the parallel trend test. The results show that the estimated coefficients of the DID term fluctuate around zero in all four periods before policy implementation. The estimated coefficients of the DID term and its 95% confidence interval were significantly negative after policy implementation. This result indicates that the trends in carbon emission growth rates in the pilot and control groups before ICPP implementation were generally not significantly different. The control and pilot groups selected in this study satisfied the parallel trend hypothesis.

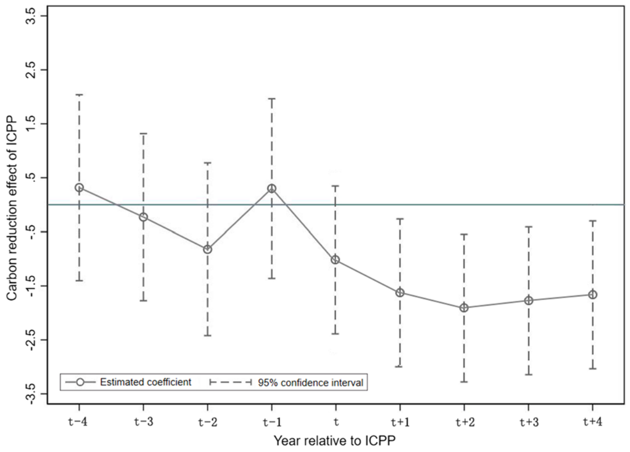


Fig. 3 Parallel trend test of Innovative City Pilot Policy (ICPP)

Placebo test

To eliminate the impact of additional policies or unpredictable factors on the alteration of the urban carbon emission growth rate, we performed a "placebo" examination of the aforementioned findings. Fifty-nine non-pilot cities were chosen randomly as placebo innovative pilot cities. Additionally, a random year was selected as the implementation time for the pilot policies in these cities. Subsequently, a "pseudo-policy dummy variable" was created. The aforementioned steps were repeated 500 times. The results are shown in Fig. 4. The estimated coefficient of the baseline results, represented by the red vertical dashed line, is − 1.418. The baseline results indicate a *P*-value of 0.05, represented by a red dashed line in the horizontal orientation. According to the findings, most of the estimated coefficients for the DID terms had *P*-values exceeding 0.05. In other words, most outcomes failed to meet the 5% significance threshold. Therefore, the impact of the policy observed in the initial findings was significant (Fig. 4). In summary, the estimation results of this study were minimally influenced by other policies or random factors and were not obtained by chance, showing the robustness of the baseline results.

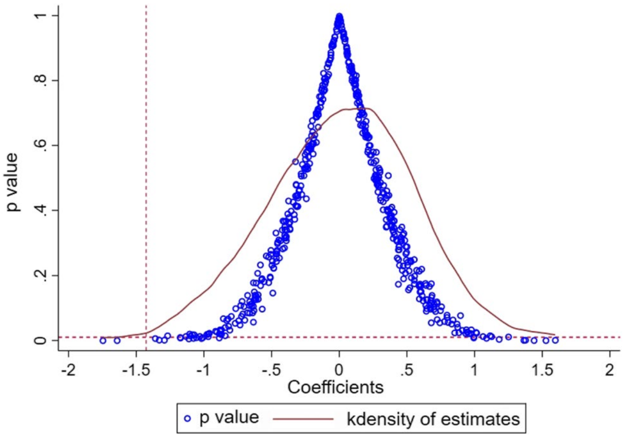


Fig. 4 Placebo test

PSM-DID

The selection of innovative cities at the national level tends to favor those with higher levels of economic development and stronger innovation capabilities. The above selection process may lead to selectivity bias in the pilot group and, thus, systematic bias in the data. This study included 59 cities in the pilot group and 209 cities in the control group. With such a large sample size, it is more likely that the above situation will occur because of the wide range and large differences in development levels. Therefore, we applied the PSM-DID approach for robustness testing. First, economic, educational, digitalization, and infrastructure levels were selected as matching variables. Three matching methods — 1:1 nearest neighbor matching, radius matching, and kernel matching — were used to match the pilot and control groups each year. Finally, the matched results were re-estimated (Table 3). Table 3 shows that the estimated coefficients of ICPP on CO_2 emission rate were significantly negative, at least at the 10% level, under all three matching methods. It indicated that innovative city construction can indeed significantly reduce the rate of urban CO_2 emissions. This further supports the baseline regression findings.

Replace core variables

To test robustness, the carbon intensity growth rate (*RCI*), sulfur dioxide emission growth rate (RSO_2), and soot emission growth rate (*RSD*) were used as proxies for carbon emission reduction in cities. Columns (4)–(6) of Table 3 show that the regression coefficients of the equations for all three growth rates were both negative and statistically significant, with a significance level of at least 10%. After eliminating the factors that could impact urban innovation, ICPP continued to play a crucial role in reducing carbon emissions and achieving a carbon emissions peak.

Table 3 Robustness test

Variable	(1) RCO_2	(2) RCO_2	(3) RCO_2	(4) *RCI*	(5) RSO_2	(6) *RSD*	(7) RCO_2
$Pilot_i * Post_t$	− 4.818**	− 1.355**	− 1.384**	− 0.099***	− 0.135*	− 0.235**	− 0.343**
	(− 2.41)	(− 2.14)	(− 2.15)	(− 2.75)	(− 1.72)	(− 2.41)	(− 2.36)
$LCC_i * LCC_t$							− 1.085**
							(3.33)
Year fixed	YES	YES	YES	YES	YES	YES	YES
City fixed	YES	YES	YES	YES	YES	YES	YES
Controls	YES	YES	YES	YES	YES	YES	YES
_cons	68.056***	110.630***	110.574***	− 0.632	1.775	− 7.203	52.890***
	(7.42)	(22.93)	(22.84)	(− 1.53)	(0.69)	(− 0.82)	(19.89)

Controlling the impact of other policies

In addition, as a result of the ICPP implementation process, the country is actively pursuing other types of pilot policies to address climate change. One policy directly related to low-carbon development is the pilot low-carbon city policy (LCC) implemented by the Ministry of Science and Technology in 2010. There is a large overlap between the implementation time and target of this exploratory policy of urban decarbonization and ICPP, and the policy has achieved significant results in reducing carbon emissions. To control for the effect of these policies on the research results, this study designated LCC_i*LCC_t as a proxy variable for the low-carbon city pilot policy based on the low-carbon city pilot list and time, following the relevant methods in the previous model setting. The above variables were introduced into the original equation, and robustness tests were conducted to remove the effect of low-carbon city pilot policy implementation. This result indicated that ICPP still had a significant inhibitory effect on the growth rate of CO_2 emissions after controlling for the effects of other low-carbon policies.

Heterogeneity analysis

Through the preceding analysis, we found that the implementation of ICPP could effectively slow the rate of CO_2 emissions and help achieve the peak carbon target. However, China is a vast country with significant regional imbalances in economic development and industrial structures among cities of different regions, sizes, and levels. Will the differences in development patterns caused by such imbalances affect the carbon reduction performance of ICPP and hinder the achievement of the carbon peak target? To answer this question, we explored the heterogeneity of the impact of ICPP on carbon dioxide emission rates from three perspectives: region, scale, and rank.

All cities were divided into three major regions — east, central, and west — according to the province in which they are located. Table 4 shows that ICPP implementation considerably decelerates the carbon dioxide emission growth rate for eastern cities, whereas the impact on carbon reduction is insignificant for central cities (Table 4, columns (1)–(3)). Cities in the western region experienced a significant increase in CO_2 emissions due to ICPP. This may be because the cities in the eastern region have advanced green production and pollution-control technologies. The implementation of a pilot policy for innovative cities can accelerate the accumulation of technologies and innovation factors related to green development, further enhancing the green advantages of these cities in terms of their innovation capacity and market environment, thereby slowing the growth rate of urban carbon dioxide emissions through the scale effect (Wang et al. 2023). In the central and western regions, the introduction of ICPP will result in the limited allocation of resources for innovation to promote economic development, given that these regions are dominated by heavy chemical industries that are highly polluting and energy-intensive because of an emphasis on GDP growth. Consequently, the initial policy did not yield the anticipated outcome in terms of reducing carbon emissions in the central and western areas.

All the cities in the study were also classified into two types: large cities (*LC*) and small and medium cities (*SMC*), based on whether the population in urban areas was greater than 1 million. Also, city status, i.e., whether the city is a provincial capital, was used to determine the level of its city rank, and cities were classified as provincial capital cities (*PCC*) or non-provincial capital cities (*NPCC*). Columns (4)–(7) of Table 4 contain the pertinent regression findings. The findings indicated that the regression coefficients in columns (4) and (6) exhibited a significant negative association at the 5% significance level, while the regression coefficients in columns (5) and (7) failed to meet the criteria for statistical significance. This indicated that ICPP has a more substantial effect on reducing carbon emissions in large cities and provincial capitals. This is consistent with the findings of Gao and Yuan (2021), who concluded that the most critical objective of implementing ICPP is to promote local technological innovation and economic development, whereas the carbon reduction effect it brings is more of a side effect. This also implies that reducing pollutant emissions depends more on market-based endogenous behavior. The industrial structure of large cities and provincial capitals is relatively

Table 4 Heterogeneity analysis

Variable	(1) *Eastern*	(2) *Central*	(3) *Western*	(4) *LC*	(5) *SMC*	(6) *PCC*	(7) *NPCC*
$Pilot_i*Post_t$	– 1.519**	– 1.332	0.859**	– 1.304**	– 0.453	– 1.820**	– 1.560
	(– 2.05)	(– 1.44)	(2.38)	(– 2.57)	(– 0.45)	(– 2.45)	(– 0.98)
Year fixed	YES	YES	YES	YES	YES	YES	YES
City fixed	YES	YES	YES	YES	YES	YES	YES
Controls	YES	YES	YES	YES	YES	YES	YES
_cons	62.741***	83.753***	65.849***	– 60.473***	– 0.651	– 83.109**	– 37.226***
	(9.03)	(14.30)	(7.48)	(– 5.57)	(– 0.07)	(– 2.19)	(– 5.35)

reasonable and is mainly dominated by headquarters and service industries. Market mechanisms are also better developed, and some manufacturing-oriented cities tend to concentrate on modern manufacturing using high-precision technologies. ICPP can enhance the scale effect of carbon emission reduction in these cities. From this conclusion, it is evident that in the process of promoting carbon emission reduction, in addition to improving the role of government environmental intervention, it is most essential to make the market play a decisive role in the spatial allocation of green resources, and bring into play the endogenous driving forces of innovation and upgrading of industrial structure to better realize carbon emission reduction.

Mechanism analysis

According to the hypothesis of a previous study, the technological innovation effect (*GP*) was measured by the number of environmentally friendly patents in urban areas, the industrial upgrading effect (*IND*) was measured by the coefficient of industrial structure change, the energy-saving effect (*ELE*) was measured by total annual electricity consumption, and the spatial intensification effect (*DEN*) was measured by population density. The mediating effect model was employed to examine the impact mechanism from four perspectives: technological innovation, industrial upgrading, energy saving, and spatial intensification effects.

The relationship between ICPP and the four different mechanisms was confirmed (Table 5, columns (2), (4), (6), and (8)). Our research revealed that adopting the ICPP can foster urban innovation, enhance industrial advancement, encourage population concentration, and effectively curb energy usage. Columns (3), (5), (7), and (9) of Table 5 added the proxy variables for the four mechanisms based on column (1). The regression coefficients of the innovative pilot policies were all significantly negative, at least at the 10% level, and the absolute values of the coefficients of $Pilot_i*Post_t$ in all four results columns were smaller than those in column (1) of the model. This indicated that all four mechanisms played mediating roles in the effect of ICPP on the mitigation of CO_2 emissions.

With the goal of low-carbon development, cities should balance stable economic growth and ecological environmental protection. The technological innovation effect stimulated by ICPP can drive economic growth while adjusting the industrial structure and promoting its optimization and upgrading. Yang et al. (2022) showed that ICPP is a necessary means of breaking dependence on local natural resources, and the implementation of this policy can reduce the ineffective input of resources and improve the efficiency of fossil energy utilization, thus reducing carbon emissions. In summary, the ICPP can promote carbon emissions reduction by exerting the effects of technological innovation, industrial upgrading, energy conservation, and spatial intensification, which is conducive to achieving the goal of peaking carbon emissions. Based on the above analysis, hypotheses 2a, 2b, 2c, and 2d were verified.

The intermediary effect ratios of technological innovation, industrial upgrading, energy saving, and spatial intensification were 26.09%, 20.94%, 18.12%, and 7.69%, respectively. The mediating effect of spatial intensification was the smallest and much weaker than that of the other three mechanisms. This shows that although urban sprawl has improved to date to some extent, the implementation of

Table 5 Examination of the mechanisms by which the IPCC affects carbon emission reductions

Variable	(1) RCO_2	(2) *GP*	(3) RCO_2	(4) *IND*	(5) RCO_2	(6) *ELE*	(7) RCO_2	(8) *DEN*	(9) RCO_2
$Pilot_i*Post_t$	– 1.418**	0.336***	– 1.048*	0.254***	– 1.121*	– 0.259**	– 1.161**	0.172***	– 1.309*
	(– 2.32)	(4.64)	(– 1.81)	(18.43)	(– 1.70)	(– 2.37)	(– 2.47)	(14.64)	(– 1.78)
GP			– 1.101***						
			(– 14.39)						
IND					– 1.169**				
					(– 2.50)				
ELE							0.992***		
							(4.65)		
DEN									– 0.634***
									(– 5.22)
Year fixed	YES	YES	YES	YES	YES	YES	YES	YES	YES
City fixed	YES	YES	YES	YES	YES	YES	YES	YES	YES
Controls	YES	YES	YES	YES	YES	YES	YES	YES	YES
_cons	– 6.620***	0.884**	24.24***	0.687***	25.449***	23.002***	22.832***	6.245***	34.778***
	(– 6.92)	(2.28)	(9.87)	(25.28)	(9.44)	(9.15)	(9.11)	(9.14)	(9.87)

ICPP has not yet achieved the inner development of cities. The problems of dysfunctional urban land structures and low utilization efficiency still need to be resolved. Therefore, the construction process of innovative cities should strengthen the role of land-use planning, continuously improve urban land use, optimize urban spatial layout, and give full play to the impact of spatial intensification on carbon emission reduction.

Conclusion and policy implications

According to the theory of environmental economics, technological innovation can not only improve the efficiency of resource and energy use, and reduce resource consumption and environmental damage, but also reduce the use and consumption of high-carbon energy through the research and development of new carbon-free energy technologies. Technological innovation, therefore, plays a vital role in low-carbon development. Urban areas play a crucial role in fostering the growth of local economies and communities. They are prominent in multiple areas of energy preservation and emission reduction and are at the forefront of technological and scientific advancement. To achieve the objective of viably decreasing carbon emissions, it is crucial that novel urban areas be established in an inventive and efficient manner. By examining data from 268 Chinese cities between 2002 and 2019, this study investigated the correlation between the urban carbon emission growth rate and ICPP.

The primary conclusions of this study are as follows:

1. ICPP can potentially mitigate the increase in carbon emissions in urban areas. In addition, it can expedite the accomplishment of carbon dioxide emissions reduction objective to a viable extent. This research was conducted by performing a variety of rigorous examinations, including PSM-DID, parallel trend, and placebo tests.
2. Implementing ICPP helped cities improve their green innovation level, upgrade their industrial structure, optimize their spatial structure, and eliminate their dependence on fossil fuels to a certain extent. Therefore, this pilot policy reduced urban carbon emissions through technological innovation, industrial upgrading, energy saving, and spatial intensification effects.
3. Although ICPP may have positively affected the reduction in carbon emissions in eastern cities, its impact on reducing carbon emissions in central cities was minimal. Conversely, it can still greatly improve the reduction of carbon dioxide emissions in cities in the West. Additionally, we discovered that the execution of ICPP significantly influenced the decrease in carbon emissions in large and provincial capital cities.

We propose the following policy recommendations from the perspective of the positive environmental externality impacts of ICPP.

1. Expand the scope of ICPP and promote the construction of innovative cities. The results of this study showed that this policy helps to accelerate the achievement of the carbon peak target. Therefore, the central government should try to incorporate peak carbon-related indicators into the assessment of pilot cities to give full play to the low-carbon leadership role of innovative cities and accelerate the achievement of urban carbon peak targets. Pilot cities should actively construct an innovation system that is market-oriented and enterprise-oriented and should combine industry, academia, and research to accelerate the realization of the urban carbon peaking goal while building an innovative city.
2. Adhere to the construction principles of adapting to local conditions and highlighting unique city or regional characteristics and explore innovative, low-carbon, and other new urban development modes that align with these conditions and characteristics. This study revealed that the effects of ICPP on cities of different scales and levels differ significantly. Therefore, we believe that a “one-size-fits-all” approach should not be used to promote the construction of new cities. Attention should be paid to summarizing, sharing, and promoting the experience of the pilot work and introducing the successful experiences of cities in the eastern region, larger cities, and high-ranking cities to cities where the policy effect has not yet been fully utilized to expand the green development effect of innovative city building.
3. Improve the urban innovation system, solve the problems of green and low-carbon development, and explore multidimensional ways to promote peak carbon in innovative city-building policies. The results of this study showed that ICPP can have a positive impact on CO_2 emission reduction in terms of improving innovation capacity, accelerating industrial upgrading, reducing energy consumption, and optimizing urban spatial layout. Therefore, each pilot city should stimulate its low-carbon development potential in various ways, such as production, transportation, buildings, and daily living and adopt a multipronged approach to accelerate the achievement of the city’s carbon peak target.

Although this study contributes to a better understanding of the impact of ICPP on urban carbon emission reduction and their mechanisms, there are still some limitations. First, the research data covered a limited time span. The research period of this paper was 2002–2019, while the last batch of innovative cities was implemented in 2018, providing only 1 year of policy impact, which failed to fully reveal the carbon emissions reduction effect of ICPP. Second, this study mainly adopted city panel data; however, the Chinese government has already compiled a list of the first set of innovative counties earmarked for development. Thus, in subsequent studies, we can use more micro county-level data to conduct in-depth analyses of the relationship between ICPP and carbon emissions reduction.

Author contribution The authors of this manuscript have contributed to the article, and there is no conflict of interest. Ye Z designed the study and proposed the methodology. Huang YC and Zou C found the data and analyzed it and wrote the paper.

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Declarations

Ethical approval I have not submitted my manuscript to more than one journal for simultaneous consideration.

This study has not been made public.
Results are presented clearly, honestly, and without fabrication or inappropriate data manipulation. Authors adhere to discipline-specific rules for acquiring, selecting, and processing data.
No data, text, or theories by others are presented as if they were the plagiarism.

Consent to participate All authors agree with the content of the submission, and all agree to continue to support the follow-up work.

Consent for publication This manuscript has not been submitted or published in other journals, and the authors agree to consent to publish.

Competing interests The authors declare no competing interests.

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