

Does smart city pilot policy reduce CO₂ emissions from industrial firms? Insights from China



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ABSTRACT

As major producers in the national economy, industrial enterprises bear great responsibility for carbon emissions. A smart city pilot policy (SCPP) with innovative advantages and environmentally friendly features provides a feasible way to scientifically achieve carbon emission reduction targets while maintaining industrial growth. However, there is a lack of specific understanding of the microscopic carbon reduction mechanisms of the policy. Thus, based on the data of A-share listed industrial firms from 2009 to 2018 in China, this study explores the impact mechanism of the SCPP on the CO₂ emissions from industrial firms with the time-varying DID methodology and the mediating effect model. The results demonstrate that the SCPP can curb CO₂ emissions from industrial firms in China by 23% by strengthening the intensity of environmental regulation and promoting green technological innovation. Further analysis indicates that the mediating effect of resource allocation efficiency only works in industrial firms in low-carbon industries, not high-carbon industries. In addition, the heterogeneity test suggests a pronounced reduction effect of the SCPP on non-state-owned enterprises (non-SOEs), and industrial enterprises in low-carbon industries, resource-based cities and eastern China. This paper is of great significance for providing theoretical and practical implications for making rational use of smart city policies to improve the carbon reduction performance of enterprises.

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Introduction

In response to the climate change caused by increased greenhouse gas concentrations in the atmosphere, nearly 200 countries around the world passed the Paris Agreement at the UN Climate Summit held in 2015 and successively formulated carbon-neutral planning routes suitable for their own national conditions. Reducing carbon emissions has become a priority for governments to curb global temperature rise at this stage. Existing research points out that the production and emission of CO₂ mainly come from industrial firms (Zhang et al., 2020). Figures released by the International Energy Agency show that the CO₂ emissions of the energy power generation and heating industry alone account for 43% of the total emissions. Even in the United States, which is in the postindustrial era, the CO₂ emissions generated in the industrial production process also account for nearly one-third of the total CO₂ emissions, and the Industrial Technology Innovation Advisory Committee was urgently established

to reduce industrial CO₂ emissions. In contrast, developing countries in the middle and late stages of industrialization are facing more severe industrial carbon emissions. However, in addition to being responsible for carbon emission reduction, industrial firms are also major contributors to national GDP, and play an important role in social and economic development (Wang & Feng, 2018). Directly cutting industrial output to curb CO₂ emissions will adversely affect economic development. Therefore, the realization of “carbon neutrality” goals must place carbon emission reduction and industrial development within the unified framework of green development, to address the dual pressures of economic growth and environmental protection.

To achieve carbon emission reduction, the United States, Japan and many countries have successively implemented a series of policies. Pure environmental regulation measures, such as carbon emission trading scheme policies, green credit policies and low-carbon pilot policies, realized the environmental benefits of policies by internalizing the external costs and aggravating the emission pressure of industrial firms, which might have a negative impact on the development of industrial enterprises and lack consideration of their economic benefits (Greenstone, 2012; Lian et al., 2022). In contrast,

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SCPPs with dual characteristics of innovation and greenness provide a more feasible way to achieve the win-win development of industrial growth and carbon emission reduction. On the one hand, the SCPP can be regarded as a digital technology revolution. Their essence is an advanced development model that integrates new-generation digital technologies such as cloud computing, the Internet of Things (Yu and Zhang, 2019; Jo et al., 2021; Jiang et al., 2021), and spatial geographic information integration into modern urban scene applications (Anand et al., 2017), which can provide an environmental intelligent management capability for industrial firms to achieve scientific transformation and green upgrades. On the other hand, the birth of “smart cities” which have a unique “green foundation” (Yigitcanlar & Kamruzzaman, 2018), is closely related to solving “urban diseases” such as energy shortages and environmental pollution caused by rapid industrialization and large-scale urbanization (Chu et al., 2021; Fan et al., 2021; Feng and Hu, 2022). Policy-makers have always incorporated green and low-carbon development goals into the top-level design framework of “Smart City”, hoping to promote energy conservation and emission reduction through this approach (Ferrara, 2015). In that way, as the main undertaker of carbon emission reduction, can industrial firms take advantage of the “digital + green” transformation opportunities brought by SCPPs to reduce CO₂ emissions? This is an issue of great practical significance, but we know little about it.

China provides a unique sample for the discussion of this topic. First, as the largest developing country in the world, China's CO₂ emissions have always ranked first in the world since 2006. By 2020, they reached 9.89 billion tons, accounting for 30.9% of the world's total CO₂ emissions (BP, 2021). In China, the industrial sector accounts for more than 70% of the total carbon emissions, which plays a pivotal role in the global carbon reduction process. In the face of enormous pressure from the international community, China announced at the 75th UN General Assembly that “China will strive to peak carbon dioxide emissions by 2030 and achieve ‘Carbon Neutrality’ by 2060”, expressing the determination to take responsibility for carbon emission reduction and climate change mitigation. A low-carbon development path will become a long-term strategy for China's development. At the same time, since IBM officially proposed the concept of the “Smart City” in 2008, China has followed the international pace, officially released the SCPP in 2012, and continued to expand the list of smart city pilots in 2013 and 2014. By 2020, China's investment in SCPPs has reached 25.9 billion dollars, ranking the second in the world. The number of smart city pilots currently under construction or in operation accounts for approximately half of the global total, showing a trend of spread from point to surface, which has exerted a profound impact on China's economic development and environmental governance. Thus, China's SCPP provides a good quasi-natural experiment for our research.

Therefore, based on the data of A-share listed industrial firms in China, this paper analyzes the carbon emission reduction effect of SCPPs in depth and tries to answer the following questions: Do SCPPs have an impact on CO₂ emissions from industrial firms? What is the impact mechanism by which the SCPPs affect CO₂ emissions from industrial firms? Are there some factors that affect the carbon reduction effect of SCPPs? The research conclusions not only provide new ideas for industrial firms to reduce CO₂ emissions to reach the world's “carbon neutrality” goal, but also provide a new reference for the improvement of smart city construction.

The remainder of this paper is organized as follows: Section 2 reviews the relevant literature, presents the institutional background of smart city construction and illustrates hypothesis development. Section 3 introduces the data and method. Section 4 presents the empirical results. Robustness tests are provided in Section 5. Section 6 further analyzes the mediation mechanism and examines heterogeneity. Section 7 concludes this study and proposes related policy implications.

Theory and hypothesis

Literature review

At present, there are few studies that directly study the influence mechanism of SCPPs on CO₂ emissions from enterprises. The literature related to this paper mainly includes two aspects: the research on the factors affecting corporate CO₂ emissions and the research on the influence of SCPPs.

The literature on the influencing factors of corporate CO₂ emissions can be roughly divided into two categories. The first category mainly focuses on the internal factors that affect corporate CO₂ emissions, such as CEOs' response to climate change (Garel & Petit-Romec, 2022), liability structure (Chen & Zhu, 2022), ownership structure (Yang et al., 2019), the technical level, company size, manager perception (Yang et al., 2019), and board features (Ben-Amar et al., 2017). The second type of literature mainly focuses on the impact of the external factors on corporate CO₂ emissions, such as the business environment (Liu, 2012), environmental regulation (Chen et al., 2018; Ren et al., 2022), degree of internationalization (Sadler, 2016), and regional differences (Cole et al., 2013). The literature on the influencing factors of corporate CO₂ emissions is still based on the traditional perspective, which can provide an important reference for the selection of variables in this paper, but lacks exploration of the relationship between SCPPs and corporate CO₂ emissions. In addition, most studies use firms from all industries as research samples, ignoring the fact that industrial firms are the primary source of CO₂ emissions, resulting in biased research objects.

Another category of literature relevant to this paper discusses the effects of SCPPs. These studies discussed the role of SCPPs in economic and environmental aspects at the city level or the industry level. First, the economic effect research mainly finds that SCPPs play a significant role in industrial transformation and upgrading (Jo et al., 2021), total factor productivity improvement (Yu & Zhang, 2019; Jiang et al., 2021), employment creation (Bakici et al., 2013), economic growth (Caragliu & Del, 2018), and the low-carbon economy (Fan et al., 2021). Most of these studies show that technological innovation serves as an intermediary transmission mechanism. Second, environmental effect research has verified that SCPPs can effectively alleviate urban environmental pollution (Chu et al., 2021; Feng & Hu, 2022), improve the urban ecological environment (Contreras & Platania, 2019; Yao et al., 2020), and promote sustainable urban development (Yigitcanlar & Kamruzzaman, 2018). In such studies, a few scholars have also paid attention to the possible impact of SCPPs on CO₂ emissions. Cavada et al. (2015), Zawieska and Pieriegud (2018) and Guo et al. (2022) confirmed the impact of SCPPs on reducing urban CO₂ emissions and transportation industry CO₂ emissions. Wang et al. (2019), Sun and Zhang (2020), and Zhang et al. (2022) also introduced the exogenous impact of SCPPs in the empirical process of studying the urban CO₂ emission reduction effect of the digital economy, which confirmed from the theoretical side that SCPPs can indeed reduce urban CO₂ emissions. In contrast, there are relatively few studies discussing the impact of SCPP on micro-enterprises, and they mainly focus on promoting enterprise development, such as improving enterprise TFP, and promoting high-quality enterprise development. A few studies involving corporate emission governance have only analyzed the impact of SCPPs on enterprise emission behavior at the theoretical level (Shi et al., 2018). On the whole, the existing empirical studies on the impact of SCPPs are abundant, which can broaden the perspective and provide ideas for the research in this paper. In addition, while some studies have discussed the carbon emission reduction effect of SCPPs from theoretical and macro perspectives, providing theoretical and methodological support for this paper,

in-depth research on the microscopic carbon emission reduction effects of SCPPs remains lacking. In particular, the research on the actual impact mechanism of SCPPs on enterprise carbon emissions is insufficient, and cannot provide guidance for government administrators to give full play to the role of policy. As a result, in the following section, an analysis of the impact of the SCPP on enterprises' carbon emission reduction from a micro perspective is proposed.

Background on smart city construction

The germination of the "Smart City" is closely related to the realization of the goals of urban environmental governance and sustainable development. It first appeared in the concept of "Smart Growth" proposed by the American New Urbanism movement in the 1980s and was formally defined in "Smarter Planet: A Leadership Agenda for the Next Generation" released by IBM in 2008. IBM explained that the process of the construction of a smart city involves embedding smart sensors with various data collection and transmission functions into the infrastructure or natural environment and then monitoring the running status of the city's economy and environment in real time through the new generation of digital technology; this promotes the realization of intelligent urban governance and sustainable development. At present, the relevant practice of SCPPs has been rolled out around the world. Most European countries, such as the United Kingdom, Italy, and Sweden, have successively formulated smart city development strategies with the core goal of promoting coordinated development of the environment and economy. In 2012, the European Union (EU) launched the "European Innovation Partnership for Smart Cities and Communities" to strengthen the construction of smart cities in basic fields such as energy and transportation. Following that, the EU fully recognized the important role of technological innovation in the process of solving the climate problem and further proposed to making "Smart Europe" one of the long-term development goals of "Europe 2020" and expanding the construction of smart cities with the theme of green ecology (Beretta, 2018). In Asia, Japan, South Korea, Singapore and many other countries have launched smart city construction projects such as "I-Japan" and "U-Korea", aiming to build cities with both digital links and environmental protection features. Thus, solving the problem of environmental governance and promoting the realization of green and low-carbon goals not only exists in IBM's smart city vision but also operates through the practice of smart city construction in various countries. In addition, Cohen (2014), a US climate change strategist, has reaffirmed the importance of building a "Smart Environment" in the "Smart Cities' Wheel". Other studies have also found that smart cities cover the environmentally friendly features of "low exhaust emissions" and "optimal resource allocation", which have already surpassed through the simple category of "digitization and informatization" (Ferrara, 2015).

China's smart city construction practice also prioritizes green and low-carbon targets. In 2012, China launched the SCPP, designating 90 prefecture-level and county-level cities as the first batch of pilot cities. In the following two years, China announced two other batches of smart city pilot lists and issued a number of guiding policies, such as "The Guiding Opinions On Promoting the Healthy Development Of Smart Cities", to guide the construction of online intelligent monitoring platforms for the natural environment and pollution discharge and fully stimulate the intensive, intelligent, green and low-carbon functions of smart cities. In 2019, the SPCC was reaffirmed as a powerful measure to promote environmental protection and emission reduction in the "China-ASEAN Smart City Cooperation Initiative Leaders' Statement". It is foreseeable that the SCPP will have a significant and far-reaching impact on the realization of China's "carbon neutrality" and "carbon peaking" goals.

Hypothesis development

According to the above background, the focus of smart city construction whose top-level goals always contain promoting green and low-carbon development, is to use a new generation of information technology to promote the intelligentization of urban construction, management and operation to create a livable city system with harmonious development of economy, society and environment. Driving green and low-carbon development with smart city construction essentially means providing support and guarantees for environmental governance and emission control through technological innovation. The "green means" of smart cities can be classified into three categories: smart monitoring, smart management and smart development. "Smart monitoring" refers to realizing real-time environmental monitoring and early warning through modern monitoring methods and providing accurate data for relevant decision-making departments. "Smart management" refers to using the information processing advantages of big data and cloud computing to assist environmental governance and then help improve management efficiency and scientific decision-making (Ramaswami et al., 2016). "Smart development" refers to using smart technology upgrades to promote the green transformation of traditional industries and reduce energy consumption and carbon emissions. When the above three measures work together on the low-carbon transformation of industrial firms, they can effectively reduce the CO₂ emissions of firms by enhancing the intensity of environmental regulation, promoting green technology innovation and optimizing the efficiency of resource allocation.

First, the SCPP reduces the CO₂ emissions of industrial firms by strengthening the intensity of environmental regulations. Considering the character of environmental sustainability in smart cities, governments often have stricter environmental protection requirements for smart cities than for other ordinary cities. For example, it is clearly stated in the "National Smart City Pilot Index System" in China that smart cities should achieve the smart management of the urban ecological environment, which will improve the intensity of local environmental regulation at the institutional level. Moreover, the "Smart Monitoring" method of smart cities uses satellite remote sensing and infrared detection technology to integrate urban environmental conditions and corporate pollution into real-time monitoring, and then provides a timely and reliable basis for environmental regulatory authorities to formulate environmental policies through the early warning network based on the Internet of Things technology. As a result, the intensity of environmental regulation can be improved by SCPPs at the technical level. In addition, the widespread use of digital platforms will further strengthen the online public's supervision of high-carbon companies and promote the formation of informal environmental regulations. The increase in the intensity of environmental regulation will prompt the government to impose strict emission control on high-consumption, high-pollution, and high-emission enterprises. When firms face higher government pressure and emission costs, they will actively choose to reduce CO₂ emissions by reducing output or adjusting production technology.

Second, the SCPP reduces the CO₂ emissions of industrial firms by promoting green technological innovation. In addition to the general functions of innovation, green technology innovation is also well equipped with the characteristics of energy saving, emission control and environmental improvement (Shahzad, 2022), which is one of the powerful means to promote the CO₂ emission reduction performance of firms. Similar to ordinary technological innovation, funds, talent and technology are the three core foundational elements of green technological innovation (De Marchi, 2012; Gu, 2022). Different from general innovation, green technology innovation often faces higher technical barriers, a longer development cycle and greater R&D risks. In terms of funds, local governments are facing greater pressure for green transformation in the process of smart city construction, so they will choose to implement incentive policies to

support the green innovation activities of firms and stimulate their willingness to carry out green innovation (Zygiaris, 2013). Furthermore, the SCPP promotes the application of digital technology in the financial field, enhances the credit rating capabilities of financial institutions, alleviates the problem of information asymmetry in traditional lending, and facilitates external financing for firms. In terms of talent, the intelligent development of cities can improve the level of urban public services and generate a large number of rigid demands for innovative talent, which may attract scientific and technological talent to gather and provide sufficient intellectual support for the green innovation of firms (Caragliu & Del Bo, 2018). In terms of technical support, the development of new infrastructure with features of cleanliness, energy saving and recycling promotes enterprises to innovate green technologies at the lowest cost. Moreover, the wide application of digital technology breaks the time and space limitation of information flow, reduces the search cost of firms for external technical information, promotes knowledge exchange and technology diffusion among firms, and provides sufficient technical input for firms to carry out green technology innovation activities.

Third, the SCPP reduces the CO₂ emissions of industrial firms by optimizing the efficiency of resource allocation. The problem of resource allocation is the main cause of the development conflict between the economy and the environment. Studies have proven that optimizing resource allocation has a significant impact on improving carbon emission efficiency (Wang et al., 2021). SCPPs promote the large-scale application of emerging information technology, break through the institutional and technological constraints under the traditional urban operation mode, and provide strong support for the revitalization and optimization of enterprise resource allocation. Based on big data technology, corporate decision-makers can mine the market demand quantity and demand preference, formulate reasonable production plans, reduce unnecessary output, avoid wasting resources, and reduce carbon emissions. Through deep learning and other new computing technologies, corporate producers can find the optimum parameter configuration of production raw materials and use intelligent sensing and monitoring equipment to dynamically collect energy consumption and exhaust emissions data in the production process, constantly optimizing the energy consumption structure in the production process to achieve carbon emission reduction. In addition, digital technology can help corporate buyers find the optimal quantity and quality of factors of production to reduce carbon emissions in the process of raw material trading and transportation (Shi et al., 2018). Moreover, the emergence of information-based management modes and the popularization of new management methods such as paperless offices and teleconferencing gradually promote the transformation of enterprise management to intelligent governance, helping to avoid the waste of resources caused by low management efficiency. These tips also contribute to the achievement of carbon emission reduction targets (Witkowski, 2017).

Thus, this paper proposes the following four hypotheses.

- H1:** SCPPs reduce CO₂ emissions from industrial companies.
- H2a:** SCPPs reduce the CO₂ emissions of industrial firms by strengthening the intensity of environmental regulations.
- H2b:** SCPPs reduce the CO₂ emissions of industrial firms by promoting the ability of green technological innovation.
- H2c:** SCPPs reduce the CO₂ emissions of industrial firms by optimizing the efficiency of resource allocation.

Research design

Data

Taking the three batches of SCPPs launched in China in 2012 as a natural experiment, we adopt the time-varying difference-in-

differences (DID) methodology to explore the impact of SCPPs on CO₂ emissions from industrial firms. In this research, A-share listed industrial firms are taken as our sample, and the research period is set between 2009 and 2018 to ensure the availability of data and the consistency of statistical caliber. Meanwhile, to ensure the validity and stability of the sample, we process the sample data as follows: (1) keep firms belonging to industrial sectors; (2) exclude the firms that suffer continuous losses and are special treated (ST or *ST); (3) exclude firms with fewer than 8 employees; and (4) exclude the firms with missing critical data. Eventually, we obtain a sample of 1079 A-share listed industrial firms from 2009 to 2018. The data are collected from different sources, which can be seen in [Supplementary Materials \(SM\) Page S1](#).

Variables

Dependent variable: CO₂ emissions (CE). Due to the inability to directly obtain the corporate CO₂ emissions data, we calculate the data based in a feasible way, following Ren et al. (2022). The detailed computation process is presented in the [SM \(Pages S1-2\)](#).

Independent variable. The SCPP was launched in three batches in China in 2012, and it impacted different cities at different times. SCPP is set as a dummy variable, including whether the city where the firm is located is established as a smart city (*Treat*) and before or after the establishment time of the SPCC (*Post*). *Treat* equals 1 if the city is established as a smart city and equals 0 otherwise. *Post* equals 1 if the time after the establishment of a smart city for the city and equals 0 otherwise. Therefore, $SCPP_{it} (Treat_{it} \times Post_{it})$ equals 1 in the current year and every subsequent year if the city where firm *i* is located is established as a smart city at time *t* and equals 0 otherwise.

Mediating variables. According to theoretical analysis, SCPPs may affect the CO₂ emissions of industrial firms by strengthening the intensity of environmental regulation, promoting green technological innovation, and optimizing resource allocation efficiency. Therefore, we choose the following mediating variables to discuss the impact mechanism: environmental regulation (*ER*), green innovation (*GI*), and resource allocation (*RA*). The measurement of the three variables will be specified in the [SM \(Page S3\)](#).

Control variables. Based on the existing related studies (Zawieska & Pieriegud, 2018; Guo et al., 2022; Garel & Petit-Romec, 2022; Obobisa et al., 2022), we select the following control variables. (1) Firm-level control variables: The carbon emissions of a firm are always influenced by other company characteristics. We add some variables in the model to control the potential effect on carbon emissions: establishment age of the firm (*Age*), firm size (*Size*), debt-to-asset ratio (*Lever*), capital intensity (*Capital*), return on total assets ratio (*ROA*), cash flow (*Cash*), and shareholding structure (*Larshare*). (2) Regional control variables: The CO₂ emissions of a firm are also affected by the characteristics of the city where the firm is located. To eliminate endogenous errors caused by regional characteristics, we select economic development (*Pgdp*), population (*Pop*), foreign direct investment (*Fdi*), industrial structure (*Ind*), internet development level (*Net*), government finance structure (*Gov*), and financial development (*Fin*) as control variables. The definitions of all variables are displayed in [Table A1 \(SM, Page S3\)](#).

Model specification

Unlike ordinary experiments, the implementation of public policies is nonrandom. Thus, direct comparison of changes in the mean value of outcome variables before and after the implementation of policies will lead to estimation errors. For the SCPP in China, a multi-time progressive quasi-natural experiment, it is necessary to use the difference-in-differences (DID) methodology proposed by Ashenfelter and Card (1985) for the test. The DID method uses the idea of regression to better control for systematic differences between the

experimental and control groups while being able to avoid the endogeneity problems that arise when policy is used as an explanatory variable (Beck et al., 2010). The basic research idea is to set the firms located in cities that have implemented SCPPs as the treatment group, and set the firms located in non-pilot cities as the control group. In addition, a small number of smart city pilots are set up in districts or counties whose development levels are different from those of prefecture-level cities, so this research only sets the firms located in prefecture-level cities that have implemented SCPPs as the treatment group to avoid deviating from the empirical results. Then, on the basis of controlling other factors, the time-varying DID can evaluate whether SCPPs reduce the CO₂ emissions of industrial firms. Following Wolff (2014), the model of the time-varying DID estimation is as follows.

$$SCPP_{it} = Post_{it} \times Treat_{it} \quad (1)$$

$$CE_{it} = \alpha + \beta SCPP_{it} + \theta \sum X + \gamma_t + \delta_r + \mu_j + \varepsilon_{it} \quad (2)$$

where i and t denote firm and year respectively; CE_{it} refers to the CO₂ emissions of firm i in year t ; $SCPP_{it}$ is the interaction term of time dummy variable ($Post_{it}$) and dummy variable of whether policy is implemented ($Treat_{it}$), which indicates whether firm i is located in pilot city in year t ; X denotes a series of firm-level control variables and regional control variables; α represents a constant term; ε_{it} represents a random disturbance term; γ_t , δ_r and μ_j represent year, regional and industrial fixed effects, respectively; and β is the coefficient of the core explanatory variable, which reflects the effects of the SCPP program on the CO₂ emissions of industrial firms.

To ensure the exogeneity of the target estimator, the grouping and timing of the experiment should be randomized to achieve the basic condition in Eq. (3).

$$E[\varepsilon_{it}|SCPP_{it}] = 0 \quad (3)$$

At this point, the real effect $\hat{\beta}$ after experimental treatment can be easily obtained.

$$\hat{\beta} = E[CE|SCPP_{it} = 1] - E[CE|SCPP_{it} = 0] \quad (4)$$

In reality, however, most of the policy evaluations by the DID method are real social experiments. Researchers generally cannot accurately control for all extraneous factors and errors, and in this case we just need to ensure that $E[\varepsilon_{it}] = 0$.

Empirical results

Descriptive statistics

For the total sample, the mean value of the CO₂ emissions of industrial firms is 10.478, and the standard deviation is 2.630, which indicates a significant difference among samples. The statistical results of other variables also indicate that substantial variance exists among samples. Furthermore, the treatment group consists of firms located in cities that implemented SCPPs between 2009 and 2018, whereas the control group consists of firms located in non-pilot cities during the same period. For the treatment group, the mean value of the CO₂ emissions of industrial firms is approximately 10.347. For the control group, it is approximately 10.661. The descriptive results imply that the implementation of SCPPs may lead to a reduction in the CO₂ emissions of industrial firms. The descriptive statistical results are shown in Table A2 (SM, Page S4).

Parallel trend analysis

The premise of adopting the time-varying DID method is to satisfy the parallel trend, namely, the CO₂ emissions in the treatment group and the control group have a similar trend before the start of the

SCPP. Referring to Beck et al. (2010) and Gehrsitz (2017), the event study method will be used to test parallel trends in this paper. The specific econometric model is as follows.

$$CE_{it} = \alpha + \beta_1 SCPP_{it}^{-4} + \beta_2 SCPP_{it}^{-3} + \dots + \beta_8 SCPP_{it}^{+3} + \beta_9 SCPP_{it}^{+4} + \theta \sum X + \gamma_t + \delta_r + \mu_j + \varepsilon_{it} \quad (5)$$

where $SCPP_{it}^{-n}$ represents the city where the firm i is located in the n th year prior to smart city construction, and $SCPP_{it}^{+n}$ represents the city where firm i is located in the n th year following smart city construction.

Fig. 1 presents the test result of the parallel trends. The result suggests that the estimated coefficients of SCPP are not significant before the implementation of the policy, and the coefficient values all fluctuate around 0. Therefore, there was no significant difference in the changing trends of corporate CO₂ emissions between the treatment group and the control group before the implementation of the policy, which indicates the satisfaction of the parallel trends. In addition, after the implementation of the policy, the estimated coefficients of SCPP are significantly negative and the absolute values of the coefficients increase gradually over time, indicating that the marginal effect of smart city construction on inhibiting the CO₂ emissions of industrial firms presents an increasing process.

Analysis of benchmark regression results

Table 1 presents the baseline regression results, and more specific regression results are shown in Table A3 (SM, Page S5-6). Specifically, in Column (1), a series of control variables and fixed effects are not added to the model, and the coefficient of SCPP is significantly negative at the 1% level. Column (2) incorporates year fixed effects, regional fixed effects and industrial fixed effects on the basis of Column (1), and the coefficient of SCPP is still significantly negative at the 1% level, which preliminarily indicates that the SCPP could reduce the CO₂ emissions of industrial firms. For further study, Columns (3) and (4) control a series of control factors that may affect CO₂ emissions based on Columns (1) and (2), respectively, and the coefficients of SCPP are statistically significant, which is in line with the empirical results in the literature (Guo et al., 2022). In Column (4), the estimated coefficient of SCPP is -0.233 and significant at 1%, indicating that the CO₂ emissions of industrial firms are 23.30% lower after the implementation of the SCPP. Thus, the policy has a strong statistical and economic significance in reducing the CO₂ emissions of industrial firms, and Hypothesis H1 is confirmed.

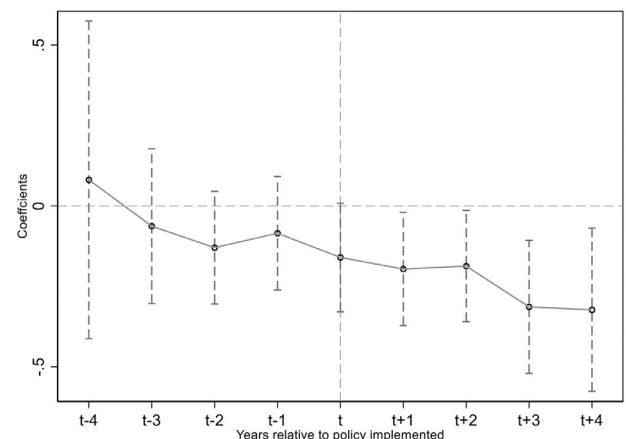


Fig. 1. Testing for the parallel trend assumption.

Table 1
The impact of SCPPs on carbon emissions from industrial firms.

Variables	(1)	(2)	(3)	(4)
SCPP	-0.261*** (0.053)	-0.334*** (0.060)	-0.352*** (0.046)	-0.233*** (0.050)
Constant	10.579*** (0.031)	10.607 (0.032)	-3.735*** (0.303)	-2.292*** (0.439)
Control variables	NO	NO	YES	YES
Year fixed effect	NO	YES	NO	YES
Regional fixed effect	NO	YES	NO	YES
Industrial fixed effect	NO	YES	NO	YES
Observations	10790	10790	10790	10790
Adjusted R ²	0.0022	0.2178	0.4519	0.5373

Notes: * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$. Robust standard errors are reported in parentheses. The same below.

Robustness tests

The baseline results reflect that the SCPP significantly reduces CO₂ emissions from industrial firms. We conducted a series of robustness tests as follows to verify whether the results are robust.

PSM-DID

To avoid estimation error and potential endogeneity problems caused by self-selection bias, we adopt the propensity score matching (PSM) method to match the treatment group and control group. For the PSM model, we select the firm-level control variables Age, Size, Lever, Capital, ROA, Cash, Larshare as the covariates to perform a logit regression to obtain the propensity score of firms in the treatment group and then match the control groups with similar characteristics using the nearest-neighbor matching method (Bowen et al., 2010). According to Fig. 2, the absolute standardized bias is significantly

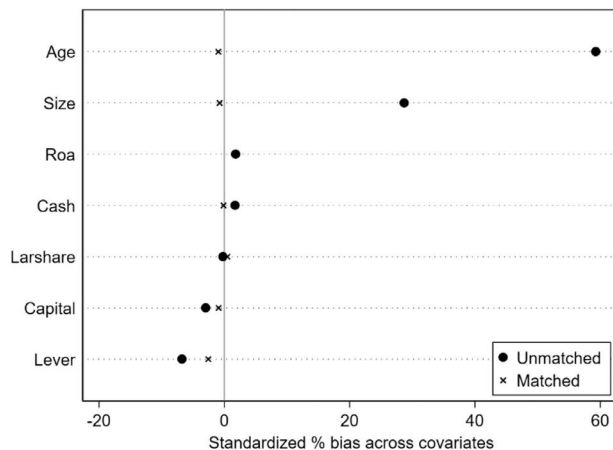


Fig. 2. Standardized bias values for matched data.

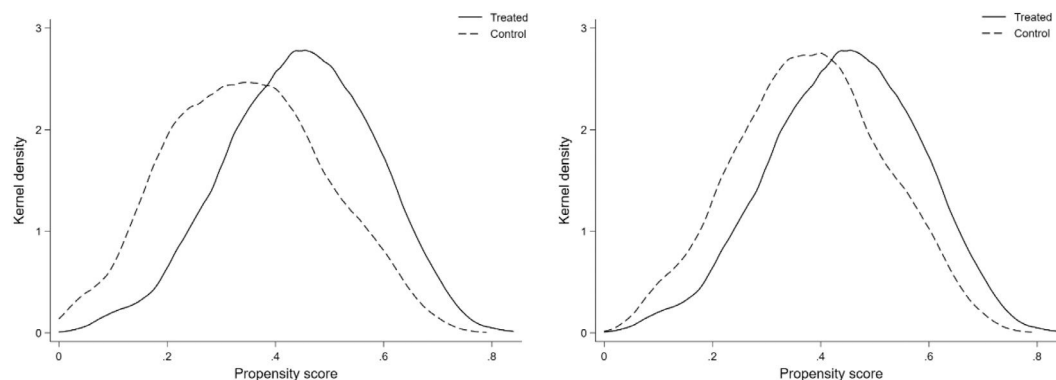


Fig. 3. Density map of the propensity scores by treatment and control group: before(left) and after(right) nearest-neighbor PSM.

reduced to less than 10% among all covariates, which indicates the reduction of self-selection bias (Rosenbaum & Rubin, 1985). In addition, the kernel density map of the propensity score value is shown in Fig. 3. We can see that the differences between the treatment group and control group are significantly reduced after matching. Column (1) of Table 2 reports the estimation results of the PSM-DID model. We find that the coefficient of SCPP is -0.217, significant at the 1% level, reconfirming the robustness of the baseline results.

Placebo test

Considering that the micro carbon reduction effect of SCPPs may be affected by some other random factors, a placebo test must be conducted. Following Zhao et al. (2020), we choose “false smart cities” randomly as the treatment group, and set the policy launch time of the treatment group at random. Subsequently, we estimate the coefficients in Column (4) of Table 2 using the newly generated treatment and control groups, thus completing a placebo test. The above process is repeated 500 times to obtain the estimated coefficient distribution of false SCPP to confirm the reliability of the baseline results. Fig. 4 plots the kernel density diagram of the estimated coefficient of false SCPP after 500 iterations. The results of the placebo test reveal that, the coefficient estimates show an approximate normal distribution trend with a mean value close to 0, which is significantly different from the coefficient of SCPP in the baseline regression. The above analysis fully illustrates that the negative effect of the SCPP on the CO₂ emissions of industrial firms is robust.

Replace the dependent variable

Considering the large differences in scale and operating capacity among different firms, we adopt the carbon emission intensity (CEI) as a proxy variable of CO₂ emissions (CE) for the robustness test to avoid the influence caused by the selection of different explained variables. CEI is calculated by dividing CE by the main business income of

Table 2
The results of robustness tests.

Variables	(1)	(2)	(3)	(4)	(5)	(6)
SCPP	-0.217*** (0.053)	-0.223*** (0.046)	-0.220*** (0.051)	-0.235*** (0.051)	-0.144*** (0.044)	-0.223*** (0.055)
LCPP			-0.106* (0.057)			
ETS				0.024 (0.075)		
Constant	-2.530*** (0.500)	-1.204*** (0.395)	-2.271*** (0.439)	-2.287*** (0.440)	-0.366 (0.410)	-2.219*** (0.462)
Control variables	YES	YES	YES	YES	YES	YES
Year fixed effect	YES	YES	YES	YES	YES	YES
Regional fixed effect	YES	YES	YES	YES	YES	YES
Industrial fixed effect	YES	YES	YES	YES	YES	YES
Observations	9146	10790	10790	10790	10790	9711
Adjusted R ²	0.5382	0.3130	0.5374	0.5373	0.5825	0.5275

the firm. Column (2) of Table 2 shows the result by replacing the dependent variable. The coefficient of SCPP is -0.223, which is significant at the 1% level, reaffirming that the results are relatively robust.

Exclude the impact of other contemporary policies

During the implementation of the SCPP, China also established a series of environmental policies to reduce pollution emissions. Incorporating only the dummy variable SCPP into the model cannot determine whether the carbon reduction effect is caused by the smart city pilot policy or other policies. Thus, to evaluate the net effect of the SCPP on corporate carbon emissions, the dummy variable LCPP representing the low-carbon pilot policy and the dummy variable ETS representing the carbon emission trading scheme policy are successively incorporated into the regression model. As shown in Columns (3) and (4) of Table 2, the coefficients of SCPP are still significantly negative after eliminating the interference of concurrent events.

Exclude the influence of outliers

Outliers of some variables will affect the results of the benchmark regression, so corresponding measures must be taken. In this research, the dependent variable and the firm-level control variables are winsorized by 5% to mitigate the error caused by outliers. As shown in Column (5) of Table 2, the coefficients of SCPP are still significantly negative after winsorization.

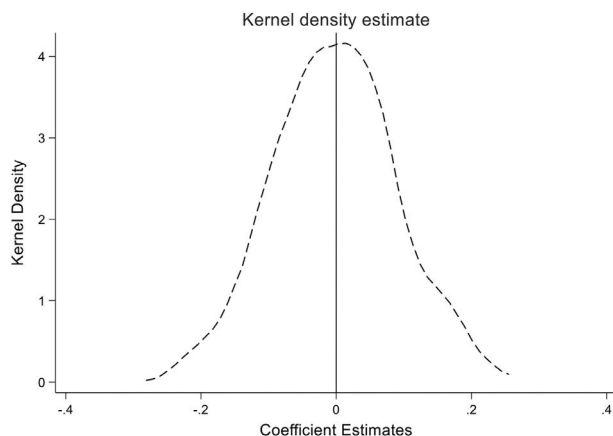


Fig. 4. Distribution for coefficients of treat (placebo test).

Lag test

Considering that the impact of SCPPs on the CO₂ emissions of industrial firms may not be immediate, we treat the dependent variable and all control variables with a one-period delay. As shown in Column (6) of Table 2, the coefficient of SCPP for the first lag period is -0.223, which is significant at the level of 1%, indicating that the possible lag of the policy effect does not affect the core conclusions in this paper.

Further analysis

Mechanism analysis

The above results of the baseline regression and the robustness tests demonstrate that the SCPP is conducive to the reduction of CO₂ emissions from industrial firms. Then, what are the mechanisms? Clarifying this issue is of great significance for future policy formulation and improvement. Based on the aforementioned theoretical analysis of mechanisms, the policy may impact CO₂ emissions through the following three mechanisms: the intensity of environmental regulation, the ability of green technological innovation, and resource allocation efficiency. Therefore, we adopt ER, GI and RA which have been defined in Section 2, as mediating variables for further tests. According to Baron and Kenny (1986), the mediation effect equations are established using the causal steps regression approach as follows:

$$M_{it} = c_0 + c_1 SCPP_{it} + \theta \sum X + \gamma_t + \delta_r + \mu_j + \varepsilon_{it} \quad (6)$$

$$CE_{it} = \varphi_0 + \varphi_1 SCPP_{it} + \varphi_2 M_{it} + \theta \sum X + \gamma_t + \delta_r + \mu_j + \varepsilon_{it} \quad (7)$$

where M_{it} refers to a mediating variable. Eq. (6) represents the effect of the SCPP on the mediating variables, which incorporate ER, GI and RA. In Eq. (7), the coefficient φ_2 represents the impact of the mediating variable on corporate carbon emissions.

Table 3 reports the mechanism analysis results of the inhibitory effect test. Columns (1) and (2) of Table 3 display the results with the mediating variables in Eq. (6) as ER and GI, respectively. The coefficients of SCPP are significantly positive at the 1% level, indicating that the implementation of the SCPP is conducive to strengthening the intensity of environmental regulation and promoting the ability of green technological innovation. Column (3) of Table 3 displays the result with the mediating variable RA in Eq. (6), the coefficient of SCPP is insignificant, implying that the resource allocation effect is not the effective channel. Then, we incorporate the independent, dependent and mediating variables into Eq. (7), the relevant estimation

Table 3
The results of mechanism analysis.

Variables	The first step			The second step		
	(1) <i>ER</i>	(2) <i>GI</i>	(3) <i>RA</i>	(4) <i>CE</i>	(5) <i>CE</i>	(6) <i>CE</i>
<i>SCPP</i>	0.167*** (0.013)	1.746*** (0.454)	0.228 (0.232)	-0.200*** (0.050)	-0.230*** (0.050)	-0.233*** (0.050)
<i>ER</i>				-0.198*** (0.036)		
<i>GI</i>					-0.002** (0.001)	
<i>RA</i>						-0.0003 (0.0009)
<i>Constant</i>	3.669*** (0.127)	-45.137*** (7.250)	4.889* (2.523)	-1.564*** (0.455)	-2.362*** (0.440)	-2.291*** (0.439)
Control variables	YES	YES	YES	YES	YES	YES
Year fixed effect	YES	YES	YES	YES	YES	YES
Regional fixed effect	YES	YES	YES	YES	YES	YES
Industrial fixed effect	YES	YES	YES	YES	YES	YES
Observations	10790	10790	10790	10790	10790	10790
Adjusted R ²	0.7658	0.1126	0.0420	0.5386	0.5375	0.5373

results are reported in Columns (4), (5) and (6) of Table 3. In Columns (4) and (5), the coefficients of *ER* and *GI* are significantly negative at the 1% level, and the absolute values of the coefficients of *SCPP* are lower than 0.233 in Column (4) in Table 1, implying that the strengthening of environmental regulation and the progress of green technological innovation can help curb the CO₂ emissions of industrial firms. In summary, the *SCPP* will reduce CO₂ emissions from industrial firms by strengthening the intensity of environmental regulation and promoting the ability of green technological innovation, while the path of resource allocation efficiency does not play a role, so Hypotheses **H2a** and **H2b** are confirmed.

Heterogeneity analysis

In this section, we further analyze the heterogeneities of industrial differences, firm characteristics and regional differences in the relationship between *SCPPs* and the CO₂ emissions of industrial firms, which will provide further guidance for achieving the targets of reducing CO₂ emissions.

Industrial heterogeneity

A smart city is a technologically advanced city, that takes low-carbon development as one of its goals (Vanolo, 2014), thus *SCPPs* may have different effects on firms located in industries with different carbon emission levels. To examine the heterogeneities of industrial differences, all industries are divided into high-carbon industries and low-carbon industries, according to the classification standard in the

“China emissions trading rights report (2017)”. An Industry that accounts for more than 2% of all CO₂ emissions will be classified as a high-carbon industry. Columns (1) and (2) of Table 4 present the impact of the *SCPP* on corporate CO₂ emissions in different industries. The coefficients of *SCPP* are significantly negative at the 1% level. The results show that corporate CO₂ emissions are 30.20% lower after the implementation of the policy in low-carbon industries, while they are 14.70% lower in high-carbon industries. One potential explanation is that the initial CO₂ emissions of high-carbon industries are relatively high, and their percentage of CO₂ emissions decline is not as high as that of low-carbon industries when impacted by smart city construction.

Furthermore, Ioannou et al. (2016) pointed out that firms in low-carbon industries prefer to reduce CO₂ emissions by saving resources and optimizing resource allocation, while firms in high-carbon industries prefer to promote green technological innovation to achieve CO₂ emissions reduction. Based on this, we envisage that *SCPPs* may reduce CO₂ emissions by optimizing resource allocation in low-carbon industries, in addition to strengthening environmental regulations and promoting green innovation. Then, we adopt Eqs. (6) and (7) to re-examine the mediating effect of resource allocation efficiency based on samples of different industries. The results are revealed in Table 5 Columns (1) and (2) illustrate that the mediating effect of resource allocation efficiency plays a significant role in low-carbon industries, but is not significant in high-carbon industries, which explains to a certain extent why the CO₂ emissions of firms in low-carbon industries have fallen more sharply when hit by the policy.

Table 4
Heterogeneity effects of industrial differences and firm characteristics.

Variables	Industry		Ownership structure	
	(1) Low-carbon	(2) High-carbon	(3) SOEs	(4) Non-SOEs
<i>SCPP</i>	-0.302*** (0.056)	-0.147*** (0.070)	-0.106 (0.070)	-0.368*** (0.070)
<i>Constant</i>	-4.637*** (0.504)	0.071 (0.600)	-0.542 (0.662)	-2.178*** (0.633)
Control variables	YES	YES	YES	YES
Year fixed effect	YES	YES	YES	YES
Regional fixed effect	YES	YES	YES	YES
Industrial fixed effect	YES	YES	YES	YES
Observations	7900	2890	5650	5140
Adjusted R ²	0.4896	0.6447	0.5854	0.4005

Table 5

The mediating effect of resource allocation efficiency on the samples of different industries.

Variables	Low-carbon industry		High-carbon industry	
	(1) RA	(2) CE	(3) RA	(4) CE
SCPP	0.422*** (0.172)	-0.301*** (0.056)	-0.269 (0.897)	-0.147** (0.070)
RA		-0.002*** (0.001)		0.001 (0.001)
Constant	6.592*** (1.635)	-4.623*** (0.504)	-5.521 (7.793)	0.074 (0.600)
Control variables	YES	YES	YES	YES
Year fixed effect	YES	YES	YES	YES
Regional fixed effect	YES	YES	YES	YES
Industrial fixed effect	YES	YES	YES	YES
Observations	7900	7900	2890	2890
Adjusted R ²	0.0537	0.4897	0.3130	0.6446

Different firm characteristics

Chinese firms can be divided into state-owned firms (SOEs) and non-state-owned firms (Non-SOEs) according to their ownership structure. They have different characteristics and advantages. SOEs often have some political tasks and nonmarket functions, and play important roles in regional economic development (Jiang et al., 2018). Additionally, SOEs have absolute advantages over Non-SOEs in terms of government funding support and policy preference, and suffer softer environmental constraints than Non-SOEs. Moreover, managers of SOEs pay more attention to the benefits during their tenure and tend to avoid the uncertainty of profits brought by innovation when making decisions. Thus, the intermediary effect of environmental regulation and green innovation caused by SCPPs in SOEs may be weaker than that in non-SOEs. In addition, non-SOEs face intense competition, so they are more sensitive to changes in the market and environment and are better equipped with the ability to capture opportunities in the face of smart city pilot policy shocks.

Following Chakraborty and Chatterjee (2017), we classify firms into an SOE group and a non-SOE group, and we adopt Eq. (2) to estimate the coefficient of SCPP based on two samples respectively, the results are shown in Columns (3) and (4) of Table 4. We find that the coefficient of SCPP is -0.368, and is significant at the 1% level in the non-SOE group, while it is insignificant in the SOE group. The results indicate that SCPPs can reduce the CO₂ emissions of non-SOEs.

Regional heterogeneity

The economic development and resource endowment of cities will affect the behavior of firms in the region. To explore the regional heterogeneity of the carbon reduction effects of SCPPs, we classify

firms into a resource-based-city group and a non-resource-based city group, according to the *National Sustainable Development Plan for resource-based cities (2013-2020)* issued by the State Council of China. Columns (1) and (2) of Table 6 present the impact of the policy on corporate CO₂ emissions in different types of cities. The coefficients of SCPP are both significantly negative at the 1% level. However, the coefficient in Column (1) is lower than that in Column (2), indicating that the carbon reduction effects of SCPPs are more effective among the firms in resource-based cities.

Furthermore, based on the geographical location of the city, we divide cities into three subsamples: eastern China, mid-China, and western China. The economic development of eastern China is better than that of mid-China, and western China. Columns (3), (4) and (5) of Table 6 present the SCPP's micro carbon reduction effect in different regions. The coefficient of SCPP is significantly negative at the 1% level in Column (3), while the coefficients of SCPP are insignificant in Columns (4) and (5), indicating that the carbon reduction effects are only significant among the firms in eastern China.

In summary, better economic development and rich resource endowment of cities would strengthen the SCPP's micro carbon reduction effect. The potential explanation is that better-developed cities are able to master and disseminate digital technologies more quickly and provide a more solid hard environment and a greater soft environment for corporate green technological innovation to reduce corporate carbon emissions, while facing policy shocks.

Conclusions and Implications

Under the dual pressure of stable economic growth and carbon emission reduction, it is of great practical significance to explore the influence mechanism of smart city construction on the CO₂ emissions of industrial enterprises. Based on the panel data of 1079 A-share listed industrial firms from 2009 to 2018 in China, this study sets the SCPP as a quasi-natural experiment and applies the time-varying DID method and intermediate approach to test the impact of the policy on the CO₂ emissions from industrial firms.

The main conclusions are as follows. First, the results of the time-varying DID baseline regression illustrate that smart city construction can significantly reduce CO₂ emissions from industrial firms. This conclusion remains constant after a series of robustness tests, including a parallel trend test, PSM-DID test, placebo test, replacing the dependent variable, excluding the impact of other contemporary policies, excluding the influence of outliers, and a lag test. Second, the results of the mechanism analysis suggest that the SCPP can lead to decreased CO₂ emissions from industrial firms by strengthening the intensity of environmental regulation, and promoting green technological innovation. Moreover, the resource allocation efficiency is not the mechanism impact of the SCPP on the CO₂ emissions from industrial firms in high-carbon industries but plays a mediating role in the

Table 6

The results of regional heterogeneity.

Variables	City type		City location		
	(1) Resource-based	(2) Non-resource-based	(3) Eastern	(4) Mid	(5) Western
SCPP	-0.232** (0.115)	-0.102** (0.057)	-0.314*** (0.067)	-0.071 (0.107)	-0.082 (0.122)
Constant	-3.108*** (1.011)	-3.620*** (0.521)	-4.601*** (0.624)	-2.546** (1.002)	3.960*** (0.998)
Control variables	YES	YES	YES	YES	YES
Year fixed effect	YES	YES	YES	YES	YES
Regional fixed effect	YES	YES	YES	YES	YES
Industrial fixed effect	YES	YES	YES	YES	YES
Observations	1820	8970	6650	2250	1890
Adjusted R ²	0.6476	0.5171	0.5216	0.5913	0.5805

process of reducing the CO₂ emissions of industrial firms in low-carbon industries. Finally, heterogeneity analysis shows that the micro carbon reduction effect of SCPPs varies with the industrial differences, firm characteristics and regional differences. Specifically, the effect is stronger for non-SOEs and the industrial firms in low-carbon industries, resource-based cities and eastern China.

Theoretical implications

The study provides a beneficial supplement to the effect evaluation of SCPPs from the perspective of micro environmental governance, and extends the existing research on the determinants of corporate carbon emission reduction. The findings support the idea that SCPPs can effectively reduce carbon emissions, which is consistent with the conclusions of previous studies (Cavada et al., 2015; Zawieska & Pieriegud, 2018; Liu et al., 2022). However, due to the limitation of enterprise carbon emission data, previous studies can only explain the microscopic carbon emission reduction effect of SCPPs at the theoretical level (Zawieska & Pieriegud, 2018; Shi et al., 2018), or conduct empirical research at the city level (Wang et al., 2019; Sun & Zhang 2020; Zhang et al., 2022). Our study effectively fills the research gap and further explores how the carbon emission reduction effects of SCPPs change over time.

Second, this is the first study to analyze and test the potential mechanism of SCPPs affecting the CO₂ emissions of industrial firms from both theoretical and empirical aspects, which reveals the role of the micro carbon emission reduction effect of SCPPs. In the research on the effects of SCPPs, the optimization of resource allocation and the improvement of innovation ability are often regarded as intermediary effects (Caragliu & Del, 2018; Yu & Zhang, 2019; Fan et al., 2021; Jiang et al., 2021; Jo et al., 2021). It shows that scholars have a deep understanding of the SCPP's innovative function but ignore its green features. Therefore, in the mechanism analysis of this study, we elaborated three mediating effects (including enhancing the intensity of environmental regulation, promoting green technology innovation and optimizing the efficiency of resource allocation) that policy can produce through three green means to reduce the carbon emissions of enterprises. The findings will provide guidance for government policy-makers and scholars to further understand the nature and function of SCPPs.

Finally, by analyzing the heterogeneity of SCPPs' micro carbon emission reduction effect in terms of the industries, ownership structures and regions where the firms belong, this study implemented the carbon reduction function of SCPPs in the actual management of different regions and enterprises. Unlike the extant literature, which focuses on the heterogeneous effects arising from the age, size, and industrialization of firms (Liu et al., 2022), the factors concerned in this study are more valuable for extending the function of the policy.

Practical implications

This study also offers the following policy implications. (1) To achieve the goal of "carbon peak" and "carbon neutrality" as soon as possible, the Chinese government should expand the scope of smart city construction and especially carry out SCPPs in the cities with a high proportion of industrial firms and large industrial CO₂ emissions. Other countries can benefit from China's extensive experience in dealing with the problems of climate change and environmental degradation caused by CO₂ emissions. (2) To curb CO₂ emissions, industrial firms should continue to increase R&D investment, apply advanced digital technologies to promote green technological innovation and improve clean production processes. In addition, industrial firms in high-carbon industries should deeply realize the positive effect of resource allocation optimization on carbon emission reduction and put it into practice. (3) Because the carbon emission reduction effect of SCPPs is obviously stronger in Non-SOEs, the

government should strengthen the awareness of the carbon emission reduction of SOEs and encourage them to actively seize the opportunities offered by the policy to reduce CO₂ emissions. (4) Because the carbon emission reduction effect of SCPPs has regional heterogeneity, the government should develop a differentiation strategy and promulgate the different preferential policies according to the development of different regions, such as providing special financial support to backward regions to achieve balanced development, effectively guiding firms to capture the advantages that SCPPs bring to curb CO₂ emissions.

Of course, this research can still be further improved. The limitations of this study and further research directions are listed in the SM (Pages S6–7).

Disclosure statement

No potential conflict of interest was reported by the authors.

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Supplementary materials

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