Hu *et al. Carbon Footprints* 2024;3:16
DOI: 10.20517/cf.2024.28

Carbon Footprints

Original Article

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Exploring carbon emission effects of national-level industrial park policies on cities in China

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How to cite this article: Hu X, Zhang YW, Geng Y, Yu H, Li L. Exploring carbon emission effects of national-level industrial park policies on cities in China. *Carbon Footprints* 2024;3:16. https://dx.doi.org/10.20517/cf.2024.28

Received: 26 Aug 2024 **First Decision:** 29 Sep 2024 **Revised:** 25 Oct 2024 **Accepted:** 31 Oct 2024 **Published:** 9 Nov 2024

Academic Editor: Jennie Li **Copy Editor:** Fangling Lan **Production Editor:** Fangling Lan

Abstract

Serving as the backbone of economic development, industrial parks have strong implications for reducing carbon emissions in China under the “carbon peak and carbon neutrality” background. This study explores the carbon emission reduction effects of three different types of national-level industrial parks on prefectural-level cities in China, including economic and technological development zones (ETDZs), eco-industrial demonstration parks (EIDPs), and low-carbon industrial parks (LCIPs). Data on 204 prefectural-level cities over the period of 1999 to 2019 were examined by using the difference-in-differences method and the mediating effect model. The study revealed that (1) the three types of industrial parks significantly reduced the intensity of city carbon emissions by 1,155, 395, and 450 tons per million CNY, respectively; (2) There existed lag effects of 7 years for the ETDZ and 3 years for the EIDP; (3) Industrial structure exhibited significant mediating effects, with ETDZ and EIDP reducing city carbon emission intensity by 58 and 56 tons per million CNY, respectively; (4) Strong heterogeneity in the effects was found, arising from the differences in geographical location, resources endowment, and amount of industrial parks; and (5) ETDZ and EIDP reduced the carbon emission intensity of neighboring cities by 174 and 144 tons per million CNY, respectively, while LCIP increased that by 686 tons per million CNY. The major contribution of this study is analyzing the city-level impacts of ETDZ, EIDP, and LCIP, three different types of national industrial park policies with different implementation periods, regional distributions, and policy focuses. This not only fills a gap in the analyses of ETDZ and LCIP policies in this area of research, but also draws analogies and contrasts between the effects of the three different policies. This study suggests that the stability and long-

term nature of industrial park policies be maintained and further transformation and upgrading of industrial structure be attained. Additionally, intercity coordination could be introduced or enhanced.

Keywords: Carbon emission intensity, national economic and technological development zone, national eco-industrial demonstration park, national low-carbon industrial park, difference-in-differences

INTRODUCTION

To mitigate climate change caused by excessive anthropogenic greenhouse gas emissions, humankind has made great efforts. From the United Nations Framework Convention on Climate Change in 1992 to the Kyoto Protocol in 2005, and then to the Paris Agreement in 2015, these international agreements aim to limit global temperature rise and ultimately achieve net zero emissions[1]. As the world's largest developing country[2], China is among the largest carbon emitters, and consequently, China's emission reduction results are crucial to global carbon reduction[3]. In response, the Chinese government proposed the goal of "carbon peak and carbon neutrality" in 2020[4].

According to the Statistical Review of World Energy 2022[5], in 2021, China's energy-based carbon dioxide emissions accounted for 31.1% of the global total. The industrial sector is the main contributor, with its energy consumption accounting for 65% of the national total in 2021[6] and 62% in 2019, at a level of 6,236 million tons[7]. Industrial processes are primarily carried out in industrial parks, where over 2,500 national and provincial industrial parks contributed to more than half of the country's industrial output[8,9] and 31% of the carbon dioxide emissions[10]. This renders industrial parks key to achieving the "carbon peak and carbon neutrality" goals[11].

In recent years, China has introduced various policies to promote the green, circular, and low-carbon development of industrial parks. Among them, the focus has been on economic and technological development zones (ETDZs), eco-industrial demonstration parks (EIDPs), and low-carbon industrial parks (LCIPs). Economic and Technological Development Zones (ETDZ) are government-designated zones that aim to attract foreign and domestic investment, promote industrial development, and enhance technological innovation. ETDZs are often focused on rapid economic growth, and their carbon emissions can vary depending on the types of industries they attract, which may range from manufacturing to high-tech industries. Their emphasis on economic growth may sometimes conflict with environmental goals, leading to higher emissions in some cases. EIDPs are designed to promote sustainable industrial practices by encouraging the integration of cleaner production technologies and industrial symbiosis, where waste or by-products from one company are used as inputs by another. These parks focus on environmental sustainability and aim to reduce emissions by improving resource efficiency and minimizing waste. As a result, they are generally expected to have lower carbon emissions compared to more traditional industrial parks. LCIPs are specifically aimed at reducing carbon emissions through the adoption of low-carbon technologies and renewable energy. These parks emphasize the development of green industries, including renewable energy, energy efficiency, and low-carbon manufacturing processes. LCIPs are designed to be at the forefront of China's efforts to meet its carbon neutrality goals, and as such, they typically aim to achieve the lowest carbon emissions among the three types of parks. Despite these policies, there has been limited research investigating the overall impact of these industrial parks on regional carbon emissions. Existing studies often focus on the emissions of individual or specific parks, while few have assessed how the construction of multiple types of industrial parks influences urban carbon emissions at the broader level. Thus, understanding the role that industrial parks play in reducing emissions is essential for achieving China's carbon goals. This study aims to fill the gap by analyzing the impact of industrial park policies on urban carbon emission reductions in China, focusing on the effects of different industrial parks on city carbon emissions and exploring the differences and similarities between various types of parks.

Literature review

China has raised policies to promote green, circular, and low-carbon development of industrial parks, such as economic and technological development zones, ecological industrial parks, and low-carbon industrial parks. Few studies have focused on the effects of the presence of industrial parks on the overall carbon emissions of a region. Existing studies often focus on the carbon emissions accounting of one or a few parks, using methods such as the IPCC greenhouse gas inventory method, life cycle assessment (LCA), or input-output (IO) method for further analyses[12-17]. Research into carbon emissions from large parks is limited[18,19]. However, as an important policy vehicle, how the construction of various types of industrial parks affects cities and whether it helps cities reduce carbon emissions are worthy of serious exploration. This study analyzes the effects of constructing industrial parks from the perspective of city carbon emission reduction.

When examining the effects of a policy on a certain indicator for a region, the difference-in-differences (DID) method and its extensions have been widely adopted. For example, using balanced panel data covering 270 prefecture-level cities in China from 2003 to 2018, Meng *et al*. applied the DID method and the mediated effects model to study the impacts of national resource-based cities' sustainable development planning policies on pollution emission intensity and found that these policies significantly reduced pollution emission intensity[20]. For industrial parks, the EIDP has been the focus of studies investigating the emission reduction effects of different EIDPs, the factors involved, heterogeneity with respect to development paths and geographic locations, and spatial spillover effects. For example, Nie *et al*. assessed the impacts of national-level eco-industrial parks on low-carbon development and reported that with national eco-industrial parks, the carbon intensity of pilot cities decreased by 7.2%, suppressing the peak of the environmental Kuznets curve and helping to reach the inflection point earlier[21]. The environmental impacts of three types of park policies, including EIDP, LCIP, and recycling policy, were also analyzed, with the empirical results showing that all three types of park policies significantly reduced regional industrial SO_2 emissions[22].

Going beyond the question of whether industrial park construction can reduce regional carbon emissions, scholars have delved into this question in greater depth. The first concerns the timing of the impacts, which are generally lagged and long-term, with a lag period of 2 to 3 years[22]. There are also heterogeneity analyses examining the intensity of environmental regulations[22], city size[23], spatial location[23], resource endowment[23], and the number of parks[23]. The second concerns the mechanism of the impacts. Specifically, the construction of industrial parks may affect urban carbon emissions through a variety of channels, and the mediating variables widely investigated include improving the level of environmental regulation[24], enhancing the level of green innovation[24], increasing energy use efficiency and upgrading the energy use structure, and increasing the level of local technology[25]. The third issue concerns whether the impacts exhibit spatial spillover effects. Many studies have shown that there are significant spatial spillover effects on the urban environment and carbon emissions within a certain distance, which can lead to carbon emission reductions in neighboring cities[25]. The fourth addresses the potential heterogeneity in effects, such as those with respect to the development paths of industrial parks and the underlying transformation drivers of EIDPs, including ETDZs and National High-tech Industrial Parks. Cao found that the EIDPs transformed from ETDZs exhibited greater impacts on a city's SO_2 and CO_2 emissions reductions. Besides industrial parks, other factors also influence carbon emissions[25]. Yang *et al*. analyzed zero-carbon energy strategies at the national level, using a by-production approach to reveal how factors such as energy intensity contribute to carbon reduction. This complements the analysis of industrial parks by highlighting broader energy policy effects[26]. Additionally, urban expansion is another crucial factor. Zhang *et al*. used machine learning to investigate the impact of land-use changes in Wuhan, Hubei Province, on surface temperature and carbon emissions[27]. They found significant increases in carbon emissions arise due to expanding urban areas. This indicates a need to take into account urban growth alongside industrial park development when devising carbon emission reduction strategies[27].

In addition, there are also other types of national-level industrial parks, such as LCIP, which started to be approved and certified in 2014. The impacts of these parks on urban industrial carbon emissions, as well as the differences in the effects between these types of parks, remain to be further studied. Moreover, China has introduced a series of policies to promote the transformation and upgrading of industrial parks and introduce green cycling, which may help reduce carbon emissions as well. It is thus desirable to further examine the type-specific impacts of industrial parks on city carbon emissions and the inter-type differences. This may help understand the effectiveness of national-level industrial park policies and provide policy insights for the application for and the approval of industrial parks.

Given the above, this study uses data from 204 cities at or above the prefecture level in China from 1999 to 2019 and applies the DID method to examine the impact of three types of industrial parks on urban carbon emissions, namely, economic and technological development zones (ETDZ), eco-industrial demonstration parks (EIDP), and low-carbon industrial parks (LCIP). Specifically, the carbon reduction effects and dynamic paths of these industrial park policies are first explored. Second, the mediating effects are analyzed, with policy levers of carbon reduction clarified. Third, the heterogeneity in the effects with respect to a city's geographical region, resources endowment, and the amount of relevant industrial parks, as well as their spatial spillover effects, are studied.

The main contribution of this study is that it looks into the type-specific effects of national industrial park policies on city carbon emissions, taking into consideration different implementation timing, locations, and policy emphases. In particular, this study contributes to analyses of ETDZs and LCIPs, deriving analogies and contrasts for the impacts of three different types of industrial parks.

METHODOLOGY

Research framework

Figure 1 provides an overview of the study's analytical framework, demonstrating the connection between industrial park policies studied, the models employed, and the subsequent empirical analyses of the effects on city carbon emissions.

Model specification

Benchmark model

The DID method, widely used for examining policy effects, is employed in this study. The Difference-in-Differences (DID) methodology is a robust and widely used technique for causal inference, especially in policy evaluation and impact studies. In this study, DID was chosen to assess the causal impact of the construction of different types of industrial parks (ETDZ, EIDP, and LCIP) on urban carbon emissions. The rationale for selecting DID is based on its ability to compare changes over time between a treatment group (cities with industrial parks) and a control group (cities without industrial parks), thereby isolating the effects of industrial park policies on carbon emissions. Herein, cities with the parks under study are set as the treatment group, while cities without set as the control group.

The benchmark model is as follows in Eq. 1.

$$CARBON_{i,t} = \alpha + \beta * TREAT_{i,t} + \theta * CONTROL_{i,t} + \gamma_t + \mu_i + \varepsilon_{i,t} \quad (1)$$

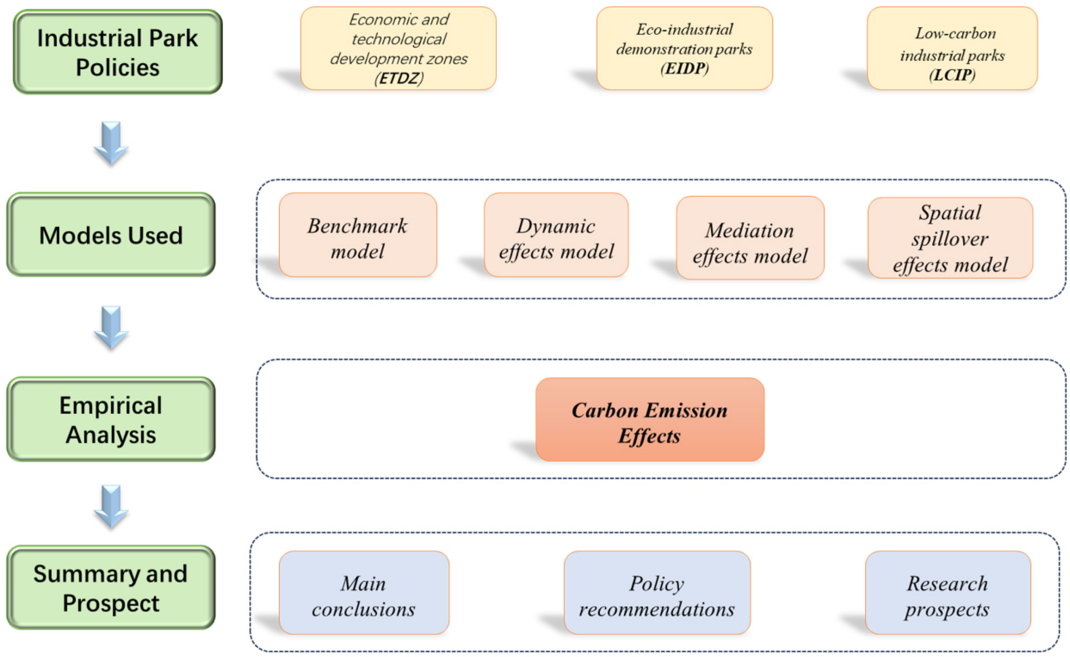

Figure 1. Flowchart of the analysis.

where i denotes city, t time, and $CARBON_{i,t}$ the city's carbon emission intensity. $TREAT_{i,t}$ indicates if the city has constructed relevant industrial parks, when its value is 1; if 0, then the opposite. $CONTROL_{i,t}$ represents the control variables. For coefficients, α is the constant term, and β the estimated coefficient of the treatment variable, which herein means the effects of relevant industrial parks on the city's carbon emissions. θ denotes the estimates for the control variables. Additionally, γ_t refers to the time fixed effects, μ_i the city fixed effects, and $\varepsilon_{i,t}$ the random perturbation term.

Dynamic effects model

The benchmark model measures the park's average effects on city carbon emissions. However, the timing of park construction varies, potentially causing dynamic effects. Referencing previous research[7,18], a dynamic effects model gets developed, as in Eq. 2.

$$CARBON_{i,t} = \alpha + \beta * TREAT_{i,t} \cdot GROUP_{i,t} + \theta * CONTROL_{i,t} + \gamma_t + \mu_i + \varepsilon_{i,t} \quad (2)$$

where $GROUP_{i,t}$ is the grouping variable related to the timing of park construction. Specifically, the year of the park establishment is set as "current", the years prior to the establishment are denoted by "before-1" to "before-10", and the years after are indicated by the range of "after-1" to "after-15."

Mediation effects model

The benchmark and the dynamic effects models assess how industrial parks influence city carbon emission intensity over time. A mediating effects analysis helps explore how this impact occurs. This model was chosen to explore the underlying mechanisms through which industrial parks influence city carbon emissions. Specifically, it allows us to assess how industrial structure adjustments (e.g., shifts from secondary to tertiary industries) contribute to carbon reduction. By analyzing the mediating role of factors such as industrial structure and green innovation, we can better understand the pathways through which different types of industrial parks affect carbon intensity. The mediated effects model is particularly applicable in this context, as it highlights the indirect effects of policy interventions, which are crucial for capturing the complexity of emissions reduction. This study considers city industrial structure, hypothesizing that industrial parks affect carbon emission intensity by inducing changes in industrial structure. Based on the availability of data and with reference to other studies[28], this paper takes the city industrial structure as the mediating variable, with an underlying hypothesis that the establishment of relevant industrial parks would indirectly affect city carbon emission intensity via the industrial structure. The model is set up as follows by Eqs. 3 and 4.

$$M_{i,t} = \alpha_m + \beta_m \cdot TREAT_{i,t} + \theta_m \cdot CONTROL\_M_{i,t} + \gamma_t + \mu_i + \varepsilon_{i,t} \quad (3)$$

$$CARBON_{i,t} = \alpha_d + \beta_{d1} \cdot TREAT_{i,t} + \beta_{d2} \cdot M_{i,t} + \theta_d \cdot CONTROL\_C_{i,t} + \gamma_t + \mu_i + \varepsilon_{i,t} \quad (4)$$

where $M_{i,t}$ is the mediating variable, while $CONTROL\_M_{i,t}$ and $CONTROL\_C_{i,t}$ represent the control variables for analyzing the effects of relevant industrial parks on industrial structure and carbon emission intensity, respectively.

Spatial spillover effects model

The spatial spillover effects model was selected to account for the potential regional interdependencies in carbon emissions reduction. Industrial parks, especially eco-industrial and low-carbon parks, may generate spillover benefits that extend to neighboring cities, as industries share best practices, technologies, and resource efficiencies. This model is well-suited for examining the spatial diffusion of carbon reduction impacts, which is critical given China's regional economic and industrial clustering. The use of spatial econometric techniques allows us to quantify how policies implemented in one city influence the environmental outcomes of nearby cities. City boundaries are not unbridgeable physical boundaries. Considering the increasing economic exchanges between cities, constructing industrial parks may affect neighboring cities, and both negative and positive spatial spillover effects are possible. Eq. (1) is extended to include terms on spatial spillover effects, as specified by Eq. 5.

$$CARBON_{i,t} = \alpha + \beta \cdot SPATIAL_{i,t} + \theta * CONTROL_{i,t} + \gamma_t + \mu_i + \varepsilon_{i,t} \quad (5)$$

where $SPATIAL_{i,t}$ is the grouping variable. Specifically, if a city has relevant industrial parks, it belongs to the "park" group; if it does not and its neighboring cities do, then it is assigned to the "nabour" group; otherwise, it is "non".

Variable definition and data sources

Dependent variable

This study explores the effects of industrial parks on city carbon emissions, focusing on carbon emission intensity due to varying city size, population, and economic development levels. The dependent variable, city carbon emission intensity (kg/CNY), is defined as the ratio of annual city carbon emissions to GDP. The data on city CO_2 emissions come from the CEADs database, and the city GDP data come from the China City Statistical Yearbooks. The carbon emission intensities of 204 prefecture-level cities over the period from 1999 to 2019 are examined.

Core indicator variables

The core independent variable is the implementation status of industrial park policies, indicated by whether a certain type of industrial park is established (1) or not (0). The studied policies include ETDZ, EIDP, and LCIP, each launched at different times with varied objectives, construction periods, quantities, and regional distributions. The interaction variable $TREAT_{i,t}$ is set up as follows: if a city establishes a relevant industrial park, $TREAT_{i,t}$ is 1; otherwise, it is 0. Furthermore, to ensure the reasonableness of the analysis results, this study defines that if industrial parks are established in July and later in a year, then the time is labeled the next year; if the parks are established before July, then the time is labeled the current year. According to the "Statistical Table of Administrative Divisions of the People's Republic of China" published by the Ministry of Civil Affairs of the People's Republic of China in 2022, there are a total of 333 prefecture-level administrative units in the Chinese mainland. For completeness of the data for analysis, this paper selects 204 prefecture-level cities, and the study period is from 1999 to 2019. For the list of parks, the ETDZ data come from the website of the Ministry of Commerce of the People's Republic of China[29], the EIDP data come from the website of the Ministry of Ecology and Environment of the People's Republic of China[30-33], and the LCIP data come from the website of the Ministry of Industry and Information Technology of the People's Republic of China[34,35].

Control variables

Several control variables are included, based on literature on carbon emissions. Specifically, drawing on Chen *et al*., energy utilization efficiency (GDP per unit of energy consumption in CNY/ton of coal equivalent) is included[36]. Average investment level (ratio of total fixed asset investment to GDP), industrial development (logarithm of total industrial output value), economic development (GDP per capita), and population density (resident population to area ratio) are also considered. The average investment level is expressed as the ratio of total investment in fixed assets of a city to its GDP, industrial development is represented using the logarithm of the total industrial output value, and economic development is indicated by the GDP per capita, with the data obtained from the Statistical Yearbook of China's Cities (1999-2019). Population density is given by the ratio of the resident population of prefecture-level cities to the area of prefecture-level cities, where the data on the resident population come from the China City Statistical Yearbook and the data on the area of cities from the CEIC database.

Intermediary variables

Building on previous research[22,25], mediators usually involve energy and technology development. This study considers urban industrial structure, a variable that may influence city carbon emissions due to varying industry-specific intensities. The mediator variable is defined as the ratio of secondary to tertiary industry GDP, and the data are from the China City Statistical Yearbooks.

Data processing

For the 333 prefecture-level cities in mainland China, we selected 204 cities based on the availability and completeness of data over the study period (1999-2019). These 204 cities exhibit a reasonably balanced distribution across different regions of China, making it possible to capture the geographical and economic diversity necessary for a comprehensive analysis. We checked that the selected cities exhibited consistency between variables, including carbon emissions, industrial park establishment, and other control variables, such as GDP and population density. The selected cities include those with established national-level industrial parks, which are the focus of this study. Overall, the sample includes a diverse range of cities in terms of geography, economic development, and industrial structure, which would allow a comprehensive evaluation of how industrial parks affect carbon emissions.

The time frame of 1999 to 2019 was used, aiming to cover a sufficiently long period for analyzing the effects of the various types of industrial parks (ETDZ, EIDP, LCIP), as these parks were introduced and/or established at different times. This period provides a potentially adequate window for observing both the short-term and long-term effects of industrial park policies on carbon emissions.

To repeat, the cities studied were selected based on the availability of consistent and reliable data on city carbon emissions, industrial activities, economic indicators, and other relevant factors over the period of 1999 to 2019. The availability of high-quality data across these cities was essential for applying the Difference-in-Differences (DID) methodology and ensuring the accuracy of the results.

RESULTS

Descriptive analysis

The number of ETDZs grew from 38 in 1999 to 230 in 2024. EDIPs have increased steadily since 2008. As Figure 2 shows, both ETDZ and EIDP are primarily located in the eastern region, and their presence in central and western regions is less than half. In 2015 and 2016, 51 LCIPs were established, with 47.06% in the eastern region, 25.49% in the central, and 27.45% in the western. In general, ETDZ has the longest history, the largest amount, and the broadest distribution. EDIP has grown slowly, while LCIPs were approved in 2015 and 2016, with no new additions since.

Benchmark results

To apply the DID method appropriately, the carbon emission intensities of the treatment and control groups are supposed to show parallel trends before the construction of relevant industrial parks. Figure 3 confirms this, with the X-axis showing the difference between the current year and the year of construction of the relevant industrial park, and the Y-axis exhibiting the estimated coefficients of the core independent variables. The 95% confidence intervals of the coefficient estimates contain 0, indicating no significant pre-construction difference in carbon emissions existed between the groups. Thus, the DID method is suitable for evaluating treatment effects.

Table 1 presents the baseline results. ETDZ significantly reduces city carbon emission intensity, with a coefficient of -1.1545. EIDP and LCIP demonstrate statistically significant coefficients of -0.3949 and -0.4504, respectively, indicating they reduce carbon emissions, though less than ETDZ.

In addition, the effects of industrial parks on city carbon emissions may vary by region, resource endowment, and the amount of parks. Heterogeneity analyses concerning these aspects were thus carried out. As provided in the Supplementary Materials, Supplementary Table 1 exhibits the varying effects with regard to geographical location. Supplementary Table 2 shows the effects arising from the differences in resource endowments across cities. Supplementary Table 3 exhibits the heterogeneity in effects with respect to the city-level number of industrial parks.

Dynamic effects analysis

Figure 4 shows the impact of three types of industrial parks on city carbon intensity over the periods of 10 years before and 15 years after, using the current year as the base group. It shows that for ETDZ, significant negative effects on carbon intensity would appear starting from the 7th year post-construction. For EIDP, the negative effects started in the 3rd year post-construction. While for LCIP, no significant effects were observed within three years post-construction.

Mediating effects analysis

Table 2 shows the effects of industrial parks on city carbon emission intensity via industrial structure (IS). The coefficients appear all significantly negative, suggesting that the presence of industrial parks can raise the share of tertiary industry and/or reduce that of secondary industry. Additionally, the mediator variable appears to have positive effects on city carbon emissions, implying the contributing role of secondary industry.

Table 1. Benchmark results for the impact of industrial park construction on city carbon emissions

	ETDZ	EIDP	LCIP
TREAT	-1.1545*** (0.0576)	-0.3949*** (0.0450)	-0.4504*** (0.0499)
Energy efficiency	-0.0193* (0.0113)	-0.0193* (0.0113)	-0.0193* (0.0113)
Investment level	0.0189 (0.0310)	0.0189 (0.0310)	0.0189 (0.0310)
Population density	1.3754e-04** (5.9951e-05)	1.3754e-04** (5.9951e-05)	1.3754e-04** (5.9951e-05)
Industrial development	-0.1450*** (0.0292)	-0.1450*** (0.0292)	-0.1450*** (0.0292)
Economic level	0.0146*** (0.0036)	0.0146*** (0.0036)	0.0146*** (0.0036)
Constant	2.2756*** (0.1784)	1.5870*** (0.1945)	1.6425*** (0.1863)
N	4,284	4,284	4,284
City fixed effects	Y	Y	Y
Time fixed effects	Y	Y	Y
R^2	0.4986	0.4986	0.4986

*P < 0.1, **P < 0.05, ***P < 0.01. The values in parentheses are standard errors.

Table 2. Mediation effect model results of the impact of industrial park construction on city carbon emissions

	ETDZ		EIDP		LCIP	
	IS	EI	IS	EI	IS	EI
TREAT	-0.093*** (0.023)	-0.058*** (0.011)	-0.484*** (0.032)	-0.056*** (0.017)	-0.229*** (0.027)	0.074*** (0.014)
Industrial structure		0.075*** (0.008)		0.071*** (0.008)		0.082*** (0.008)
N	4,284	4,284	4,284	4,284	4,284	4,284
CONTROL	Y	Y	Y	Y	Y	Y
City fixed effects	Y	Y	Y	Y	Y	Y
Time fixed effects	Y	Y	Y	Y	Y	Y

***P < 0.01. Values in parentheses are standard errors.

For ETDZs and EIDPs, the effects of industrial parks on city carbon intensity remain significantly negative after including the mediator, suggesting that altering the industrial structure helps reduce carbon intensity. For LCIPs, the coefficient turns positive, likely because industrial structure is not their primary channel of reducing carbon intensity, and the short study period may not help capture their full impacts.

Effects on neighboring cities

Table 3 presents the impact of industrial parks on the carbon emissions of neighboring cities. The regression coefficients reflect the relationships between the "nabour", "park", and "non" groups.

For ETDZs, the coefficients of the "nabour" and "park" groups are significantly negative, indicating that ETDZs reduce carbon emissions in both the reference and neighboring cities, with a stronger effect for the city where the park is located. In addition, ETDZs have stronger effects than EIDPs on reducing emissions in cities where parks are located and in neighboring cities. For LCIPs, the coefficients are, however, positive, possibly due to the short-term study period and the selection of cities for LCIP establishment.

Table 3. Spatial spillover effects of the impact of industrial park construction on city carbon emissions

	ETDZ	EIDP	LCIP
Nabour	-0.1742*** (0.0447)	-0.1439*** (0.0140)	0.6860*** (0.0265)
Park	-1.3279*** (0.0707)	-0.3949*** (0.0450)	0.2384*** (0.0628)
Constant	2.5202*** (0.1880)	1.5870*** (0.1945)	0.9528*** (0.1910)
N	4284	4284	4284
CONTROL	Y	Y	Y
City fixed effects	Y	Y	Y
Time fixed effects	Y	Y	Y
R^2	0.4986	0.4986	0.5004

***P < 0.01. The values in parentheses are standard errors.

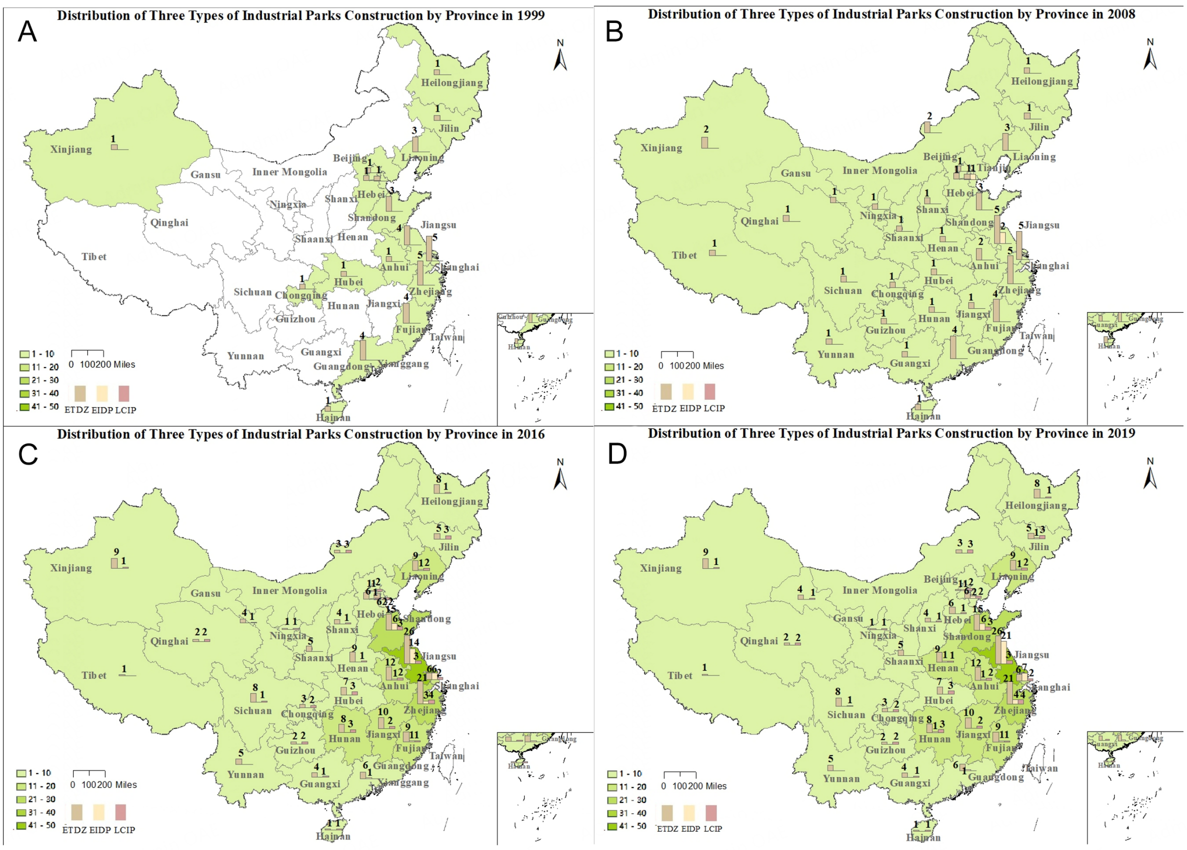

Figure 2. Distribution of the three types of industrial parks by province in 1999 (A), 2008 (B), 2016 (C) and 2019 (D). The shade of the fill color indicates the province-level amount of relevant industrial parks for a given year, and the three-color bar charts show the province-level amount of ETDZs, EIDPs and LCIPs for a given year.

Robustness check

Placebo test

To check the robustness of the DID results, placebo tests were conducted. Figure 5 shows the kernel density distribution of placebo tests for the three types of industrial parks. Significant differences between the placebo and actual regression coefficients confirm the robustness of the baseline model results.

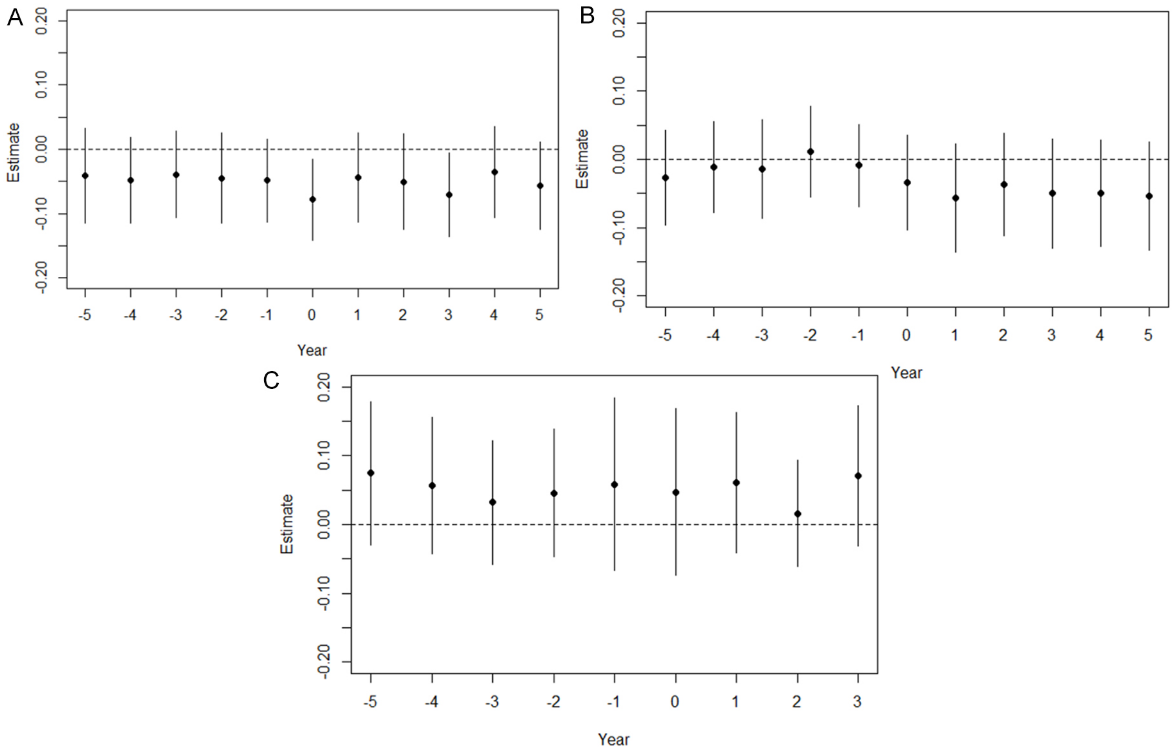

Figure 3. Parallel trend test of carbon emission intensity - ETDZ (A), EIDP (B), and LCIP (C).

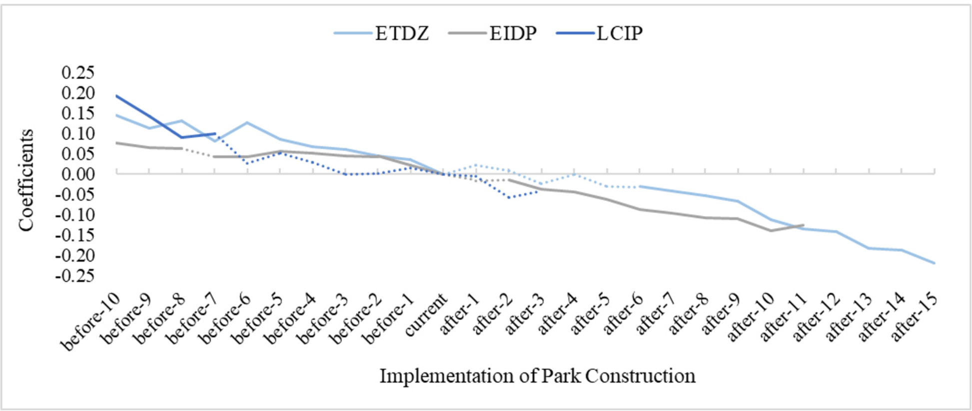

Figure 4. Results of the dynamic effect model analysis of the impact of park construction on a city's carbon emissions. notes: the solid line indicates that the regression coefficient is significant; the dashed line indicates that the regression coefficient is insignificant.

Exclusion of special sample test

Special samples, like Suzhou with numerous industrial parks, could potentially skew the results. Therefore, cities with three or more parks of the same type were removed for robustness analysis, and the remaining data were reanalyzed using the baseline model.

Table 4 shows that after excluding special samples, the coefficient for ETDZs changed slightly from -1.1545 to -1.1515, both significant at the 1% level. Other variables remained largely unchanged, indicating that the presence of special samples did not bring about significant effects. For EIDPs, small changes in coefficient

Table 4. Excluding special sample test analysis of the impact of industrial park construction on city carbon emissions

	ETDZ		EIDP		LCIP	
	Before	**After**	**Before**	**After**	**Before**	**After**
TREAT	-1.1545*** (0.0576)	-1.1515*** (0.0591)	-0.3949*** (0.0450)	-0.3942*** (0.0452)	-0.4504*** (0.0499)	-0.4504*** (0.0499)
Constant	2.2756*** (0.1784)	2.3426*** (0.1900)	1.5870*** (0.1945)	1.5895*** (0.1992)	1.6425*** (0.1863)	1.6425*** (0.1863)
N	4,284	4,284	4,284	4,284	4,284	4,284
CONTROL	Y	Y	Y	Y	Y	Y
City fixed effects	Y	Y	Y	Y	Y	Y
Time fixed effects	Y	Y	Y	Y	Y	Y
R^2	0.4986	0.4899	0.4986	0.4956	0.4986	0.4986

***P < 0.01. The values in parentheses are standard errors.

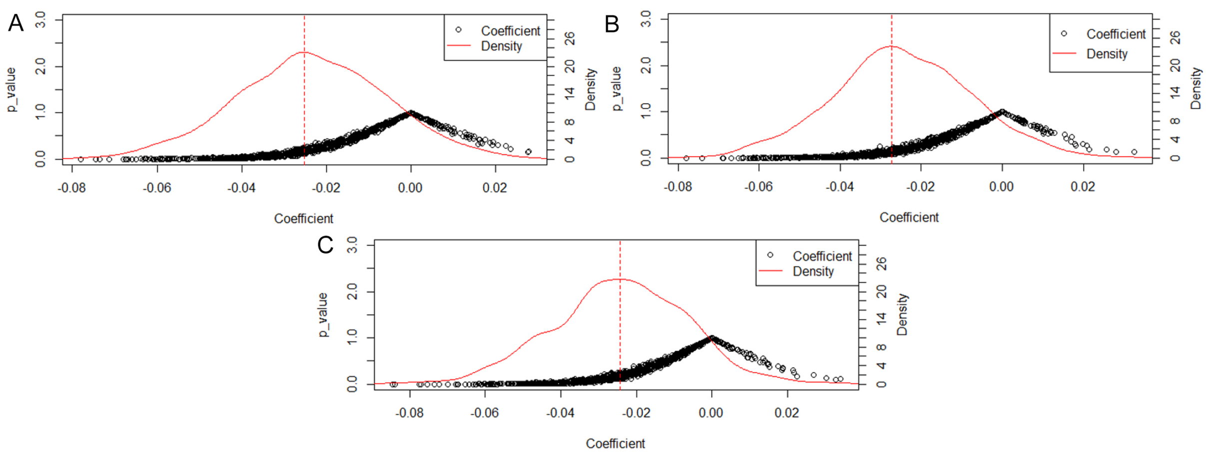

Figure 5. Placebo test for the carbon emission impact - ETDZ (A), EIDP (B), and LCIP (C). notes: the black hollow circles are the random regression coefficients obtained from each regression, and the red curve shows its kernel density distribution, with the highest point of the kernel density distribution marked by the red dashed line.

magnitudes and continued statistical significance were found. For LCIPs, there was virtually no difference after excluding special samples, further supporting the robustness of the regression results.

Consideration of other policies

During the study period, China implemented the low-carbon city pilot policy with known carbon reduction effects[37]. To examine its impact on the results, the variable "low carbon city pilot policy" was added to the baseline model, where its value is assigned to 1 if pilot cities and 0 otherwise.

Table 5 shows that the core coefficients for all three types of industrial parks remain negative and statistically significant at the 1% level. This confirms that, even after controlling for other relevant policies, the construction of industrial parks significantly promotes urban carbon reduction.

Additionally, this study carried out the analysis using the propensity score matching (PSM) method. Supplementary Figure 1 in the Supplementary Materials presents the absolute standardized mean differences before and after PSM matching for the three types of industrial parks. Supplementary Table 4 shows the PSM-based analyses of the impact of industrial park construction on city carbon emissions, which also confirm the robustness of the results.

Table 5. Accounting for other policy analyses for the impact of industrial park construction on city carbon emissions

	ETDZ		EIDP		LCIP	
	(1)	**(2)**	**(3)**	**(4)**	**(5)**	**(6)**
TREAT	-1.1545*** (0.0576)	-0.0781*** (0.0149)	-0.3949*** (0.0450)	-0.3949*** (0.0450)	-0.4504*** (0.0499)	-0.4504*** (0.0499)
Low carbon city pilot policy		-1.0764*** (0.05282)		-0.7596*** (0.0193)		-1.1545*** (0.0576)
Constant	2.2756*** (0.1784)	2.3466*** (0.1784)	1.5870*** (0.1945)	2.3466*** (0.1784)	1.6425*** (0.1863)	2.7970*** (0.1526)
N	4,284	4,284	4,284	4,284	4,284	4,284
CONTROL	Y	Y	Y	Y	Y	Y
City fixed effects	Y	Y	Y	Y	Y	Y
Time fixed effects	Y	Y	Y	Y	Y	Y
R^2	0.4986	0.4986	0.4986	0.4986	0.4986	0.4986

***$P < 0.01$. The values in parentheses are standard errors. Columns (1), (3), and (5) show the results without the introduction of the low-carbon city pilot policy variable, while columns (2), (4), and (6) show the results with the new variable.

DISCUSSION

This study investigated the effects of three different national-level industrial park policies on urban carbon emissions in China: Economic and Technological Development Zones (ETDZs), Eco-Industrial Demonstration Parks (EIDPs), and Low-Carbon Industrial Parks (LCIPs). The role of industrial structure in the emission change process and the spatial spillover effects of industrial parks on neighboring cities were also explored. Different types of industrial parks appear to exhibit varying degrees of effectiveness in reducing city carbon emissions, depending on the policy focuses, geographical locations, and city resource conditions.

First, ETDZs showed the strongest impact on reducing carbon emissions, particularly in more developed areas. This is likely due to the focus on attracting high-tech industries, promoting innovation, and industrial upgrading, which improve energy efficiency. However, the reduction effects would not manifest until a lag of around 7 years. For High-Tech Industrial Development Zones (HTIDZs) located in the economically developed eastern coastal areas, they exhibit stronger carbon emission control capabilities thanks to better infrastructure, stronger policy support, and more concentrated technological and financial resources. The rapid development of the zones, coupled with their higher degree of openness to foreign investment, brings about an advantage in curbing carbon emissions compared to their counterparts in less developed regions. Therefore, this study suggests that more incentives for green technology investment and industrial upgrading be provided, especially in central and western regions, so as to raise the level of carbon reduction outcomes.

Second, EIDPs achieved significant emission reductions by promoting cleaner production and industrial symbiosis, with effects visible within 3 years. These parks improve resource efficiency and waste utilization, leading to lower carbon emissions. Therefore, expanding the EIDP model, particularly in regions dominated by heavy industry, may help promote resource-sharing and circular economy practices and thus potentially reduce carbon emissions.

Third, although LCIPs aim to reduce emissions by deploying low-carbon technologies, their effects were not significant during the study period, likely due to the recent establishment and a need for more time to exhibit visible impacts. Hence, long-term support and financial incentives would be needed to promote low-carbon technologies.

CONCLUSIONS

Using a dataset covering 204 cities across China over the period of 1999-2019, this study investigated the effects of three different types of industrial park policies on city carbon emissions. The DID method and the mediation effects model were employed. The results show that: (1) the construction of all three types of industrial parks, ETDZ, EIDP, and LCIP, significantly reduced city carbon emission intensity, with ETDZ exhibiting the strongest effect; (2) Lag effects exist, where it takes an average of 7 years for ETDZ to exhibit emission reductions, and for EIDP an average of 3 years. LCIP has not yet shown dynamic emission reduction effects during the study period; (3) Both ETDZ and EIDP induce carbon emission reductions by raising the GDP share of the tertiary sector relatively, yet the mediating role of industrial structure for LCIP was not evident; (4) The emission effects of industrial parks would vary in sign and magnitude with respect to city's geographical region, resource endowments, and their own amounts; and (5) All three types of industrial parks exhibit spatial spillover effects, with ETDZ and EIDP reducing the carbon emission intensity of surrounding cities, while LCIP does the opposite.

Limitations

The study has several limitations that may affect the findings. First, the data period of 1999-2019 may not be long enough to fully capture the long-term effects of some industrial parks, especially LCIP. Second, the control variables used (investment level, industrial development, economic development, and population density) may not capture the influence of other potentially important factors like energy mix, technological innovation, transportation infrastructure, and environmental policies, which could also influence carbon emissions. Additionally, the study focuses on three types of industrial parks, potentially overlooking the effects of other industrial park types. These limitations suggest that the results may not have fully reflected the broader or longer-term impacts of industrial park policies on carbon emissions. Future research could extend the data range, incorporate additional control variables, and consider more types of industrial parks to address these issues[38-40].

DECLARATIONS

Authors' contributions

Made substantial contributions to the conception and design of the study and performed data analysis and interpretation: Hu X, Zhang YW

Performed the data acquisition and provided administrative, technical, and material support: Geng Y, Zhang YW, Yu H, Li L

Availability of data and materials

The data used for this study could be available from the corresponding author upon reasonable request.

Financial support and sponsorship

This work was supported by the National Natural Science Foundation of China (72088101) and Shanghai Jiao Tong University (WF220428008).

Conflicts of interest

Geng Y is the Guest Editor of the Special Issue "Pathway and Policy Implications of Urban Low-Carbon Transition under Carbon Neutrality" and the Editor-in-Chief of the journal *Carbon Footprints*. While the other authors declared that there are no conflicts of interest.

Ethical approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

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