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Can place-based policy reduce carbon emissions? Evidence from industrial transformation and upgrading exemplary zone in China

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The effect of the place-based policies on sustainable development has received substantial attention in economic research. In China, the industrial transformation and upgrading exemplary zone policy is a prominent example of such policies, as it targets old industrial and resource-based cities. The paper provides an early assessment of the policy's capability to reduce carbon emissions. Specifically, we use data from old industrial and resource-based cities for the period of 2012–2019 and apply the difference-in-differences method to examine the policy's influence on total carbon emissions and intensity. The results show that the policy can effectively reduce carbon emissions through reducing energy consumption, promoting urban green innovation and tertiary industry agglomeration. Compared to resource-based cities, cities with a low level of economic development and central, western cities, this impact is more notable in old industrial cities, cities with a high level of economic development and eastern cities. Additional analysis reveals that the policy has beneficial spatial radiation impacts on the nearby cities as well. In the meanwhile, the strategy may have a synergy effect on reducing carbon emissions and pollution. The results of this study may have an impact on how nations implement place-based policies and reduce carbon emissions.

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Introduction

Climate warming has emerged as a worldwide issue threatening humanity's life and growth. Exploring specific methods to identify the carbon reduction (CR) mechanisms at the regional policy level is crucial for addressing the issue. In this context, place-based policies have attracted increased attention from academics and policy makers, as they hold potential to achieve sustainable development goals while considering regional variations (Ehrlich and Seidel, 2018; Kiesel et al. 2022; Tian and Xu, 2021). As a key global player and the planet's biggest emerging nation and carbonate emitter, China has established a number of place-based policies to promote an eco-friendly and zero-carbon economy, including the ecological civilization pilot zones, technological and economic development zones, and the financial reform pilot zones (Chai et al. 2023; Li et al. 2023; Zhang and Chen, 2023)[1].

In the existing place-based policy layout of China, the industrial transformation and upgrading exemplary zone (ITUEZ) policy is a special one. First of all, the ITUEZ policy is jointly backed by five main ministries, including the *National Development and Reform Commission*, which has multilateral backing and official authority that other place-based policies may lack. More significantly, the ITUEZ policy's implementation scope is unique as it is restricted to the old industrial (OI) cities and the resource-based (RB) cities. Unlike other types of cities, these two have relied on an ordinary economic growth model marked by substantial investment, energy usage, and pollution (Wan et al. 2015). These cities' green and low-carbon evolution is key to fulfilling China's carbon peaking and carbon neutrality (Dual Carbon) ambitions.

Given the preceding context, a pertinent query arises: Can the implementation of ITUEZ policy genuinely facilitate carbon emission (CE) reduction? This research aims to address this question. Specifically, taking 145 OI and RB cities as our research samples and using the difference-in-differences (DID) method, we assess the CR effect of the ITUEZ policy and explore the internal mechanisms. Our data show that the ITUEZ approach is successful in lowering CE, with an average drop of 27.66 and 27.72% in total CE and intensity, respectively. Furthermore, the ITUEZ strategy can lower CE via the scale effect, technological effect, and agglomeration effect. Furthermore, heterogeneity analyses demonstrate that the CR effect attributed to the ITUEZ is higher in OI cities than in RB and compound cities; cities with high levels of economic development better than cities with low level of economic development; eastern cities outperform central cities in terms of CR effect, while western cities have the lowest magnitude effect. Finally, additional investigation reveals that the ITUEZ policy has positive geographical spillover effects on cities within 300 km, which can reduce their CE. Moreover, the policy also has a synergistic effect on pollution control (PC) and CE.

Compared to previous investigations, the possible marginal contributions of this work are discussed below: first, as for the research topic, we offer an assessment of the ITUEZ policy's CR impacts based on the sample of OI and RB cities, expanding the knowledge about place-based policies and CR. Prior researches have primarily assessed the economic benefits of place-based policies like the resource-exhausted city programs, the pilot free trade zones, and special economic zones (Lu et al. 2022; Feng et al. 2023; W. Xu et al. 2023). They have not considered as much to the eco-benefits effects, particularly with regard to the CR influence of the ITUEZ. Considering the key role of OI and RB cities in achieving carbon neutrality and carbon peaking in China, along with their close relationship with the energy transition, the CR effect of the ITUEZ policy in OI and RB cities is especially important, which is the concern of this study.

Second, as far as the research framework and content, this paper delves deeply into the CR impact of the ITUEZ policy. We focus on both total CE and intensity, as well as the influence mechanisms such as the scale, technology and agglomeration effect. Meanwhile, this investigation explores toward the heterogeneous impacts of the ITUEZ policy on CE from a variety of viewpoints, involving city type, economic development, and geographical location. Furthermore, this study enhances the depth and breadth of preceding research by investigating the regional spillover effect of the ITUEZ policy and the synergistic effect of pollution reduction and CR.

Ultimately, as regard to research implications, by deeply analyzing the mechanism and heterogeneous impacts of ITUEZ policies in realizing CR, this paper contributes to the measuring the feasibility about the place-based policies and further promotes research related to green transformation and development in OI and RB cities. In addition, by comprehensively and systematically estimating the influence of the ITUEZ policy on CE, this study not simply provides a critical direction for China's subsequent execution of the ITUEZ policy, but also for its adjustment and optimization in various regions. It also serves as a valuable reference and support for countries to promote CR through place-based policies.

The remainder of this investigation will be described in the sections that come after. In Section 2, the relevant literature is evaluated. Section 3 presents the theoretical theories, as well as the ITUEZ's background. Section 4 describes the research design. Section 5 gives empirical results, which are followed by robustness tests and heterogeneity analyses in Section 6 and further analyses in Section 7. The final discussion is offered in Section 8.

Literature review

The impacts of the place-based policies. Examining the impacts of place-based policies is a popular topic in the social sciences, especially when relating to how these policies affect economies (e.g., Hasan et al. 2021; Brussevich, 2023; Guo et al. 2023). Few academics have explored the sustainable development consequences of place-based initiatives, for example, using a geo-coded dataset of 2,720 counties from 1998 to 2016, Hua et al. (2023) found that development zones reduced PM2.5 concentrations by about 1.8% through administrative means, environmental monitoring systems, and other government incentives. The environmental benefits vary by the dominant industry, geographic area, administrative affiliation, and establishment time of the development zone. Liu et al. (2023) observed that green fiscal policy could increase the ecologic innovation success of enterprises in pilot zones through boosting R&D investment, promoting regional industrial transformation and upgrading, and raising corporate leaders' concern for the environment. Heterogeneity analysis showed that this effect is particularly pronounced in state-owned enterprises, high-energy-consuming fields, or enterprises in areas that have greater concentrations of industry. S. Li et al. (2023) found that the National Eco-Industrial Demonstration Park Policy primarily lowers metropolitan pollutants by strengthening local ecological laws and encouraging green technological creation. Nie et al. (2024) discovered that revitalizing historic revolutionary base places in China successfully boosted urban green innovation.

The influencing factors of CE. To effectively deal with the adverse effects of CE, more and more studies have explored the main factors affecting CE, which primarily consist of the subsequent elements. Initially, the implication of energy consumption structure on CR (Huang et al. 2023; Sun et al. 2024; Xiao and

Peng, 2023). Second, the effect of economic activities on CE (Sun et al. 2023; Y. Zeng et al. 2023). Third, the influence of industrial structure on CE (Gu et al. 2022; Zhao et al. 2023; Chen et al. 2023). The research that examined the impact of place-based policies on reducing CE is most pertinent to this article. For instance, Wang et al. (2023) discovered that National Industrial Relocation Demonstration Zones can actively reduce CE through modernizing the industrial framework, attracting foreign investment, and getting government funding. Large urban areas, resource places and cities in the core area exhibit a greater degree of this effect. Employing panel data spanning 287 Chinese cities during 2012–2019, Xue et al. (2023) found that the pilot free trade zone reduced CE mainly through technological progress, with the decreased impacts rising as time passes. Besides, the heterogeneity study revealed that the CR role is more obvious in the coastal area.

Research evaluation. In summary, existing research provides empirical and theoretical foundation for this study. While the current literature has done more research on the monetary implications of place-based policies, with little attention paid to the CE effect of these policies, especially from the viewpoint of dual control on total CE and intensity. More importantly, these studies have not sufficiently focused on the impact of the ITUEZ policy. This article extends the existing literature. First, we have supplemented previous studies on place-based policies in terms of CE reduction impacts, with a specific emphasis on the CR effects of the ITUEZ initiative. Second, we investigate the policy's effects on total CE and CE intensity, as well as its influence mechanisms and heterogeneity effects. Lastly, the research's scientific worth lies in providing empirical support for the implementation of relevant place-based policies, in addition to serve as a reference and support for achieving the Dual Carbon objective.

Context of the ITUEZ policy and Theoretical hypotheses

Context of the ITUEZ policy. The OI and RB cities have served as crucial material bases for China's industrial growth, yet they are also tough areas for industrial transformation and upgrading. Towards the industry transition and upgradation of the two groups of cities, the Chinese government departments jointly issued the *Notice on Supporting the Construction of the First Batch of ITUEZ in the OI and RB Cities* and the *Notice on Further Promoting the Construction of ITUEZ* in April 2017 and September 2019, respectively. Two batches of ITUEZ were established (see Fig. 1).

The government gave particular attention to promoting environmentally friendly practices when enacting the ITUEZ strategy. Specifically, the *Notice* in 2017 proposed to promote "greening" as the centerpiece of technical transformation, emphasizing the promotion of transformation and upgrading under the premise that "the ecological environment will not be damaged". The *Notice* in 2019 stressed to strengthen the efficient and intensive land use and ecological protection, actively explore new mechanisms to accelerate the green construction of ITUEZ. Moreover, the *Fourteenth Five-Year Plan* made a strong case for supporting OI and RB cities shift into green, carbon-free settlements. Figure 2 shows the Theoretical and empirical analyses framework.

After the launch of the ITUEZ strategy, significant progress has been made in the domains of energy transition and environmental growth. For example, Changzhi, Shanxi Province, focused on coal coking, coal power, coal gasification, coal liquefaction, and have continuously expanded the clean and efficient use of coal industry clusters. Loudi, Hunan Province, took the progress of its cultural tourism business as a foundation for the modernization and expansion of the coal sector, gradually transforming "mining coal" into "mining culture."

Theoretical analyses and hypotheses

The impact of the ITUEZ policy on CE. As an important place-based policy, the ITUEZ policy can promote CR through policy-driven tangible impacts. For one side, in the deployment of the ITUEZ policy, the government placed special emphasis on PC and CR. First, authorities created legal frameworks and incentives to establish emission standards, promoted the use of clean energy, and penalized ecologically detrimental behaviors. Second, policies frequently grant funding or provide subsidies for activities like as PC or technology improvements, and these financial incentives could bolster OI and RB cities' alteration to low-carbon, green environments. Third, the ITUEZ policy aims to raise public awareness of environmental challenges and promote behavioral change. This can increase demand for environmentally friendly products and services, impact market dynamics, and encourage green and sustainable practices in the business. With policy support, cities have achieved noteworthy progress in green development[2]. For example, Ordos City, Inner Mongolia, enacted legislation for the development of green mines, and by the end of 2020, it had completed the reclamation of almost 20,000 hectares of open-pit coal mines. Songyuan City in Jilin Province has coordinated the ecological conservation and sustainable development of Lake Chagan, converting almost 1,400 hectares of cropland into wetlands.

For the other side, relying on the pre-existing industrial base of the OI and RB cities, the ITUEZ policy actively encourages the green transformation and upgrade of industries. This is achieved through various measures, including the comprehensive stimulation of supply-side structural reform. The precise pathways of execution are as follows. Initially, expedite the greening of the electric power, iron and steel, petrochemical, and other industries, reduce obsolete production capacity, and promote green manufacturing methods. Assist Tangshan, Baotou, Anshan, and Daqing, along with other "steel cities" and "oil cities" in expediting their transformations through technological innovation, expanding the beneficial industrial chain, and cultivating new industries. In response to evolving demands, assist Zigong, Xiangtan, Pingxiang, Pingdingshan, and other cities in establishing a robust industrial base for new materials and environmentally friendly equipment, along with fostering an energy-efficient and environmentally conscious sector. These policy measures influence the city's manufacturing system, favoring more eco-friendly and efficient construction that lowers CE (X. Xu et al. 2023; Wei and Zhang, 2020; Chu et al. 2021). Hence, we make the following assertion:

Hypothesis 1: the ITUEZ policy can effectively promote CR.

The influencing mechanisms of ITUEZ policy on CE. In light of the policy compilation of the ITUEZ policy and the relevant foundations of present scholarship, this study contends that the ITUEZ influences CR via three major pathways.

First, the scale effect: One of the key objectives of the ITUEZ policy is to decrease the total volume of embodied energy of the OI and RB cities. Specifically, the ITUEZ policy can help reduce energy use in two ways. On the one hand, eliminating backward production capacity and disposing excess capacity in steel, coal, and other raw material industries while steadily reducing energy consumption. On the other hand, the ITUEZ policy implementation emphasized energy conservation and efficiency. For example, Tongling, Anhui Province, transformed recycling, expanded the use of industrial solid waste such as tailings and

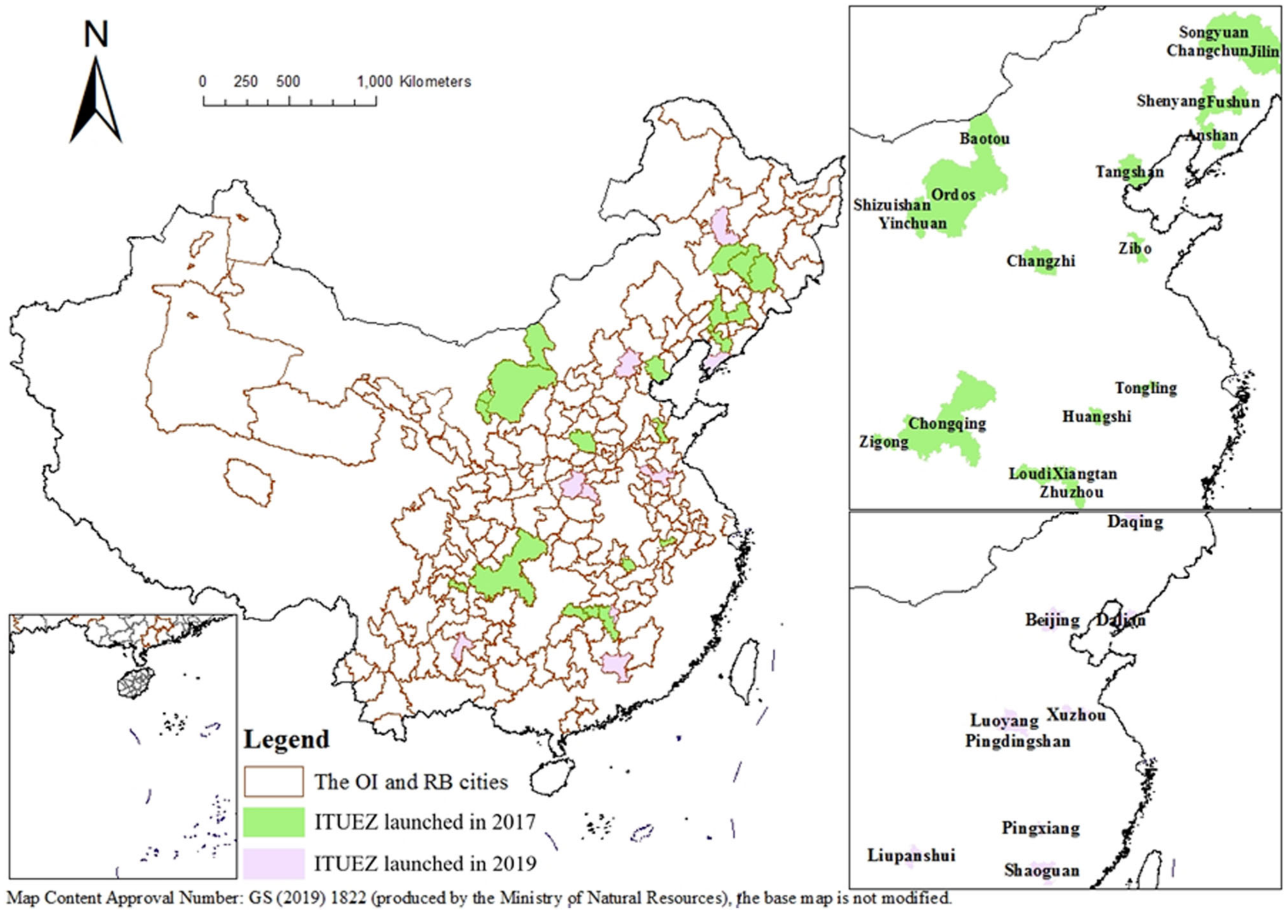


Fig. 1 Study area and the list of ITUEZ.

phosphonyls, and became the province's sole national waste-free pilot city. Zigong, Sichuan Province, has vigorously supported the formation of sector clusters for climate and energy conservation. Zibo shuttered 17 coal power plants this year, resulting in 930,000 kW of energy savings and CR renovations, alongside a more than 3.5% drop in energy use per unit GDP. Meanwhile, Poor resource efficiency and high energy waste has been considered as one of the main factors of CE (Wei et al. 2022; Mo and Jeon, 2022; Eskandari et al. 2022). Consequently, we can offer this hypothesis:

Hypothesis H2a: the ITUEZ policy can contribute to CE reduction through reducing energy consumption.

Second, the technical effect: The ITUEZ policy's tax incentives and financial subsidies provided financial support for enterprises' innovative events, which could not merely increase the profit level, but also help enterprises obtain cost advantages, thereby enhancing the enterprises willingness for green innovation. Additionally, according to the impact of signal transmission, the ITUEZ policy may convey a favorable signal to the wider public, of which might be used to lessen the information imbalance and financial frictions between enterprises and institutional investors. The financial limits for green invention are thus loosened, which may promote the vitality of new green ideas and cleaner urban innovation (Hong et al. 2021; Wang and Wang, 2021). Plus, it has previously been established that green innovation, a pattern of innovation closely tied to ecologically conscious growth (Fang et al. 2021; Shao et al. 2021; Feng et al. 2023), is a crucial means to effectively promote CE reduction. As a result, we propose a theory that follows.

H2b: the ITUEZ policy can lower CE by promoting urban green innovation.

Third, the agglomeration effect: At one side, the ITUEZ policy attached importance to fostering emerging industries, upgrading industrial value chains, and promoting the production with high added value. Gradually, the third industry replaces the elementary and secondaries in the industrial system. On another side, similar to other place-based policies, the ITUEZ policy also focused on giving financial support and subsidies to the tertiary industry in the implementation process, leading to a signaling effect that attracts talent and capital to cluster and introduce new green technologies. The policy actively promotes cleaner production audits and ensures effective integration with management systems such as energy-saving reviews, environmental impact assessments and emissions permits. Likewise, the policy supports locations that meet the requirements to conduct overall audit pilots for industrial clusters in order to comprehensively improve the greening of industries. Through the continuous developing of low-carbon economy and the vigorous growth of resource-saving as well as environment-friendly emerging sectors, the industrial chain gets extended and the tertiary industry continues to agglomerate (Yu and Wang, 2021; Miao et al. 2021; Liu and Dong, 2021). In furtherance of these, a vast array of studies has found that tertiary industry agglomeration can exert positive externalities through knowledge spillovers and talent reserves, thus improving urban CE performance (Li et al. 2021; Shen and Peng, 2021). As such we put up the follow hypothesis.

Hypothesis H2c: the ITUEZ policy can facilitate tertiary industry agglomeration, thus promoting CR.

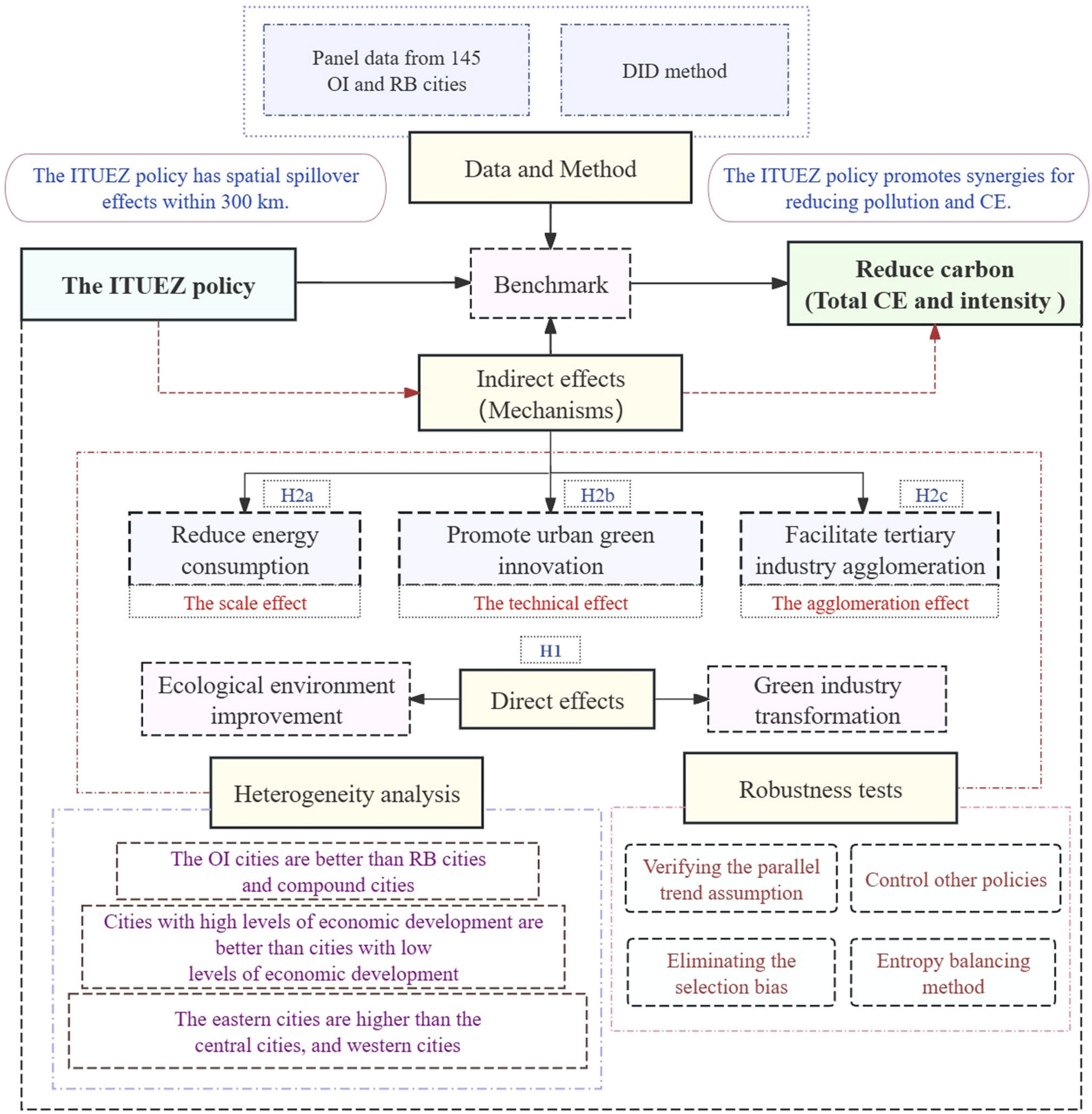


Fig. 2 Theoretical and empirical analyses framework.

Research design

Methodology. This study employed the DID approach to evaluate the impact of the place-based policy on lowering CE, with the ITUEZ policy serving as a quasi-natural experiment. Specifically, the baseline regression model is as follows:

$$Carbon_{i,t} = \alpha_0 + \alpha_1 Treat \times Year + \lambda Control_{i,t} + \mu_i + \gamma_t + \varepsilon_{i,t} \quad (1)$$

where, respectively, the subscribe i and t denote the city and the year. The dependent variable $Carbon_{i,t}$ is the CE of city i in year t. Based on the dual control practice of total CE and intensity in China, $Carbon_{i,t}$ is reflected with two dimensions of total CE and intensity. $Treat \times Year$ is a dotted covariate for the ITUEZ policy, which is the central explanation variant in this study. $Control_{i,t}$ stands for a collection of control variables. μ_i *and* γ_t are city and year FE, accordingly. $\varepsilon_{i,t}$ is the robust error term. For the above model, what we are mainly concerned with is the coefficient α_1, and α_1 is notably negative, signaling that the ITUEZ policy is favorable towards CR.

The definitions of Variables

Dependent variable. This article defines CE from two aspects: total amount and intensity, which are expressed by the logarithm of total CE (CO_2_total) and the logarithm of CE intensity ($CO_2\_intensity$). Among them, CE intensity refers to total CE per unit of GDP. This study, in particular, uses the methodologies of (Glaeser and Kahn, 2009) and (Fu et al. 2021) to calculate total CE across four categories of fuel storage: natural gas, petroleum liquid gas, community-wide electricity supply and heating.

Independent variable. The core explaining covariate $Treat \times Year$ consists of interaction terms for *Treat* and *Year*. Specifically, the variable *Treat* indicates if a city was selected as a ITUEZ or not, that receives a value of 1 for the cities selected as a ITUEZ and 0 for the remaining cities. We mainly concentrate on the impact of the first batch of ITUEZ since of constraints on data, hence the variable *Year* determines whether the ITUEZ policy is conducted or not. It is equal to 1 during the period 2017–2019 and 0 before 2017.

Control variables. We include many control variables in the regression model with reference to the body of literature currently available on CE: (1) The degree of economic progress (PGDP), measured as the logarithm of the grand domainer. The functioning of the economy constitutes an of the main elements altering CE (Liu et al. 2020). (2) City proportion (*POP*) calculated using the quantity of persons logarithm. Theoretically, the increasing size of the city may create a congestion effect, which in turn increases CE (Balezentis, 2020; Pfluger, 2021). (3) Government involvement (*GOV*), determined by the percentage of budget expenditures to GDP, as Chinese governments exert an enormous effect on the advancement of society and the economy (Feng and Nie, 2024). (4) Fiscal growth level (FIN), defined as the proportion of GDP that is made up of savings and loans held at banks and credit unions, as financial development is recognized as a key element influencing CE (Shoaib et al. 2020). (5) The extent of openness (FDI), calculated by the actual FDI as a percentage of GDP. Direct investments from abroad can have an immense effect on CE, relating to the well-known "pollution paradise" and "pollution halo" hypotheses (Okeke, 2023). (6) Human assets quality (HUM), which measures urban human resources quality with the proportion of students attending college. As established, employee status can influence the economic environment and breakthrough technologies, hence impacting CE (Khan et al. 2020).

Table 1 Descriptive statistics.

Variables	Obs	Mean	Std. Dev	Min	Max
CO_2_Total	1,160	5.93	0.89	2.75	10.04
CO_2_Intensity	1,160	8.05	0.85	5.47	13.60
Treat×Year	1,160	0.04	0.20	0.00	1.00
PGDP	1,160	10.63	0.50	9.26	12.28
POP	1,160	5.72	0.70	2.99	7.12
GOV	1,160	0.22	0.10	0.07	0.68
FIN	1,160	2.22	1.00	0.64	21.30
FOR	1,160	0.01	0.02	0.00	0.21
HUM	1,160	0.01	0.01	0.00	0.06

Data and descriptive statistics. To guarantee similarity between the treatment and control groups, we limited the study sample to OI and RB cities, since the ITUEZ policy was developed for these two types of cities. In particular, we employ a sample of 145 OI and RB cities in China between 2012 and 2019, of which 129 were in the control group and 16 were in the treatment group. The year 2012 as the beginning year for our investigation is essential for two reasons. Firstly, it marked a pivotal year for policy adjustments and economic transformation in China, with the nation experiencing a notable deceleration in economic growth and entering a new phase. Secondly, 2012 witnessed the refinement of official statistics at the city level, rendering it a pivotal year for obtaining relatively comprehensive and reliable data. The research data were mostly collected through the *Chinese Research Data Services Platform* (CNRDS), the *CEIC database*, the *China City Statistical Yearbook*, the *China Urban Construction Statistical Yearbook* (CNUCS), and the *statistical bulletin*. Table 1 reports the detailed descriptive statistics.

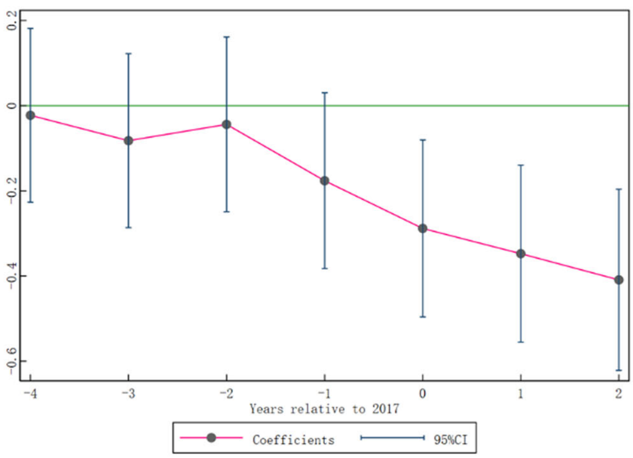
Empirical results and analyses

Verifying the parallel trend assumption. Before deploying DID modeling, it is imperative to complete the parallel trend testing (Roth et al. 2023). The convergent trend assumption implies that, prior to the enactment of the ITUEZ policy, there is no systemic variance among the trial and experimentation groupings in the shifting trend of CE. Since parallelism trending scrutiny, the case scrutiny procedure was adopted in this dissertation, referencing (Feng and Nie, 2022).

$$Carbon_{i,t} = \beta_0 + \beta_k \sum_{k=-4}^{2} Treat \times Year^{\pm k} + \lambda Control_{i,t} + \mu_i + \gamma_t + \varepsilon_{i,t} \quad (2)$$

Where the $Treat \times Year^{\pm k}$ denotes a few imaginary variables related to the year the policy was put into effect. If city i is in the kth year before (after) 2017, the $Treat \times Year^{-k}$ ($Treat \times Year^{k}$) equals 1, otherwise 0. The definitions of the other variables follow the format seen in Eq. (1). We treat the 5th year before policy adoption (i.e., $Treat \times Year^{-5}$) as the basis year. This study focuses on parameter β_k. If β_k insignificant when $k < 0$, then the paralleled trends assumption is met.

Figure 3 depicts the estimated coefficients β_k with a 95% confidence interval[3], delivering an exhaustive examination of the policy's temporal dynamics. The results reveal compelling insights into the policy's effectiveness over time. Notably, the coefficients before 2017 are statistically insignificant away from 0, providing dedicated support for the parallel trend hypothesis



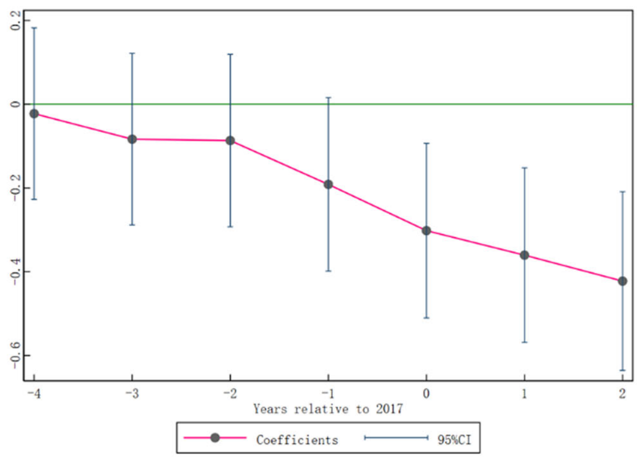


Fig. 3 Event-Study Estimates of CO_2_*total* (left) and CO_2_*intensity* (right).

Table 2 Basic regression.

	(1) CO_2_Total	(2) CO_2_Intensity	(3) CO_2_Total	(4) CO_2_Intensity
Treat×Time	−0.2820*** (0.0539)	−0.1220** (0.0587)	−0.2766*** (0.0563)	−0.2772*** (0.0565)
PGDP			0.1136 (0.0851)	−0.8322*** (0.0854)
POP			0.6243*** (0.2068)	0.0227 (0.2076)
GOV			0.3481 (0.2930)	0.5723* (0.2942)
FIN			−0.0144 (0.0130)	−0.0113 (0.0130)
FOR			−0.6918 (0.8404)	−0.7772 (0.8436)
HUM			10.0129*** (3.8048)	9.2751** (3.8195)
Constant	5.8022*** (0.0231)	8.1053*** (0.0252)	0.9106 (1.5556)	16.4966*** (1.5616)
City FE	√	√	√	√
Year FE	√	√	√	√
N	1160	1160	1160	1160
R^2	0.1291	0.0282	0.1421	0.1853

Note: Standard errors in parentheses. *$p < 0.1$, **$p < 0.05$, ***$p < 0.01$.

earlier. It demonstrates that in the years prior to the ITUEZ policy, there was no consistent variation in the changing pattern of CE between the treated and test groups.

Moreover, the coefficients post-2017 exhibit a noteworthy pattern. They are consistently negative and exhibit an increasing absolute value as the years progress. This trend signifies a progressive influence of the ITUEZ on CR. The temporal perspective illuminates a strengthening influence of the policy on total CE and intensity over time. This temporal evolution aligns with the proposition that the ITUEZ policy exerts a sustained and escalating influence on CR. The increasing absolute values of β_k before policy implementation, coupled with the progressively negative coefficients after 2017, substantiate the claim that the policy is associated with a noticeable and increasing impact on CR.

Basic regression. Model (1) serves as the foundation for this study's research of the impact of the ITUEZ policy on CR, while Table 2 presents the baseline regressed results. Regardless of any additional constraints, lines (1) and (2) possess that the coefficients of $Treat \times Time$ are all negative and of statistical significance. This result preliminarily indicates that the ITUEZ policy helps in encouraging the decrease of CE. After further adding controls, the coefficients of $Treat \times Time$ in column (3) and (4) are −0.2766 and −0.2772, correspondingly, which are statistically significant at the 1% level, corroborating the theoretical expectation. The aforementioned findings show that the ITUEZ policy has a vital role in advancing CR, implying that such a policy will assist in quickening the transition to low-carbon growth in OI and RB cities.

Mechanisms tests. As previously stated, the ITUEZ policy has dramatically lowered total CE and intensity. To further study the underlying processes, we create the following mediating effect model for testing:

$$Carbon_{i,t} = \alpha_0 + \alpha_1 Treat \times Year + \lambda Control_{i,t} + \mu_i + \gamma_t + \varepsilon_{i,t} \quad (3)$$

$$Med_{i,t} = \beta_0 + \beta_1 Treat \times Year + \lambda Control_{i,t} + \mu_i + \gamma_t + \varepsilon_{i,t} \quad (4)$$

$$Carbon_{i,t} = \gamma_0 + \gamma_1 Treat \times Year + \gamma_2 Med_{i,t} + \lambda Control_{it} + \mu_i + \gamma_t + \varepsilon_{it} \quad (5)$$

where *Med* denotes for the intermediate mechanism variable, and the remaining parameters are identical to Eq. (1). The test techniques for the arbitration affect modeling are as follows. To appraise the overall effect of the ITUEZ strategy upon CE reductio, first calculate model (3) (i.e., α_1). Second, if α_1 is significant, the next step is to estimate model (4) to look at the potential influence of the ITUEZ policy on the mediator variable (i.e., β_1). Third, if β_1 is significant, then estimate Eq. (5) to look into the implications of the ITUEZ policy and mediator variables on CR.

Table 3 The scale effect.

	(1) Energy_Com	(2) CO_2_Total	(3) CO_2_Intensity
Treat×Time	−0.3022*** (0.0801)	−0.2029*** (0.0547)	−0.2022*** (0.0547)
Energy_Com		0.2803*** (0.0217)	0.2891*** (0.0217)
Constant	2.7781 (2.1442)	0.2018 (1.4565)	15.7753*** (1.4551)
Control variables	√	√	√
City FE	√	√	√
Year FE	√	√	√
N	1135	1135	1135
R^2	0.5233	0.2658	0.3101

Note: Standard errors in parentheses. ***$p < 0.01$.

We focus on the relevance and magnitude of β_1, γ_1 and γ_2. When β_1 and γ_2 are both significant, an intermediary effect is present. When γ_1 is not evident, there is still a complete intermediate influence. Moreover, if γ_1 is distinct and encounters a lower absolute value than α_1, then a partial mediating role is present. Complying with the theoretical presumptions, we will conduct mechanism analysis from three angles: the scale, technical, and agglomeration effect.

The scale effect. We apply an energy use by unit GDP (*Energy_-Com*) to measure energy consumption as well as to verify the scale effect (Tran et al. 2022; Lu et al. 2018). The estimation leads are given in Table 3. The resulting in (1) indicates that the coefficient of $Treat \times Time$ is noticeably negative, meaning that the ITUEZ policy can decrease energy costs. Columns (2) and (3) give positive coefficients for *Energy_Com*, which are significantly at one percent, proving that a drop in fossil fuel consumption may drastically lower both cumulative CE and sensitivity. Besides,

Table 4 The technical effect.

	(1)	(2)	(3)
	Green_inno	*CO_2_Total*	*CO_2_Intensity*
Treat×Time	15.2792*** (3.8665)	−0.2603*** (0.0566)	−0.2600*** (0.0568)
Green_inno		−0.0011** (0.0005)	−0.0011** (0.0005)
Constant	−4.1e + 02*** (106.8335)	0.4735 (1.5636)	16.0348*** (1.5691)
Control variables	√	√	√
City FE	√	√	√
Year FE	√	√	√
N	1160	1160	1160
R^2	0.2431	0.1467	0.1901

Note: Standard errors in parentheses. **p < 0.05, ***p < 0.01.

Table 5 The agglomeration effect.

	(1)	(2)	(3)
	Ter_agg	*CO_2_Total*	*CO_2_Intensity*
Treat×Time	0.0083** (0.0041)	−0.2687*** (0.0563)	−0.2676*** (0.0565)
Ter_agg		−0.9438** (0.4330)	−1.1536*** (0.4342)
Constant	−0.4794*** (0.1133)	0.4582 (1.5665)	15.9437*** (1.5707)
Control variables	√	√	√
City FE	√	√	√
Year FE	√	√	√
N	1160	1160	1160
R^2	0.4288	0.1462	0.1910

Note: Standard errors in parentheses. **p < 0.05, ***p < 0.01.

the coefficient of *Treat×Time* for *CO_2_Total* and *CO_2_Intensity* is respectively −0.2029 and −0.2022, of which the absolute values are correspondingly lower than 0.2766 and 0.2772 in the basic model. Therefore, the ITUEZ can mitigate total CE and intensity through the scale effect. The hypothesis H2a is verified.

The technical effect. Refers to Du et al. (2021) and Xue et al. (2022), this research utilizes the amount of issued green inventive patents to quantify green innovation *(Green_inno)* and evaluate the technical effect. Table 4 displays outcomes of the extrapolation. The calculated coefficient of *Treat × Time* in column (1) is positive and passes the 1% significance test, signaling that the ITUEZ policy is capable of encouraging urban green innovation. The computed *Green_inno* in (2) and (3) are negative and significant, demonstrating that green innovation facilitates to diminish overall CE and intensity. Besides, the coefficients of *Treat × Time* for *CO_2_Total* and *CO_2_Intensity* is respectively −0.2603 and −0.2600, of which the absolute values are correspondingly lower than 0.2766 and 0.2772 in the basic model. Therefore, it is proved that the ITUEZ policy can promote CR through the technical effect. Hypothesis H2b is verified.

The agglomeration effect. We apply tertiary value added per unit of floor area to measure tertiary industry agglomeration (*Ter_agg*) and assess the agglomeration effect (Zhou et al. 2019). Table 5 displays the analysis. The estimated coefficient *Treat × Time* is quite favorable, as shown in Column 1, demonstrating that the

Table 6 The entropy balancing method.

	(1)	(2)
	CO_2_Total	*CO_2_Intensity*
Treat×Time	−0.2200*** (0.0251)	−0.2067*** (0.0255)
Constant	−0.6444 (1.2579)	12.0144*** (1.2769)
Control variables	√	√
City FE	√	√
Year FE	√	√
N	1160	1160
R^2	0.9521	0.9429

Note: Standard errors in parentheses. ***p < 0.01.

ITUEZ policy can help to encourage the clustering of tertiary industries. The predicted *Ter_agg* correlations in columns (2) and (3) are both significantly negative, signaling that tertiary industry clustering leads to reduce CE. Besides, the coefficient of *Treat × Time* for *CO_2_Total* and *CO_2_Intensity* is respectively −0.2687 and −0.2676, of which the absolute values are both lower than that in the basic model. Therefore, the ITUEZ policy can promote the tertiary industry agglomeration, thus promoting CE reduction. The hypothesis H2c is verified.

Robustness tests and Heterogeneity analyses

Robustness tests

Eliminating the selection bias. Given that the selection of ITUEZ may not random, which may lead to selection bias problem. We address this issue using the entropy balance (EB) approach. The EB methodology maps every treated group of samples to an exactly equivalent controlled set of groups (Anwasia and Simic, 2022). Compared to the Predictive Scoring Matching (PSM) method, the EB method has the advantages of balancing on a greater dimension without any loss of sampling, greater applicability, and a superior algorithm (Y. Guo et al. 2022; Lu et al. 2023).

The phases that comprise the EB method are outlined below: make the controlling factors within the standard model as the defining variables, after which create an array of weights to basically equalize total CE and intensity among the two groups of participants in terms of the median, variance, along with bias of those parameters. With these weights, we can conduct the weighted least squares estimation (Fu, 2022). Table 6 presents the corresponding estimation findings. The co-efficient of estimates for *Treat × Time* are all negative, with magnitudes similar to the basic regression, validating the study's primary finding.

Eliminating interference caused by other policies. The ITUEZ may also affected by multiple national-level place-based policies. We control two standard policies to eliminate the disturbance caused by these elements and improve the reliability of the simulation process. First, the low-carbon pilot policy (*Low_CO_2*), the nation launched a low-carbon pilot arrangement in three phases: 2010, 2012, and 2017. The program has been proven beneficial in improving CR (Song et al. 2020; S. Zeng et al. 2023).

Another is the CE trading pilot policy (*CO_2_trade*). The setting up of a CE trading mechanism is vital for China's ambition of being carbon neutral. China created a CE trading system in 2011 and launched the CE trade pilot policy in 2013. Studies have demonstrated that the CE trade pilot program could substantially enhance ecological effectiveness and CR performance (Lv and Bai, 2021; Shi et al. 2022; Yu and Luo, 2022).

Table 7 shows the estimated results after controlling for these two policies. Regression testing implies that the magnitude of the correlation between *Treat × Time* is negative and with a 1%

Table 7 Controlling for other policies.

	(1) CO_2_Total	(2) CO_2_Intensity	(3) CO_2_Total	(4) CO_2_Intensity
Treat×Time	−0.2667*** (0.0566)	−0.2663*** (0.0568)	−0.2775*** (0.0564)	−0.2780*** (0.0566)
Low_CO_2	−0.1185* (0.0704)	−0.1301* (0.0706)		
CO_2_trade			0.0304 (0.0828)	0.0264 (0.0831)
Constant	0.9083 (1.5541)	16.4941*** (1.5597)	0.9319 (1.5573)	16.5151*** (1.5633)
Control variables	√	√	√	√
City FE	√	√	√	√
Year FE	√	√	√	√
N	1160	1160	1160	1160
R^2	0.1446	0.1880	0.1423	0.1854

Note: Standard errors in parentheses. *p < 0.1, ***p < 0.01.

Table 8 The OI, RB, and compound cities.

	The OI cities		*The RB cities*		*The compound cities*	
	(1) CO_2_Total	(2) CO_2_Intensity	(3) CO_2_Total	(4) CO_2_Intensity	(5) CO_2_Total	(6) CO_2_Intensity
Treat×Time	−0.5449*** (0.1732)	−0.5497*** (0.1733)	−0.4077*** (0.1545)	−0.3741** (0.1552)	−0.0562 (0.0455)	−0.0633 (0.0460)
Constant	−4.3083 (5.8243)	11.2193* (5.8275)	3.2012 (2.7345)	17.9178*** (2.7463)	−5.4113*** (2.0785)	10.2361*** (2.1017)
Controls	√	√	√	√	√	√
City FE	√	√	√	√	√	√
Year FE	√	√	√	√	√	√
N	312	312	456	456	392	392
R^2	0.2079	0.2724	0.2132	0.1689	0.2318	0.4153

Note: Standard errors in parentheses. *p < 0.1, **p < 0.05, ***p < 0.01.

significance level. Therefore, the study's main conclusions remain unchanged after controlling the impact of these two treaties.

Table 9 Heterogeneity in cities' economic development level.

	High-level		*Low-level*	
	(1) CO_2_Total	(2) CO_2_Intensity	(3) CO_2_Total	(4) CO_2_Intensity
Treat×Time	−0.2836*** (0.0557)	−0.2710*** (0.0561)	−0.1021 (0.3317)	−0.0960 (0.3340)
sConstant	7.3084*** (2.4411)	21.4335*** (2.4572)	3.5549 (2.7737)	18.9945*** (2.7930)
Controls	√	√	√	√
City FE	√	√	√	√
Year FE	√	√	√	√
N	580	580	580	580
R^2	0.1628	0.1938	0.1381	0.1710

Note: Standard errors in parentheses. ***p < 0.01.

Heterogeneity analyses

The OI cities, RB cities, and compound cities. It is vital to evaluate the varied effects of the ITUEZ strategy on OI and RB cities. While OI and RB cities are two distinct ideas, there are some notable overlaps in some cities. Consequently, according to the CNUCS, this article divides the sample of the study into three sub-samples, namely, OI cities, RB cities, and composite cities. These three sets refer to: just OI cities, just RB cities, and both OI and RB cities, with 39, 57, and 49 cities in our sample, respectively. Table 8 displays the outcomes of the baseline regression model. The coefficients of $Treat \times Time$ in columns (1) and (2) are highly significant at the 1% level, with values of −0.5449 and −0.5497, respectively, surpassing the cumulative coefficients in columns (3) and (4). The coefficients shown in (5) and (6) for $Treat \times Time$ are −0.0562 and −0.0633, which are not notable. It concludes that, in comparison to RB along with compound cities, the ITUEZ policy has greater influence on the overall CE and intensity in OI cities.

The conclusions stated above may be founded on the factors listed below. On one side, the RB cities are resource-rich and highly dependent on resources. The thermal sector of RB urban is relatively homogeneous, with a high proportion of polluting RB industries in economic development. Therefore, these cities are prone to the phenomenon of "resource curse" and their industrial transformation and upgrading is difficult (Zhang et al. 2022; X. Wang et al. 2022), which underscores the ITUEZ policy's barely any impact on CE decline in such municipalities. Conversely, most of the OI cities are in the hub and center with developed road transportation and extensive internal and external economic connections. Meanwhile, the industrial structure system of the OI cities is well developed. Furthermore, the government and media have given more attention and support to the ITUEZ establishment in the OI cities, prompting a more significant policy effect (Gao and Wadley, 2021; Li et al. 2020).

In addition, there may be the potential reasons why the ITUEZ policy is not salient to the CR of compound cities. Initially, because the industrial structures in composite cities are complex and multifaceted, a single strategy cannot handle all of them. This is especially true for some traditional industries and natural resource domains, which lack cutting-edge low-carbon production processes and technology, limiting the impact of CR. Second, compound cities encompass multiple industries and levels, and

Table 10 The eastern cities, central cities, and western cities.

	eastern		*central*		*western*	
	(1)	(2)	(3)	(4)	(5)	(6)
	CO_2_Total	CO_2_Intensity	CO_2_Total	CO_2_Intensity	CO_2_Total	CO_2_Intensity
Treat×Time	−0.4051*** (0.1049)	−0.4127*** (0.1063)	−0.2113*** (0.0602)	−0.2031*** (0.0602)	−0.2340 (0.1447)	−0.2495* (0.1445)
Constant	1.9299 (8.7866)	17.3579* (8.9059)	−4.7415*** (1.7822)	9.7313*** (1.7829)	1.6419 (4.0144)	16.7188*** (4.0100)
Controls	√	√	√	√	√	√
City FE	√	√	√	√	√	√
Year FE	√	√	√	√	√	√
N	256	256	520	520	384	384
R^2	0.3425	0.4104	0.2218	0.3467	0.1693	0.1353

Note: Standard errors in parentheses. *p < 0.1, ***p < 0.01.

the absence of adequate coordination mechanisms has culminated in poor policy execution. The problem is exacerbated by regional differences in growth, with some still relying on conventional industries while others transitioned to high-tech or service-oriented sectors, causing a lower CR in some regions under the ITUEZ policy (Shah et al. 2023, Yang et al. 2021).

Heterogeneity in urban economic development levels. We parted the samples onto two distinct groups determined by the median GDP per capita in surveyed cities: areas with higher and lower economic development. Table 9 illustrates the findings for the subgroups. The coefficients of $Treat \times Time$ in columns (1) and (2) appeared statistically negative at the 1% level, but insignificant in (3) and (4). This study implies that the ITUEZ had a major impact on CE just in cities with high levels of economic development.

The probable reasons are given below. While on the surface, areas exhibiting a high degree of economic growth may be kinder to establish an innovation-driven process for industrial upgrading and an effective budget allocation system. These features can create the policy dividend and attract additional businesses and money to the ITUEZ, supporting industrial transformation and growth (Li and Liu, 2023; F. Wang et al. 2022). Plus, places with an elevated level in economic growth can use their unique advantages to further decouple their economic growth from CE. Lastly, by fully implementing the ITUEZ policy, these municipalities will be able to better advance CR (Li et al. 2019; Xu and Dong, 2023).

Regional heterogeneity. In accordance with the geographic locations of the cities, we separate the sample into three categories: the eastern, central, and western cities. Table 10 presents the results of the benchmark regression. As can be shown, all of the $Treat \times Time$ coefficients in columns (1), (2), (3), and (4) are significant at the 1% level; however, the factors in colums (1) and (2) are higher in absolute value. This implies that while both eastern and central cities can benefit from the ITUEZ initiative, eastern cities are more successful than central cities. The lackluster coefficients of $Treat \times Time$ in (5) and (6) suggest that the policy's effectiveness in lowering CE in western cities is dubious. Three factors: disparities in regional economic levels, policy execution, and industrial structure might be used to explain the occurrence.

Eastern and central Chinese cities have experienced better economic success than western cities, given that there is more modern technology and financial mechanisms that can speed up industrial improvements to satisfy CR targets. Despite slightly lower development levels than the east, the central area still enjoys superior infrastructure compared to the west, potentially facilitating smoother policy implementation. Governments in eastern and central cities may prioritize establishing CR programs, supported by robust executive capabilities and regulatory frameworks, offering increased financial support, technical guidance, and oversight. Conversely, resource constraints and enforcement challenges may hinder the provision of adequate assistance and incentives in the west, leading to lower CR performance. Eastern and central cities diversified industrial base may align better with the objectives of the ITUEZ. In contrast, the western region's reliance on traditional heavy industries and resource extraction sectors may prolong the transition to greener practices, facing greater policy opposition and hurdles. In addition, the abundance of fossil fuels such as coal in the west may discourage local industries from shifting to greener energy resources (Bai et al. 2022; Qiu et al. 2021).

Table 11 Spatial spillover effects.

	(1)	(2)
	CO_2_Total	CO_2_Intensity
Treat×Time	−0.3780*** (0.0670)	−0.3766*** (0.0673)
Dis^{100}	−0.1636*** (0.0614)	−0.1616*** (0.0616)
Dis^{200}	−0.1321** (0.0534)	−0.1224** (0.0536)
Dis^{300}	−0.1052* (0.0539)	−0.1061* (0.0542)
Dis^{400}	−0.0770 (0.0586)	−0.0835 (0.0589)
Constant	1.3300 (1.5674)	16.9001*** (1.5741)
Controls	√	√
City FE	√	√
Year FE	√	√
N	1160	1160
R^2	0.1500	0.1922

Note: Standard errors in parentheses. *p < 0.1, **p < 0.05, ***p < 0.01.

Further analyses

Spatial spillover effects. As previously stated, the ITUEZ policy has significantly reduced total CE and intensity. Then, as a place-based policy, does that the ITUEZ practices affect the CE of neighboring locations? Are there spatial effects, if any, radiative or siphoning? What comprises the spectrum of the spatially length? To address the issues raised above, the current study proposes the following model (Cao, 2020):

$$Carbon_{i,t} = \delta_0 + \delta_1 Treat \times Year_{i,t} + \sum_{s=100}^{400} \delta_s Dis^s_{i,t} + \lambda Control_{i,t} + \mu_i + \gamma_t + \varepsilon_{i,t} \quad (6)$$

While s is the sphere diameter (calculated by kilometers, $s \geq 100$) between cities. When an ITUEZ lies inside a geographic range distance of (s-100, s] from city i in year t, $Dis^s_{i,t} = 1$, otherwise,

Table 12 Synergistic effect in PC and CR reduction.

	(1) $PM_{2.5}$_total	(2) $PM_{2.5}$_intensity
Treat×Time	−0.0541*** (0.0151)	−0.0547*** (0.0165)
Constant	5.4673*** (0.4178)	2.6326*** (0.4551)
Controls	√	√
City FE	√	√
Year FE	√	√
N	1160	1160
R^2	0.7819	0.9298

Note: Standard errors in parentheses. ***p < 0.01.

$Dis_{i,t}^{s}=0$. As an instance, $Dis_{i,t}^{400}$ displays if an ITUEZ within the distances of (300, 400] from city i in year t[4]. We estimate the ITUEZ policy's spatial spillover effect built on the size and importance of the factor δ_s. Equation (1) acts as a way to define extra parameters.

Table 11 presents the estimated outcomes of Eq. (6). The coefficients Dis^{100}, Dis^{200}, and Dis^{300} are assumed to be considerable at the 1, 5, and 10% degrees, together with absolute values decreasing. Moreover, Dis^{400} is negative but insignificant. It implies that the ITUEZ strategy can have a beneficial knock-on alter on the CE decrease in near cities. Furthermore, spatial spillover effects are confined to a 300-km radius surrounding the ITUEZ.

Synergistic effect in PC and CR. The details reported above illustrate that the ITUEZ policy has the capacity of facilitating CR. Since carbon dioxide and traditional pollutants have homogenous emissions (Zhu et al. 2023), we want to continue to investigate whether the ITUEZ is capable of having a synergistic effect on reducing CE and pollution. According to Du et al. (2022) and Masselot et al. (2022), we choose the complete amount and extent of PM2.5 to provide a reply. We select the total quantity and intensity of PM2.5 (i.e., *PM2.5_total and PM2.5_intensity, respectively*) as the proxy of pollution emission, and conduct regression of the ITUEZ policy on them. *The Washington University in St. Louis' Atmospheric Composition Analysis Group* provided the data for PM2.5, which can be downed from the CNRDS database. Table 12 displays the regression analysis. The estimated $Treat \times Time$ ratios are considerably opposite at the 1% level, confirming the ability of the ITUEZ policy can also successfully decrease total PM2.5 emission and intensity. This finding implies that the ITUEZ are able to some extent, possess a synergistic effect impact of pollution and CR.

Conclusion and policy implications

Using the DID technique and a study sample of 145 OI and RB cities across China from 2012–2019, this paper analyzes the influence of the ITUEZ, a place-based policy, upon the advancement of CR at the overall CE and intensity levels. The following are the outcomes of the research's main findings:

Primarily, the ITUEZ policy is able to minimize total CE and intensity. This observation holds up when a variety of robustness testing are performed, including the parallel trend test, elimination of selectivity bias, and control of other policy disturbances. Simultaneously, the scale effect, the technological effect, and the agglomeration effect are three ways that the ITUEZ may accelerate the decline of CE. Furthermore, it appears that heterogeneity in the CR effects of the ITUEZ: the OI cities outperform the RB and compound cities; cities with a high level of economic development surpass those with a low level of economic development, while eastern cities are superior to the central and western cities. Fourth, the ITUEZ policy has spatial spillover effects within 300 km. Ultimately, the ITUEZ policy promotes synergies for reducing pollution and CE.

In light of the results, we provide two legislative considerations: First and foremost, the government should continue supporting ITUEZ's construction. On the one hand, the weak links and weak areas of the ITUEZ policy implementation should be improved, and the division of labor among the ITUEZ should be strengthened. Meanwhile, the government ought to put the incentive and withdrawal mechanisms in place to fully guarantee the efficacy of the ITUEZ policy's enforcement. On the other hand, to support the shift and escalation of the OI and RB cities collectively, the ITUEZ policy should be gradually broadened in light of experience and standard practices.

Second, give full play of the ITUEZ to promote the multidimensional channels of CR. Initially, the government ought to provide incentives to the ITUEZ to gradually eliminate outdated capacity and increase the proportion of alternative energy intake. This will help to promote green consumption power in industries. Subsequently, the administration ought to encourage the ITUEZ to implement cutting-edge low-carbon technologies and establish an innovation structure for green technology that saves energy. In the end, local governments should embrace innovation-driven development, recognize the value of regional cooperation and policy constructive collaboration, and encourage the ITUEZ's industries to advance to tertiary industries and cluster development.

Third, on the course of carrying out the ITUEZ strategy, each area should consider its local resource base, and implant suitable low-carbon industries with development prospects within the vicinity. For RB, compound and low-level economic growth cities, as well as central and western cities, suitable policy tilts and assistance should be stipulated to ensure the full benefit with the ITUEZ policy. Regarding OI cities, prosperous places and eastern cities, the ITUEZ policy ought to be better practiced and explored to make full use of its unique foundation and advantages to promote CR.

Fourth, foster regional collaboration and coordinated efforts to combat pollution and reduce CE. For example, when implementing the ITUEZ policy, attention should be made to the exchange and collaboration between the ITUEZ and nearby areas in order to maximize the policy's positive spillover impact. To promote environmental transformation in the ITUEZ and achieve the "win-win" goal of air quality management and CR, government authorities should use its synergistic effect in CR and polluted control as an instrument.

Data availability

The data generated or analyzed during this study are included in the supplementary information files.

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Notes

1 Abbreviations: CR: Carbon reduction, ITUEZ: Industrial transformation and upgrading exemplary zone, OI: Old industrial, RB: Resource-based, Dual Carbon: Carbon peaking and carbon neutrality, CE: Carbon emission, DID: Difference-in-differences, PC: Pollution control, CNRDS: Chinese Research Data Services Platform, CNUCS: the China Urban Construction Statistical Yearbook, EB: Entropy balance, PSM: Propensity score matching.

2 National Development and Reform Commission (https://www.ndrc.gov.cn/xwdt/tzgg/202110/t20211019_1300020.html).

3 β_1 and β_2 are the coefficients of 2 years and 1 year after the ITUEZ policy, respectively. β_0 is the coefficient of the current year of the ITUEZ policy. β_{-4}, β_{-3}, …, and β_{-1} are the coefficients of 4 year, 3 years, …, with 1 year prior to the ITUEZ policy.

4 China has 34 provinces regions of administration having an ~9.6 million square kilometer entirety land surface, including Hong Kong, Macao, and Taiwan. Given that every territory is recurrent, the greatest possible value of s is constrained to 400 km, and the average radius of an area is >300 km.

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