Do energy-environmental efficiency benefit from advanced policy zones? Evidence from national new zones of China

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Abstract

As global climate change aggravates, reducing energy consumption and environmental pollution is essential to sustainable economic development. This paper measures the energy-environmental efficiency of 284 prefecture-level cities in China using a non-radial directional distance function (NDDF) and data envelopment analysis (DEA), and evaluates the impact of the establishment of national new zones on energy-environmental efficiency using the multi-period difference-in-difference model (DID). The results are: first, establishing national new zones improves the energy-environmental efficiency of the prefecture-level cities in which they are located by 13%-25%, and the mechanisms include enhancing the green technical efficiency and scale efficiency. Second, national new zones have both negative and positive spatial spillover effects. Third, in terms of heterogeneity, the impact of establishing national new zones on energy-environmental efficiency increases with larger quantile of the latter; national new zones with the one-city layout have significant stimulating impacts on energy-environmental efficiency, but those with the two-city layout have no significant impact, which means there is no significant green synergistic development impact among cities. We also discuss the policy implications of the research, including enhanced policy support and regulation to support the energy environment sector.

Keywords National new zones · Energy-environmental efficiency · DID model · Efficiency decomposition

Introduction

China has experienced rapid economic development in recent years. Still, economic growth has been accompanied by large amounts of energy consumption, CO_2 emissions, and environmental pollution, and the significant accumulation of carbon emissions and pollutants has exacerbated global warming and threats to human health, which adversely affects the sustainable development of society (Dhimal et al. 2021; Sellers et al. 2019). According to the BP Statistical Review of World Energy 2021, China accounted for 26% of global energy consumption in 2020, making it the world's largest energy consumer, and it has also become the world's largest CO_2 emitter, accounting for about 31% of the global total

in 2020. According to the National Bureau of Statistics of China, although industrial wastewater, waste gas, and solid waste in China have decreased in recent years, the total emissions are still massive. Under resource constraints and environmental pressure, the Chinese government has proposed the "dual carbon" goal (carbon peaking by 2030 and carbon neutrality by 2060) to face climate change and improve environmental quality. Thus, how to use resources and reduce environmental pollution more efficiently has become an essential task in China's economic development.

The Chinese government has developed a series of environmental policies to promote green development, including strengthening ecological regulation, improving resource use efficiency, and promoting clean energy. The implementation of these policies has helped to reduce energy consumption and environmental pollution by increasing the level of green innovation and other means (Feng et al. 2017; Shen et al. 2020; Yuan and Zhang 2020), while also laying a solid foundation for sustainable economic development (Kong et al. 2014). Since the approval of the establishment of the Shanghai Pudong New Zone in 1992, national new zones, as a broad functional area shouldering the strategic task of

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national major reform and development and innovative institutional mechanisms, have driven regional economic growth (Chao 2022) and improved land use efficiency (Huo et al. 2022; Yang et al. 2019). In the context of green development, the following questions draw our attention:

(1) Does the establishment of national new zones help to improve the cities' energy-environmental efficiency?
(2) What are the impact mechanisms?
(3) Are there spatial spillover effects and heterogeneity of impacts?

The results of this research can help provide helpful policy insights for building and developing national new zones in a more low-carbon, energy-efficient, and environmentally friendly manner.

Except for the Shanghai Pudong New Zone, which was established in 1992, the remaining 18 existing national new zones were established in stages from 2006-2017. They are an advanced stage of the long-implemented special zones, such as "the Economic and Technological Development Zone" (ETDZ) and "the High-tech Industrial Development Zone" (HIDZ) (Li 2015). National new zones are part of the significant nation-level advanced regional economic policy, and they are strategically positioned higher than zones such as ETDZ and HIDZ, making the number of national new zones much smaller than other special zones. Currently, China has established 19 national new zones, while the total number of ETDZ and HIDZ exceeds 300. In addition, as the comprehensive economic zone, the planning area, administrative level and economic scale of a national new area are higher than those of other types of special zones. However, they operate similarly, with areas planned within or between cities of a certain size and a government or management committee established to undertake economic and social management functions (Martinez 2018). The existing national new zones have a planned land area ranging from 465 to 2451 km², more extensive than other special zones. National new zones can be seen as pilot areas to solve outstanding problems in economic and social development and to explore reform solutions for specific problems faced by different regions. Therefore, compared to other regions, they have larger autonomy to experiment, which is helpful for facilitating bottom-up institutional innovation (Martinez 2018).

The marginal contributions of this paper are: first, measuring energy-environmental efficiency that simultaneously considers maximizing economic output and minimizing environmental impacts, most previous literature only measured energy and environmental efficiency at the provincial level and only considered carbon dioxide as environmental impacts, we measure energy-environmental efficiency at the city level and considers carbon dioxide, wastewater, sulfur

dioxide, fume and dust all as adverse environmental impacts. In addition, two different perspectives of energy and environmental efficiency indicators are used as explanatory variables to construct the model to ensure the robustness of the research results. Second, the establishment of national new zones is used as a proposed natural experiment, and a multi-period difference-in-difference model is used to assess the impact of the establishment of national new zones on energy and environmental efficiency based on panel data of 284 prefecture-level cities in China from 2003 to 2019, and the specific mechanisms are investigated, while the economic impacts of national new zones are mainly explored in the previous literature, we integrate the economic and environmental impacts. Finally, the spatial spillover effects of the above-mentioned impacts are explored in further analysis, as well as the differences in different efficiency levels and layout patterns, which have not been discussed in detail in previous literature, providing a basis for decision making in optimizing the spatial layout of national new zones in terms of energy-environmental efficiency. Fig. 1 shows the framework of the research.

The remainder of this paper is structured as follows: Section 2 is literature review, which analyzes the literature related to special zones and energy-environmental issues, as well as an analysis of possible mechanisms; Section 3 is the research design, which introduces the sources of data and the process of constructing relevant variables, and conducts a descriptive analysis; Section 4 performs an empirical analysis, including the impact of national new zones on energy-environmental efficiency, as well as further explorations and robustness tests; Section 5 is the conclusion and policy implications.

Literature review

The impacts of China's special zones

Many studies have been conducted to examine the effects of establishing various special zones in China, including national new zones, mostly exploring the economic effects. For example, Zhuang and Ye (2018) find that national new zones help to boost urbanization and rapid economic growth in the short term. However, in the long term, national new zones cannot solve the problem of uneven development between regions, and they may even exacerbate the development gap between the city where the national new zone is located and the surrounding underdeveloped cities. Zheng et al. (2016) find that development zones promote the developed regions of China's industrial development, but the driving effect on industries in less developed regions is not significant. A few studies have explored the energy or environmental impacts of special zones. For example, Liu et al. (2007) find that the relationship between economic

Fig. 1 Research framework.
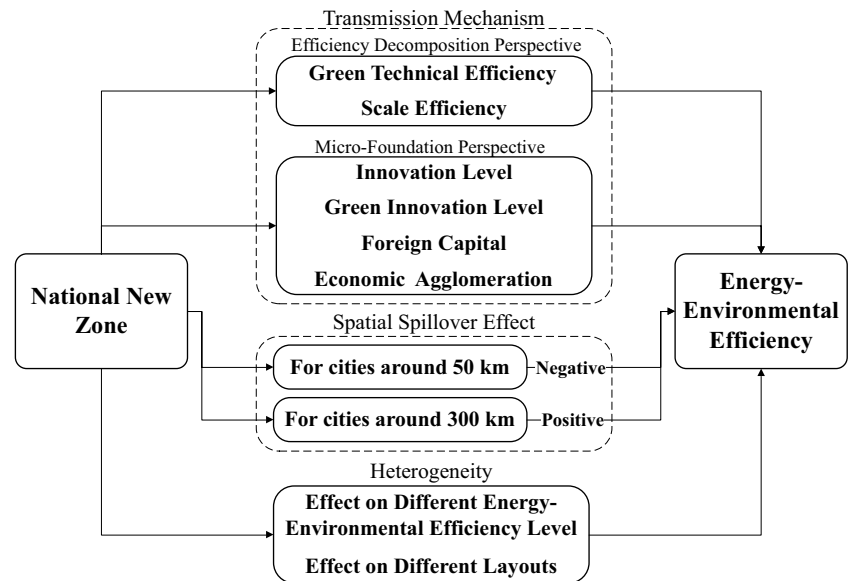
development and environmental quality in Shenzhen, which the whole city is China's earliest special economic zone, is also consistent with the environmental Kuznets curve, i.e., severe environmental pollution in the early stages of development and improved environmental quality in the later stages of development. Huang and Zhang (2021) find that establishing green finance pilot zones can reduce environmental pollution, mainly because of the role of green finance policies in them. Yang et al. (2022) find that high-tech industrial development zones (HTZs) in China can effectively promote eco-innovation in cities, and conclude that the pathway is the concentration of innovation factors, such as the concentration of talents and investments, and the latter is the main driver. At the same time, HTZs also have positive spillover effects on green innovation activities in other cities in the same province. Lee et al. (2022) show that low-carbon pilot cities help reduce energy consumption, improve energy structure, and reduce energy intensity. Wang et al. (2022) use a multi-period DID model to find that national new zones can help improve the eco-efficiency of cities, and the impact pathways include improving urbanization levels and improving transportation infrastructure.

Thus, although different special zones have different objectives, such as promoting innovation, increasing foreign trade, and facilitating green development. Most existing studies affirm the role of policy special zones in improving the environment and reducing energy consumption in the cities where they are located, but the spatial spillover effect is not fully explored. And it is worth exploring whether national new zones, as an advanced form of special zones, can also promote green development and improve energy-environmental efficiency and whether they can bring positive spillover effects.

National new zones and efficiency enhancement

The impact pathways of national new zones on energy-environmental efficiency may include improving green technology efficiency and scale efficiency.

Technical efficiency can be expressed by the ratio of actual output to ideal output at a given input factor (Farrell 1957). Considering that pollution may be generated in the production process, green technical efficiency can be derived as the gap between the actual desirable, undesirable output and the ideal output for a given number of input factors, which reflects the level of green technology of a region or an enterprise. In the face of the central government's green development and "dual-carbon" goals, local governments have added green and low-carbon requirements into urban planning when constructing national new zones (Xu 2022). Specifically, requirements include promoting the development of low-carbon and environmental industries, such as green buildings, clean energy, and waste reuse (Wang et al. 2022). As a result, the national new zones may motivate enterprises to reduce emissions and improve energy-environmental efficiency through environmental regulation and supervision (Yang et al. 2019). At the same time, compared to other regions, national new zones will receive additional development funds from central governments after the establishment (Martinez 2018), enabling to introduce a series of policy measures to support low-carbon and environmental development, such as subsidy policies to encourage enterprises to transform and upgrade, use clean energy, and improve resource efficiency. In this context, companies are motivated to acquire or improve energy-efficient and green production technologies through innovative approaches to avoid environmental fines and increase profits (Edziah et al.

2022). On the other hand, under the requirement of economic growth and energy saving and environmental protection goals, national new zones also introduce preferential policies for foreign capital, such as tax incentives. As the foreign capital introduced usually has a more advanced and environmentally friendly level of technology (Bakhsh et al. 2021), it helps to improve the cities' green technical efficiency, which can reduce energy consumption, waste emissions, and CO_2 emissions. These measures can improve cities' energy-environmental efficiency and promote sustainable urban development. Therefore, establishing national new zones may through improving the green technical efficiency to enhance cities' energy-environmental efficiency. The special ways to improve green technical efficiency may include increasing enterprises' green innovation level and increasing the amount of foreign capital employed.

Scale efficiency measures the gap between the actual production scale and the ideal scale (Farrell 1957). The establishment of national new zones not only places higher technical requirements on firms in terms of energy-environmental protection, but also supports them in terms of resources and funding (Martinez 2018), giving rise to the concentration of capital, energy, and labor factors, which may increase the scale efficiency of production. Specifically, national new zones usually introduce preferential policies in loans and investments (Li 2015), which helps make financing less costly for companies. In addition, national new zones may provide tax incentives to encourage high-quality firms to enter the area, which not only helps to improve the industrial structure and raise technology levels but also increases the level of capital and energy agglomeration. In addition, the corresponding settlement and talent introduction policies also attract a large concentration of quality labor (Chao 2022; Sun et al. 2022), increasing the scale efficiency of production.

Thus, the establishment of national new zones attracts a large concentration of labor, capital, and energy factors, which may contribute to scale efficiency. Many studies find that economic agglomeration and increased scale efficiency contribute to lower energy consumption and reduced pollution emissions (Chen et al. 2019; Chen et al. 2023; Zhang and Choi 2013), but a few articles suggest that agglomeration may increase pollution (Gao et al. 2021). Therefore, there is some potential for establishing national new zones to increase the cities' energy-environmental efficiency by improving the scale efficiency.

Models and data

Difference-in-difference model

Since national new zones are established in stages, refer to Beck et al. (2010), a multi-period difference-in-difference approach is used, specifically setting the following econometric model:

$$Y_{it} = \beta_0 + \beta_1 DID_{it} + \lambda Z_{it} + \nu_i + \mu_t + \varepsilon_{it} \quad (1)$$

where i denotes the prefecture-level city ($i = 1, 2, \ldots, 284$), and t denotes the year($t = 2003, 2004, \ldots, 2019$). The dependent variable Y_{it} is energy-environmental efficiency, expressed in two ways: the unified efficiency index(UEI_{it}) and the energy-environmental performance index(EEI_{it}), and the specific measures and results are shown in Section 3.3. DID_{it} is the difference-in-difference estimator of whether to establish a national new zone, and the specific measures and results are shown in 3.2. As control variables, Z_{it} are the other factors affecting energy-environmental efficiency, and the specific variables are shown in Section 3.4. ν_i is the individual fixed effect for prefecture-level municipalities, μ_t is year fixed effect, and ε_{it} is the error term.

To explore the transmission mechanism of the above effects, the following econometric model is set up based on Eq.(1):

$$Y_{it} = \beta_0 + \beta_1 DID_{it} + \gamma DID_{it} \times TM_{it} + \lambda Z_{it} + \nu_i + \mu_t + \varepsilon_{it} \quad (2)$$

The transmission mechanisms (TM_{it}) include $TM1_{it}$ from the efficiency decomposition perspective: green technical efficiency(TE_{it}) , scale efficiency(SE_{it}) and total factor productivity(TFP_{it}), measured in Section 3.3, and $TM2_{it}$ from the micro-foundation perspective: innovation level($lnInnov_{it}$), green innovation level($lnGreeninnov_{it}$), foreign capital($lnFcaptial_{it}$), and economic agglomeration level(Agg_{it}), measured in Section 3.4. $TM1_{it}$ are used to explore whether national new zones improve energy-environmental efficiency by increasing the TE, SE, and TFP of the city, and $TM2_{it}$ are used to explore whether national new zones improve energy-environmental efficiency by increasing the innovation and green innovation level, the amount of foreign capital employed, and the economic agglomeration level of the city.

Energy-environmental efficiency

Measurements

Considering the current environmental constraints faced by China's economic development, we refer to Zhang et al. (2014), using capital, labor, and energy as input factors, gross regional product (GRP) as the desirable output, and carbon dioxide emissions, industrial wastewater emissions, industrial sulfur dioxide emissions, and industrial fume and dust emissions as the undesirable output, measuring the energy-environmental efficiency that reflects the maximization of economic output and minimization of environmental impact. The key is measuring the relationship

between each decision-making unit (DMU, in this paper, a prefecture-level city) and the production frontier so that energy efficiency can be measured in a way that promotes economic growth and reduces pollutant emissions simultaneously. In this paper, we use the input factors, desirable output, and undesirable output data of the smallest DMU in the DEA model to construct a non-parametric frontier surface through the non-radial directional distance function (NDDF), and calculate the energy-environmental efficiency of each prefecture-level city based on whether the DMU can use as few resources as possible to gain as much desirable output and bring as little undesirable output as possible. The directional distance function (DDF) sets the desirable output to increase while the undesirable output will decrease strictly in equal proportion. Zhou et al. (2012) proposed a non-radial directional distance function that allows for inconsistent proportional increases and decreases in the desirable and undesirable outputs, while also avoiding the possible slack bias problem of the DDF (Fukuyama and Weber 2010).

We are based on panel data of prefecture-level cities in China, assuming constant returns to scale (Zhou et al. 2008). Under the framework of the DEA model, two types of energy-environmental efficiency indicators representing prefecture-level cities are measured using the total factor non-radial directional distance function (TNDDF) and energy-environmental non-radial directional distance function (ENDDF) techniques, respectively. With capital (K), labor (L), and energy (E) as input factors, GRP (Y) as the desirable output, and carbon dioxide emissions (C), industrial wastewater emissions (W), industrial sulfur dioxide emissions (S), and industrial fume and dust emissions (D) as undesirable outputs, and letters indicating the total amount of each variable for each DMU, the following production techniques are defined:

$$T = \{(K,L,E,Y,C,W,S,D) : (K,L,E) \text{ products } (Y,C,W,S,D)\} \tag{3}$$

expressed in the form of a production set as

$$P(K,L,E) = \{ (Y,C,W,S,D) : (K,L,E,Y,C,W,S,D) \in T \} \tag{4}$$

Specifically, for N DMUs, the above production techniques can be expressed as

$$T = \left\{ \begin{array}{l} (K,L,E,Y,C,W,S,D) : \sum_{n=1}^{N} z_n K_n \leqslant K, \sum_{n=1}^{N} z_n L_n \leqslant L, \sum_{n=1}^{N} z_n E_n \leqslant E, \sum_{n=1}^{N} z_n Y_n \geqslant Y, \\ \sum_{n=1}^{N} z_n C_n = C, \sum_{n=1}^{N} z_n W_n = W, \sum_{n=1}^{N} z_n S_n = S, \sum_{n=1}^{N} z_n D_n = D \end{array} \right\} \tag{5}$$

where z_n are the parameters that $z_n \geqslant 0$, $n = 1, 2, 3, \cdots, N$.

Further we define the NDDF for measuring the energy-environmental efficiency of each DMU:

$$\vec{D}(K,L,E,Y,C,W,S,D;G) = \sup\left\{ \begin{array}{l} w^T B : \left(Y + \beta_Y g_Y, C - \beta_C g_C, W - \beta_W g_W, S - \beta_S g_S, D - \beta_D g_D\right) \\ \in P\left(K - \beta_K g_K, L - \beta_L g_L, E - \beta_E g_E\right) \end{array} \right\} \tag{6}$$

where $w^T = (w_K, w_L, w_E, w_Q, w_C, w_W, w_S, w_D)$ is the weight vector, which indicates the relative importance of each element and can be chosen flexibly according to different research needs, so there is also some subjectivity. Therefore, this paper adopts the unified efficiency index (UEI_{it}) and the energy-environmental performance index(EEI_{it}) to measure energy-environmental efficiency respectively, and explores the impact of establishing national new zones on both in the econometric analysis.

$B = (\beta_K, \beta_L, \beta_E, \beta_Y, \beta_C, \beta_W, \beta_S, \beta_D)^T \geqslant 0$ is a slack vector indicating the proportion by which each element can increase or decrease. $G = (-g_K, -g_L, -g_E, g_Y, -g_C, -g_W, -$

$g_S, -g_D)$ is the direction vector, which indicates the scale at which each factor is expected to increase or decrease, usually expressed as the total amount of each factor (Zhou et al. 2012), which means $G = (-K, -L, -E, Y, -C, -W, -S, -D)$. The NDDF represented by Eq.(6) can be interpreted as follows: at a given production technology, the producer wants to increase output along the g_Y direction to maximize the desirable output, and along the $-g_K, -g_L, -g_E, -g_C, -g_W, -g_S, -g_D$ direction to minimize capital, labor, energy inputs, and undesirable outputs.

Since there is a substitution effect between energy and other input factors, the energy-environmental efficiency

measured by the UEI is first calculated using the total factor non-radial directional distance function (TNDDF). Specifically, the following DEA model is constructed using the TNDDF:

$$
\begin{aligned}
\vec{D}_T(K,L,E,Y,C,W,S,D;G) = \max\ & w_K\beta_K + w_L\beta_L + w_E\beta_E + w_Y\beta_Y + w_C\beta_C + w_W\beta_W + w_S\beta_S + w_D\beta_D \\
\text{s.t.}\ & \sum_{n=1}^{N} z_n K_n \leqslant K - \beta_K K,\ \sum_{n=1}^{N} z_n L_n \leqslant L - \beta_L L,\ \sum_{n=1}^{N} z_n E_n \leqslant E - \beta_E E, \\
& \sum_{n=1}^{N} z_n Y_n \geqslant Y + \beta_Y Y,\ \sum_{n=1}^{N} z_n C_n = C - \beta_C C,\ \sum_{n=1}^{N} z_n W_n = W - \beta_W W, \\
& \sum_{n=1}^{N} z_n S_n = S - \beta_S S,\ \sum_{n=1}^{N} z_n D_n = D - \beta_D D, \\
& z_n \geqslant 0, n = 1, 2, 3, \cdots, N \\
& \beta_K, \beta_L, \beta_E, \beta_Y, \beta_C, \beta_W, \beta_S, \beta_D \geqslant 0
\end{aligned}
\tag{7}
$$

Without a priori information, inputs, desirable outputs, and undesirable outputs are usually treated equally when UEI are constructed (Barros et al. 2012; Zhang et al. 2014; Zhou et al. 2012). Therefore, we assume that the weights of inputs, desirable outputs and undesirable outputs in the above equation are all $\frac{1}{3}$ and that the shares of each element within the three components are also treated equally, we obtain $w^T = \left(\frac{1}{9}, \frac{1}{9}, \frac{1}{9}, \frac{1}{3}, \frac{1}{12}, \frac{1}{12}, \frac{1}{12}, \frac{1}{12}\right)$. Solving for the maximum value of Eq.(7) yields $B^*_{Tn} = (\beta^*_{TnK}, \beta^*_{TnL}, \beta^*_{TnE}, \beta^*_{TnY}, \beta^*_{TnC}, \beta^*_{TnW}, \beta^*_{TnS}, \beta^*_{TnD},)^T$, which is the optimal value of the slack variable for the nth decision unit. Referring to Zhang et al. (2014), we calculate the energy-environmental efficiency of each DMU measured by UEI:

$$
\begin{aligned}
UEI_n &= \frac{1}{7}\left[
\begin{array}{c}
\frac{Y_n/K_n}{(Y_n+\beta^*_{TnY}Y_n)/(K_n-\beta^*_{TnK}K_n)} + \frac{Y_n/L_n}{(Y_n+\beta^*_{TnY}Y_n)/(L_n-\beta^*_{TnL}L_n)} \\
+ \frac{Y_n/E_n}{(Y_n+\beta^*_{TnY}Y_n)/(E_n-\beta^*_{nE}E_n)} + \frac{Y_n/C_n}{(Y_n+\beta^*_{TnY}Y_n)/(C_n-\beta^*_{TnC}C_n)} \\
+ \frac{Y_n/W_n}{(Y_n+\beta^*_{TnY}Y_n)/(W_n-\beta^*_{nW}W_n)} + \frac{Y_n/S_n}{(Y_n+\beta^*_{TnY}Y_n)/(S_n-\beta^*_{TnS}S_n)} \\
+ \frac{Y_n/D_n}{(Y_n+\beta^*_{TnY}Y_n)/(D_n-\beta^*_{TnD}D_n)}
\end{array}
\right] \\
&= \frac{(1-\beta^*_{TnK})+(1-\beta^*_{TnL})+(1-\beta^*_{TnE})+(1-\beta^*_{TnC})+(1-\beta^*_{TnW})+(1-\beta^*_{TnS})+(1-\beta^*_{TnD})}{7(1+\beta^*_{TnY})} \\
&= \frac{1-\frac{1}{7}\left(\beta^*_{TnK}+\beta^*_{TnL}+\beta^*_{TnE}+\beta^*_{TnC}+\beta^*_{TnW}+\beta^*_{TnS}+\beta^*_{TnD}\right)}{1+\beta^*_{TnY}}, n = 1, 2, 3, \cdots, N.
\end{aligned}
\tag{8}
$$

Since we are more concerned with the relationship between energy and the environment, drawing on Li and Hu (2012)'s idea of weakening the focus on capital and labor inputs, when measuring energy-environmental efficiency by EEI in Eq. (7), the energy input, desirable output, and undesirable outputs are each weighted by $\frac{1}{3}$, which means we use $w^T = \left(0, 0, \frac{1}{3}, \frac{1}{3}, \frac{1}{12}, \frac{1}{12}, \frac{1}{12}, \frac{1}{12}\right)$ to solve Eq.(7), and we obtain $B^*_{En} = (\beta^*_{EnE}, \beta^*_{EnY}, \beta^*_{EnC}, \beta^*_{EnW}, \beta^*_{EnS}, \beta^*_{EnD},)^T$, again referring to Zhang et al. (2014) to calculate the energy-environmental efficiency of each DMU as measured by the EEI:

$$
\begin{aligned}
EEI_n &= \frac{1}{5}\left[
\begin{array}{c}
\frac{Y_n/E_n}{(Y_n+\beta^*_{TnY}Y_n)/(E_n-\beta^*_{nE}E_n)} + \frac{Y_n/C_n}{(Y_n+\beta^*_{TnY}Y_n)/(C_n-\beta^*_{TnC}C_n)} \\
+ \frac{Y_n/W_n}{(Y_n+\beta^*_{TnY}Y_n)/(W_n-\beta^*_{nW}W_n)} + \frac{Y_n/S_n}{(Y_n+\beta^*_{TnY}Y_n)/(S_n-\beta^*_{TnS}S_n)} \\
+ \frac{Y_n/D_n}{(Y_n+\beta^*_{TnY}Y_n)/(D_n-\beta^*_{TnD}D_n)}
\end{array}
\right] \\
&= \frac{(1-\beta^*_{TnE})+(1-\beta^*_{TnC})+(1-\beta^*_{TnW})+(1-\beta^*_{TnS})+(1-\beta^*_{TnD})}{5(1+\beta^*_{TnY})} \\
&= \frac{1-\frac{1}{5}\left(\beta^*_{TnE}+\beta^*_{TnC}+\beta^*_{TnW}+\beta^*_{TnS}+\beta^*_{TnD}\right)}{1+\beta^*_{TnY}}, n = 1, 2, 3, \cdots, N.
\end{aligned}
\tag{9}
$$

UEI considers the utilization efficiency and environmental efficiency of all input factors and is a Combined index of all factors, and EEI excludes capital and labor factors and indicates the average value of energy efficiency and environmental efficiency. The values of UEI_n and EEI_n range from 0 to 1, and the larger the value is, the higher the energy-environmental efficiency of the nth DMU (the nth prefecture-level city). When the value is 1, it means the prefecture-level city is located on the production frontier boundary and has the highest energy-environmental efficiency.

Finally, for mechanism analysis, using the data envelopment analysis method with the slacks-based model and undesirable outputs (SBM-DEA) (Tone and Tsutsui 2006), the green technical efficiency (TE) and scale efficiency (SE) are calculated for each prefecture-level city, where TE is the gap between the actual desirable, undesirable outputs and the ideal outputs for a given number of input factors, and scale efficiency measures the gap between the actual scale of production and the ideal scale of production. On the other hand, since technical efficiency reflects the gap between actual and ideal outputs, the highest technical efficiency among all regions in the same year is taken as the ideal value (taking the value of 1) in the calculation. Therefore, if a region has technical progress but to a lesser extent than the most technologically advanced region, the decrease in technical

Fig. 2 National new zones' establishing year and distribution of sample cities.
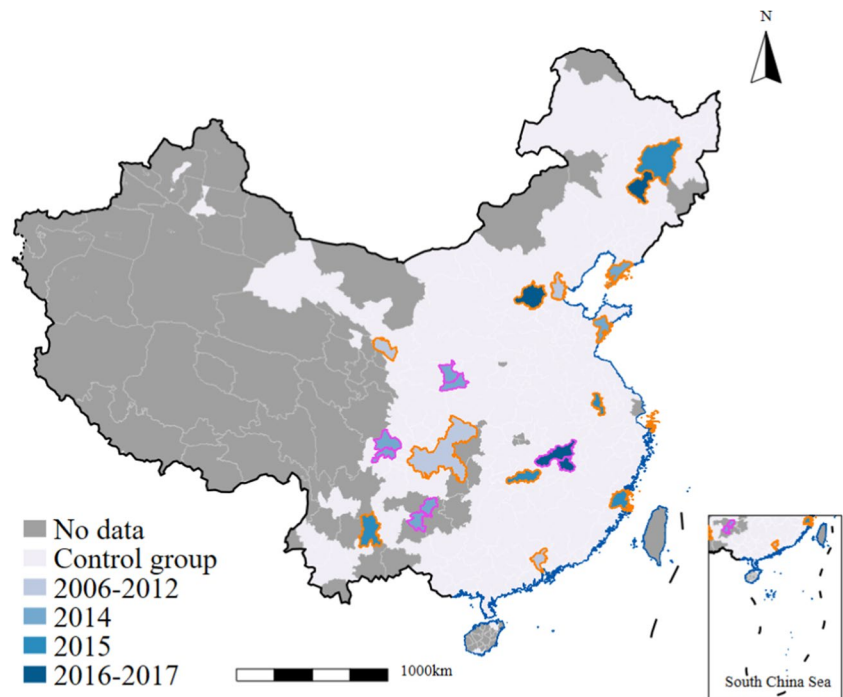
efficiency over time does not reflect its technical progress. In contrast, the Malmquist DEA method with undesirable outputs uses panel data, and the decomposed total factor productivity (TFP) considers the changes in the level of technology in the same region over time and reflects the absolute level of technology in each region more comprehensively, so it is used as the third efficiency indicator in the mechanism test as a complement to the green technical efficiency.

Data processing

The input and output factors of 284 prefecture-level cities in China are selected to measure energy-environmental efficiency from 2003-2019. The data for each variable is treated as follows.

(1)   Capital input. The capital input is measured by the capital stock at constant prices and are estimated using the perpetual inventory method, i.e., the capital stock of the city n in year t is $K_{n,t} = (1-\delta)K_{n,t-1} + \frac{I_{nt}}{P_{nt}}, t = 2004, 2005, \ldots, 2019$. The current investment (I_{nt}) is expressed by the total social fixed asset investment of city n in year t. The depreciation rate (δ) is taken as 9.6% (Zhang 2008). The real capital price (P_{nt}) is expressed as the fixed asset investment price index of city n in year t with 2003 as the base period. The capital stock in the base period ($K_{n,2003}$) is calculated by $K_{n,2003} = I_{n,2003} \times \frac{1+g_n}{g_n+\delta}$, where g_n is the average growth rate of constant price investment $\left(\frac{I_{nt}}{P_{nt}}\right)$ from

2004 to 2019 of city n. The total social fixed asset investment and fixed asset investment price index are obtained from the *China City Statistical Yearbook* and the statistical yearbook of each city.

(2)   Labor input. We use the sum of the number of employees in state-owned enterprises and the number of private and individual employees in urban areas at the end of the year from the *China City Statistical Yearbook* to measure the labor input.

(3)   Energy input. We use energy consumption to measure energy inputs. The data of energy consumption mainly comes from Chen et al. (2022), which uses nighttime satellite lighting data and uses machine learning to establish a quantitative relationship between provincial energy consumption data and provincial nighttime lighting data based on provincial energy balance sheets provided by the National Bureau of Statistics, and then estimates the energy consumption of cities based on factors such as the intensity of city lights.

(4)   Gross regional product (GRP). The nominal GRP and the real growth rate are obtained from the *China City Statistical Yearbook* and the calculation of the real GRP for other years is based on the 2003 GRP and the real growth rate for each year.

(5) CO_2 emission. The data of CO2 emissions are mainly from Chen et al. (2020), which also uses the nighttime satellite light data to establish a quantitative relationship between provincial carbon emission data and provincial nighttime light data using a machine learning

approach to estimate carbon emissions of cities based on provincial energy balance sheets and the carbon emission estimation method provided by the Intergovernmental Panel on Climate Change (IPCC) as the multiplication of fossil fuels and corresponding carbon emission factors, and then estimate the carbon emissions of cities based on city light data.

(6) Industrial wastewater, industrial sulfur dioxide, and industrial fume and dust emissions, are derived from the *China City Statistical Yearbook*.

National new zones

If in the city i in year t, a national new zone is established, then in year t and subsequent years, DID_{it} in Eq.(1) takes the value of 1; otherwise it takes the value of 0. When setting the year to establish national new zones, we consider those zones approved by the central government in the first half-year to be established one year before the approval, and those approved in the second half-year to be established in the year of the approval. This is because most of the national new zones are established through the bottom-up process of local government application and the central government's approval, and local governments may know whether they can establish a national new zone before the official approval is granted, and carry out related construction work in advance, resulting in the national new zones actually functioning earlier than the time announced by the central government (Chao, 2022). Figure 2 presents the geographical distribution of the 18 national new zones[1] and the 23 cities in which they are located[2]. The overall distribution is relatively uniform, and there are control groups near each national new zone, which helps set up the difference-in-difference models.

Other variables

Control variables

Drawing on the existing literature that explores the energy efficiency and environmental efficiency, Z_{it} in Eq.(1) include the following variables:

(1) Real GRP per capita and its square (*Pgrp* and *Pgrp2*). They can portray an inverted U-shaped environmental Kuznets curve, where the energy-environmental efficiency may differ at different stages of economic development (Liu et al. 2023; Sheng et al. 2020; Tariq et al. 2022).

(2) Environmental governance investment (*Einvest*), is expressed by the sum of municipal investment in drainage, landscaping, and sanitation in each city, using the logarithmic form. The investment in environmental management indicates the importance that the government attaches to environmental issues, and the higher the government's attention, the better the energy-environmental efficiency of the city may be (Wang and Wu 2022).

(3) The urbanization rate (*Urb*). It is expressed by the proportion of the urban population to the total population of a city. In the early stage of development, as urbanization progresses, pollution emissions increase in the transportation and industrial sectors of the region, at this time technology is less developed, energy consumption is higher, and energy efficiency is lower. In the later stages of development, as urbanization increases, the use of cleaner energy sources increases, and regional energy-environmental efficiency increases (Sun and Huang 2020).

(4) Population density (*Pdense*). It is measured by the ratio of the total city's population to the administrative area, reflecting the degree of aggregation of economic activities in a city (He et al. 2023).

(5) Industrial structure (*Second*), is expressed by the proportion of the secondary industry's added value in GRP. The secondary industry consumes more energy than other industries and is less energy efficient. With economic development and structural transformation, the proportion of secondary industry decreases, which is conducive to improving the energy-environmental efficiency (Xiong et al. 2019).

(6) Energy prices (*Eprice*). It is expressed by the price of industrial electricity in each city. Higher energy prices help improve energy efficiency, mainly because they help raise awareness of energy conservation and motivate companies to reduce energy waste (Gamtessa and Olani 2018).

(7) Marketization Degree (*Market*). Using the Marketization Indices provided by Fan et al. (2019). The degree of marketization may be one of the factors affecting energy environmental efficiency (Feng and Wang 2019; Song et al. 2022).

The above data are mainly from the *China City Statistical Yearbook* and CEIC database.

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[1] Due to incomplete data and to reduce the bias introduced by the earlier treatment group in the multi-period DID model serving as a control sample at a later stage (Goodman-Bacon 2021) , the Shanghai sample, where the Pudong New Zone was approved for establishment in 1992, was excluded from our study.

[2] The national new zones in the cities indicated by the pink border are "two-city layout", i.e. one national new zone is located in two cities; the orange border is "one-city layout".

Table 1 Descriptive statistics.

Variable	Unit	N	Mean	SD	Min	Max
UEI	-	4828	0.399	0.181	0.138	1.000
EEI	-	4828	0.288	0.209	0.028	1.000
DID	-	4828	0.031	0.175	0	1
Pgrp	yuan per person	4828	36988	30235	3023	260217
Einvest	10,000 yuan	4828	73141	257632	50	9483255
Urb	-	4828	0.233	0.210	0.022	2.466
Pdense	people per square kilometer	4828	420	311	5	2648
Second	-	4828	0.476	0.111	0.107	0.910
Market	-	4828	7.876	2.135	2.600	13.580
Eprice	yuan per kwh	4828	0.715	0.120	0.353	0.930
Labor	10,000 people	4828	96	134	6	1729
Capital	100 million yuan	4828	4000	5580	65	69164
Energy	million tons of coal equivalents	4828	1206	1085	34	9664
RGRP	10,000 yuan	4828	16941590	23695951	481213	262606238
CO_2	million tons	4828	25	21	2	154
Wwater	10,000 tons	4828	6786	8966	7	96501
SO2	tons	4828	50429	55079	2	683162
Dust	tons	4828	30030	109996	34	5168812
TE	-	4828	0.367	0.173	0.097	1.000
SE	-	4828	0.825	0.142	0.111	1.000
TFP	-	4828	1.385	1.819	0.100	19.963
Innov	per 10,000 people	4828	5.230	10.262	0	123.976
Greeninnov	per 10,000 people	4828	0.072	0.190	0	3.192
Fcapital	10,000 dollars	4828	65457	159732	0	3082563
Agg	-	4828	0.471	0.242	0.062	1.00

Other mechanism variables

In the mechanism analysis, we also explore whether the existence of national new zones affects the energy-environmental efficiency by influencing the level of innovation or green innovation, the amount of foreign capital employed, and the degree of economic agglomeration. The variables involved are as follows:

(1) Innovation (*Innov*), is measured by the number of patents granted per 10,000 people in each city.

(2) Green innovation (*Greeninnov*), is measured by the number of green patents granted per 10,000 people in each city.

(3) Foreign capital (*Fcapital*), is measured by the amount of foreign capital each city uses yearly.

(4) Economic agglomeration (*Agg*), measured by the ratio of the municipal district's GDP to the city's entire GDP.

The above data are mainly obtained from the *China City Statistical Yearbook* and the China Research Data Service Platform (CNRDS).

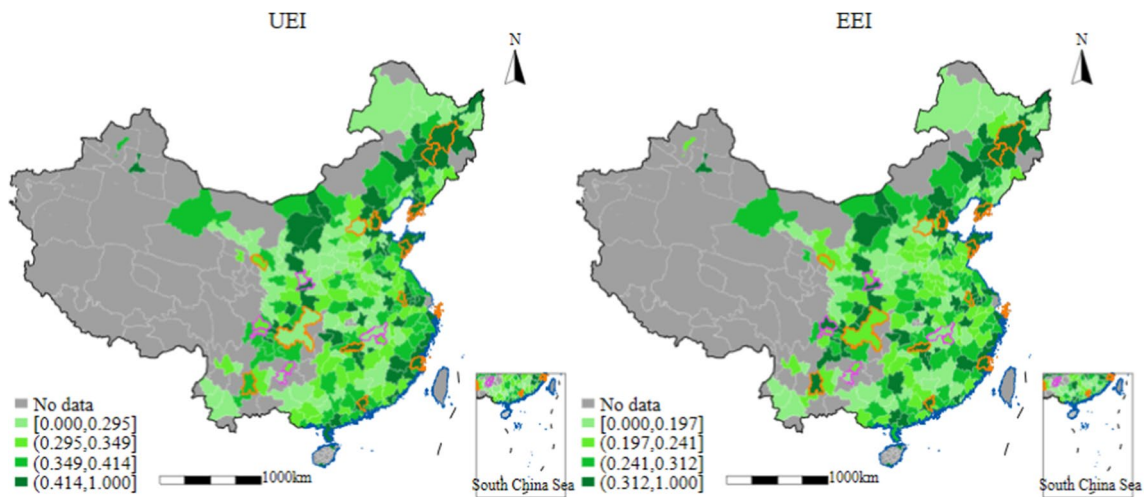**Fig. 3** Kernel density curves of UEI and EEI.
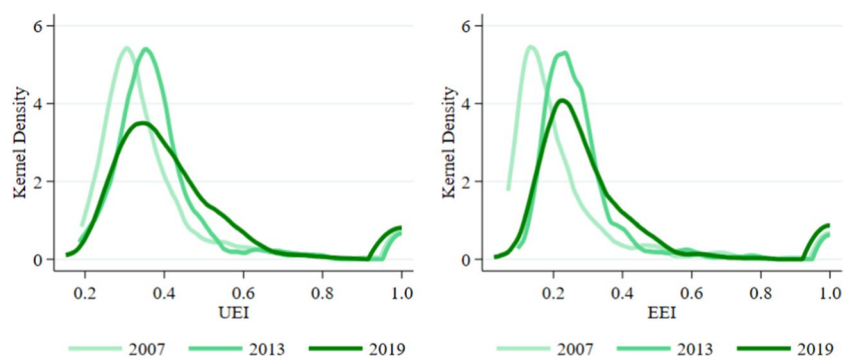
Fig. 4 Energy-environmental efficiency of each city in 2015.

The descriptive statistics of the main variables involved in the paper are shown in Table 1.

Analysis of results and discussion

Measurement results of energy-environmental efficiency

Figure 3 shows the distribution and trend of energy-environmental efficiency measured by UEI and EEI,

respectively. Overall, the energy-environmental efficiency of prefecture-level cities in China is still low, and the average values during the study period are below 0.5, but there is an increasing trend. the prefecture-level cities with the highest UEI and EEI are Shenzhen and Wuxi, and the lowest cities are Zhongwei and Wuzhong. The differences in energy-environmental efficiency measured by the two types of indexes are small, usually higher for technology and labor-intensive cities and lower for energy-intensive cities. Fig. 4 shows the geographical distribution of energy-environmental efficiency by cities in 2015.

Table 2 Benchmark regression.

| | UEI | UEI | EEI | EEI |
	(1)	(2)	(3)	(4)
DID	0.074***(0.012)	0.053***(0.012)	0.092***(0.015)	0.072***(0.014)
Pgrp		0.000***(0.000)		0.000***(0.000)
Pgrp2		-0.000***(0.000)		-0.000***(0.000)
lnEinvest		0.003(0.002)		0.005**(0.002)
Urb		-0.040(0.032)		-0.019(0.040)
Pdense		-0.000***(0.000)		-0.000***(0.000)
Second		-0.152***(0.033)		-0.131***(0.041)
Eprice		-0.052*(0.029)		0.007(0.037)
Market		-0.010***(0.004)		-0.006(0.005)
_Cons	0.460***(0.006)	0.642***(0.037)	0.349***(0.008)	0.471***0.047)
Year FE	Yes	Yes	Yes	Yes
City FE	Yes	Yes	Yes	Yes
N	4828	4828	4828	4828
R^2	0.115	0.176	0.098	0.141

Standard errors are in parentheses;*, **, *** represent 10%, 5%, and 1% significance levels, respectively.

Table 3 Mechanism analysis 1: efficiency decomposition.

	UEI (1)	UEI (2)	UEI (3)	EEI (4)	EEI (5)	EEI (6)
DID	-0.200**(0.096)	-0.128***(0.021)	-0.028*(0.015)	-0.235*(0.121)	-0.146***(0.027)	-0.028(0.019)
DID×SE	0.276***(0.104)			0.334**(0.131)		
DID×TE		0.437***(0.043)			0.524***(0.054)	
DID×TFP			0.032***(0.004)			0.040***(0.005)
Pgrp	0.000***(0.000)	0.000***(0.000)	0.000***(0.000)	0.000***(0.000)	0.000***(0.000)	0.000***(0.000)
Pgrp2	-0.000***(0.000)	-0.000***(0.000)	-0.000***(0.000)	-0.000***(0.000)	-0.000***(0.000)	-0.000***(0.000)
lnEinvest	0.003*(0.002)	0.003*(0.002)	0.003*(0.002)	0.005**(0.002)	0.006***(0.002)	0.005**(0.002)
Urb	-0.039(0.032)	-0.035(0.031)	-0.042(0.032)	-0.018(0.040)	-0.013(0.039)	-0.021(0.040)
Pdense	-0.000***(0.000)	-0.000***(0.000)	-0.000***(0.000)	-0.000***(0.000)	-0.000***(0.000)	-0.000***(0.000)
Second	-0.153***(0.033)	-0.161***(0.033)	-0.154***(0.033)	-0.133***(0.041)	-0.142***(0.041)	-0.134***(0.041)
Eprice	-0.052*(0.029)	-0.062*(0.029)	-0.060**(0.029)	0.007(0.037)	-0.005(0.037)	-0.003(0.037)
Market	-0.010***(0.004)	-0.011***(0.004)	-0.010***(0.004)	-0.006(0.005)	-0.008*(0.005)	-0.006(0.005)
_Cons	0.644***(0.037)	0.655***(0.037)	0.651***(0.037)	0.474***(0.047)	0.487***(0.046)	0.482***(0.047)
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
City FE	Yes	Yes	Yes	Yes	Yes	Yes
N	4828	4828	4828	4828	4828	4828
R^2	0.177	0.195	0.188	0.142	0.158	0.152

Standard errors are in parentheses; *, **, *** represent 10%, 5%, and 1% significance levels, respectively; control variables are the same as the benchmark regression.

Table 4 Mechanism analysis 1: efficiency decomposition (average marginal effect).

	UEI (1)	UEI (2)	UEI (3)	EEI (4)	EEI (5)	EEI (6)
DID	0.028*(0.015)	0.032***(0.012)	0.017(0.012)	0.041**(0.019)	0.046***(0.015)	0.027*(0.015)
SE	0.009***(0.003)			0.011**(0.004)		
TE		0.014***(0.001)			0.016***(0.002)	
TFP			0.001***(0.000)			0.001***(0.000)
N	4828	4828	4828	4828	4828	4828

Standard errors are in parentheses; *, **, *** represent 10%, 5%, and 1% significance levels, respectively.

Benchmark regression and mechanism analysis

Table 2 reports the results of the regression according to Eq.(1). Columns (1) and (3) do not include control variables, and the establishment of national new zones has a significant effect on energy-environmental efficiency measured by both UEI and EEI. Columns (2) and (4) including control variables, the DID variables are significant at the 1% level, so establishing national new zones increases energy-environmental efficiency measured by UEI at an average of 0.053, or 0.072 measured by EEI. As the average UEI and EEI are 0.399 and 0.288, respectively, if we take them as benchmarks, the establishment of national new zones increases energy-environmental efficiency by about 13% to 25%, which is a very significant increase. Therefore, there is a strong statistical and economic significance of the

improvement of energy-environmental efficiency by national new zones.

Next, the mechanism analysis is performed. Table 3 reports the regression results of adding the interaction terms of each efficiency and DID variables decomposed by the DEA method, as shown in Eq.(2). From columns (1)-(6), it can be seen that the interaction terms of DID and each efficiency are all significant above the 5% level. The coefficients are all positive, indicating that the impact of each efficiency on energy-environmental efficiency increases significantly when a national new zone is established. Combining the average marginal effects of DID and each efficiency shown in Table 4, we can see that scale efficiency, green technical efficiency, and total factor productivity all have significant positive effects on energy-environmental efficiency. The establishment of national

Table 5 Mechanism analysis 2: micro-foundation perspective.

	UEI (1)	EEI (2)	UEI (3)	EEI (4)	UEI (5)	EEI (6)	UEI (7)	EEI (8)
DID	-0.035(0.036)	-0.070(0.045)	0.009(0.017)	0.008(0.022)	-0.202***(0.075)	-0.274***(0.094)	-0.041(0.041)	-0.054(0.051)
DID×lnInnov	0.031**(0.013)	0.056***(0.017)						
DID× lnGreeninnov			0.144***(0.043)	0.208***(0.054)				
DID×lnFcapital					0.022***(0.006)	0.029***(0.008)		
DID×Agg							0.136**(0.056)	0.181**(0.070)
_Cons	0.650***(0.038)	0.484***(0.047)	0.649***(0.037)	0.481***(0.047)	0.648***(0.037)	0.478***(0.047)	0.645***(0.037)	0.475***(0.047)
Year FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
City FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Control variables	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
N	4828	4828	4828	4828	4828	4828	4828	4828
R^2	0.177	0.143	0.178	0.144	0.178	0.143	0.177	0.142

Standard errors are in parentheses; *, **, *** represent 10%, 5%, and 1% significance levels, respectively; control variables are the same as the benchmark regression.

new zones also has a significant positive effect, indicating that the establishment of national new new zones promotes energy-environmental efficiency by improving the cities' scale efficiency and green technical efficiency.

On the other hand, we also from the micro-foundation perspective explore whether there are mechanisms($TM2_{it}$) of innovation and green innovation, foreign capital, and economic agglomeration. Table 5 reports the regression results for adding the interaction term of DID with possible mechanisms($TM2_{it}$) to the benchmark model. We uncover that the interaction terms are all significant above the 5% level and the coefficients are all positive, indicating that the effects of innovation and green innovation, foreign capital, and economic agglomeration on energy-environmental efficiency all increase significantly when a national new zone is established. Combining the DID and the average marginal effect of each mechanism in Table 6, we find that innovation and green innovation, foreign capital use, and economic agglomeration all have significant positive effects on energy-environmental efficiency, further indicating that the establishment of national new zones promotes energy-environmental efficiency by increasing the level of innovation and green innovation, the amount of foreign capital use and economic agglomeration in the cities where they are located.

Table 6 Mechanism analysis 2: micro-foundation perspective (average marginal effect).

	UEI (1)	EEI (2)	UEI (3)	EEI (4)	UEI (5)	EEI (6)	UEI (7)	EEI (8)
DID	0.007(0.021)	-0.003(0.027)	0.018(0.016)	0.021(0.020)	0.001(0.019)	0.001(0.024)	0.023(0.017)	0.031(0.022)
lnInnov	0.001**(0.000)	0.002***(0.001)						
lnGreeninnov			0.005***(0.001)	0.007***(0.002)				
lnFcapital					0.001***(0.000)	0.001***(0.000)		
Agg							0.004**(0.002)	0.006**(0.002)
N	4828	4828	4828	4828	4828	4828	4828	4828

Standard errors are in parentheses; *, **, *** represent 10%, 5%, and 1% significance levels, respectively.

Fig. 5 Energy-environmental spillover effects of national new-level zones.
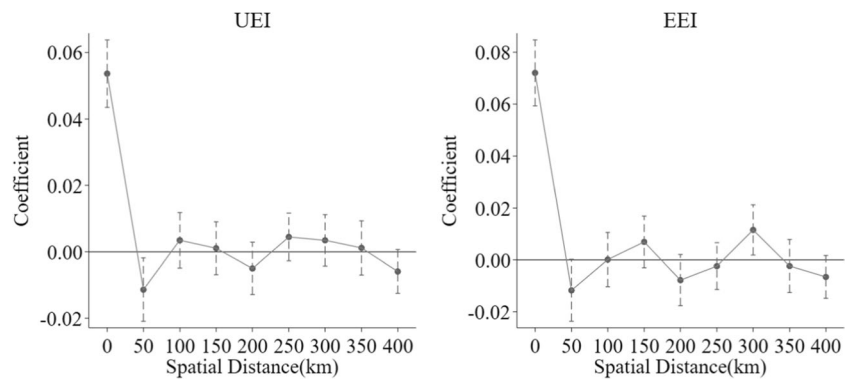
Further exploration

Spillover effects of national new zones

The impact of national new zones on cities' energy-environmental efficiency may vary with the increasing distance between cities and national new zones. Since the spatial spillover effect of agglomeration externality is limited by distance, a city where the national new zone is located has the most substantial agglomeration effect and the most substantial effect in terms of scale effect and technology enhancement. However, according to the theory of spatial economics, the central area will have a "siphonic effect" on the resources of the peripheral areas, which means the resources of the nearby cities will flow to the national new zone and the city where it is located, which will reduce the resources and agglomeration of the surrounding cities, i.e., forming a concentration shadow area around the central area (Cuberes et al. 2021), and the central area is the national new zone in this paper. This may lead to a negative impact of the national new zone on the energy-environmental efficiency of the city too close to it. Beyond a certain distance and free

from the agglomeration shadow area, the national new zone may have a positive spillover effect on the surrounding cities. As the distance increases, national new zones' contribution to energy-environmental efficiency may become smaller. Therefore, the following econometric model is set up to test the spatial spillover effect of national new zones' impacts:

$$Y_{it} = \beta_0 + \beta_1 did_{it} + \sum_{s=50}^{400} \delta_s N_{it}^s + \lambda Z_{it} + \nu_i + \mu_t + \varepsilon_{it} \quad (10)$$

where N_{it}^s indicates the city i in the year t of whether there are one or more national new zones within s km. When regressing, the value of s is 50, 100, ..., 400.

Figure 5 shows the value of β_1 and δ_s for different s, indicating that the establishment of national new zones has a negative spillover effect on the energy-environmental efficiency of cities at a distance of about 50 km, and there is no significant spillover effect for cities further away in terms of UEI; only in terms of EEI, there is a positive spillover effect on the energy-environmental efficiency of cities at a distance of about 300 km. This result is similar to the expectation of the agglomeration economy theory: when the national new zone is closer, it has a negative spillover effect on the

Table 7 Exclude cities adjacent to national new zones.

	UEI (1)	UEI (2)	UEI (3)	EEI (4)	EEI (5)	EEI (6)
	Full samples	Exclude 50km samples	Exclude 300km samples	Full samples	Exclude 50km samples	Exclude 300km samples
DID	0.053***(0.012)	0.052***(0.011)	0.045***(0.011)	0.072***(0.014)	0.071***(0.014)	0.061***(0.015)
_Cons	0.642***(0.037)	0.642***(0.038)	0.696***(0.047)	0.471***(0.047)	0.469***(0.047)	0.539***(0.060)
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
City FE	Yes	Yes	Yes	Yes	Yes	Yes
Control variables	Yes	Yes	Yes	Yes	Yes	Yes
N	4828	4663	3388	4828	4663	3388
R^2	0.175	0.183	0.242	0.140	0.147	0.194

Standard errors are in parentheses; *, **, *** represent 10%, 5%, and 1% significance levels, respectively; control variables are the same as the benchmark regression.

Table 8 Quantile regression: UEI.

	(1) 10%	(2) 25%	(3) 50%	(4) 75%	(5) 90%
DID	-0.000(0.026)	-0.001(0.004)	0.004(0.005)	0.126***(0.030)	0.193**(0.081)
Year FE	Yes	Yes	Yes	Yes	Yes
City FE	Yes	Yes	Yes	Yes	Yes
Control variables	Yes	Yes	Yes	Yes	Yes
N	4828	4828	4828	4828	4828

Standard errors are in parentheses; *, **, *** represent 10%, 5%, and 1% significance levels, respectively; control variables are the same as the benchmark regression.

energy-environmental efficiency of the surrounding cities due to the agglomeration shadow area of it; but beyond a certain distance to get rid of the agglomeration shadow zone, it generates some positive spillover effect, but the value is small compared with the effect on the city where the national new zone is located (only about 15% of the β_1 coefficient); if cities are further away from the national new zone (more than 300 km), there is no significant spillover effect. This result is inconsistent with Wang (2013) exploring the spillover effect of special zones established within cities on economic growth, where they find there is no significant negative effect for cities closer to such special zones, i.e., the agglomeration shadow zone hypothesis does not hold, but there is a positive spillover effect for cities at moderate distances. This suggests that the establishment of national new zones may lead to the migration of clean-technology enterprises from neighboring cities to the cities where the new zones are located due to special green policy (e.g., green tax credit), i.e., the spatial reallocation of stock resources leads to the energy-environmental efficiency agglomeration shadow area. However, the driving effect of the national new zone on the economic growth of the surrounding areas is a net growth effect rather than a spatial reallocation of existing resources.

Based on the above results, the impact of national new zones on energy-environmental efficiency is explored by reusing the benchmark regression Eq.(1) by excluding cities adjacent to national new zones. The regression results are reported in Table 7, showing the coefficients of DID both

decrease when the control group cities within 50 km and 300 km from the national new zone are excluded, respectively, which indicates that columns (1) and (4) of the benchmark regression results underestimate the energy-environmental efficiency of the control group cities after establishing national new zones due to the negative spillover effect on the neighboring cities. Thus, the impact of national new zones on the cities' energy-environmental efficiency is overestimated.

Quantile regression

Next, the heterogeneity of national new zones' effects on different levels of energy-environmental efficiency is further explored. In terms of the exploration method, on the one hand, due to the small sample size, if different regions are grouped and the multiple linear regression is performed separately, the results' credibility may reduce; on the other hand, based on the geographical distribution of China's energy-environmental efficiency in the descriptive analysis, it is difficult to obtain obvious patterns from the division of southern and northern regions or east, central and western regions, and the artificial grouping of samples based on energy-environmental efficiency is highly subjective. Therefore, we choose a method that can explore the influence of establishing national new zones on the entire conditional distribution of energy-environmental efficiency, i.e., quantile regression. Specifically, the impact of national new zones on energy-environmental efficiency at the 10%, 25%, 50%, 75%, and 90% quartiles is explored.

Table 9 Quantile regression: EEI.

|	(1) 10%	(2) 25%	(3) 50%	(4) 75%	(5) 90%
DID	0.016(0.044)	-0.005(0.006)	-0.004(0.007)	0.105***(0.039)	0.200***(0.051)
Year FE	Yes	Yes	Yes	Yes	Yes
City FE	Yes	Yes	Yes	Yes	Yes
Control variables	Yes	Yes	Yes	Yes	Yes
N	4828	4828	4828	4828	4828

Standard errors are in parentheses; *, **, *** represent 10%, 5%, and 1% significance levels, respectively; control variables are the same as the benchmark regression.

Table 10 Differences between one-city and two-city layouts.

	UEI	UEI	EEI	EEI
	(1)	(2)	(3)	(4)
	One-City Layout	Two-City Layout	One-City Layout	Two-City Layout
DID	0.085***(0.015)	0.003(0.018)	0.109***(0.018)	0.013(0.023)
_Cons	0.625***(0.038)	0.657***(0.038)	0.451***(0.048)	0.492***(0.048)
Year FE	Yes	Yes	Yes	Yes
City FE	Yes	Yes	Yes	Yes
Control variables	Yes	Yes	Yes	Yes
N	4692	4590	4692	4590
R^2	0.179	0.170	0.144	0.131

Standard errors are in parentheses; *, **, *** represent 10%, 5%, and 1% significance levels, respectively; control variables are the same as the benchmark regression.

Fig. 6 Common trend assumption test.
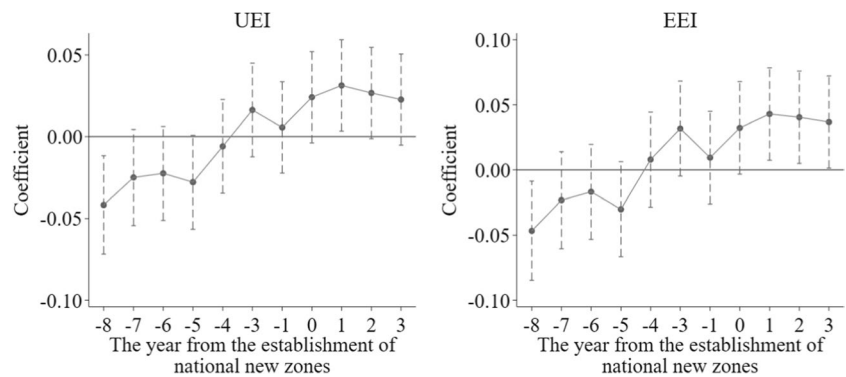
As shown in Table 8 and Table 9, the quantile regression coefficient of DID tends to increase with the increase of energy-environmental efficiency quantile, and it is significant only at the 75% and 90% quantile points both for UEI and EEI. Therefore, the impact of establishing national new zones on energy-environmental efficiency increases with the increase of the latter, indicating that national new zones don't promote the convergence of energy-environmental efficiency to a uniform level in all regions. Although there is a positive impact in benchmark regression, the promotion effect is stronger for high-efficiency regions.

Difference between one-city and two-city layout

4 of the 18 national new zones included in the sample of this paper have adopted the two-city layout mode (Fig. 2), i.e., the planning area of the national new zone covers two prefecture-level cities[3]. Next, the sample is divided into two sub-samples, one-city and two-city layout. Table 10 shows the regression results, and we can find that establishing national new zones

with the one-city layout has a significant effect on energy-environmental efficiency and is higher than the level of the benchmark regression, but the effect with the two-city layout is not significant. Zhuang and Ye (2018) argue that in the actual construction of national new zones with the two-city layout, the provincial government, as the higher government, takes the lead in coordination and promoting the synergistic development between the two cities in the areas of the industrial layout, factor allocation, urban planning and construction, and social management through the introduction of relevant policies. Thus, the two-city layout is more conducive to the economic growth rate (Zhuang and Ye 2018). However, as shown in Table 10, it is not conducive to improving the energy-environmental efficiency. This indicates that the resource allocation and industrial layout between the two cities may be more concerned with economic efficiency and lack of coordination in energy-environmental aspects.

Robustness tests

Common trend assumption test

The important premise of using a multi-period difference-in-difference model is cities with a national new zone

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[3] The original planning area of Tianfu New Zone covered Chengdu, Meishan and Ziyang City in Sichuan Province. In 2016, the new zone under the jurisdiction of Ziyang City was transferred to the jurisdiction of Chengdu City, changing the Tianfu New zone from the "three-city layout" to the "two-city layout".

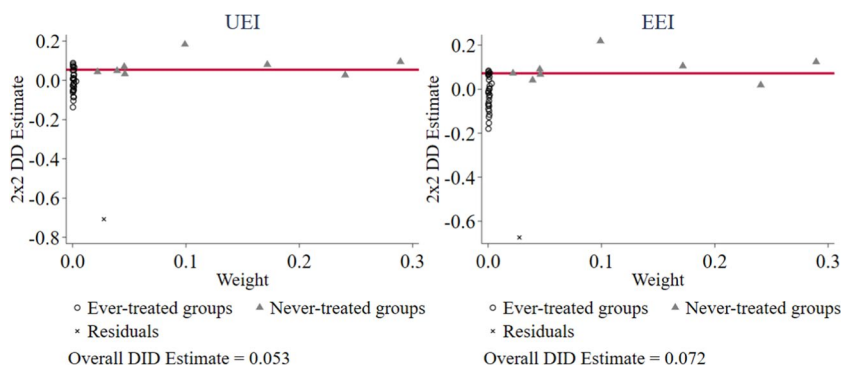**Fig. 7** Bacon decomposition of the benchmark regression.

Overall DID Estimate = 0.053   Overall DID Estimate = 0.072

Table 11 Regression results of the PSM-DID model.

	UEI	UEI	EEI	EEI
	(1)	(2)	(3)	(4)
DID	0.053***(0.016)	0.052***(0.016)	0.068***(0.020)	0.067***(0.019)
_Cons	0.437***(0.018)	0.556***(0.115)	0.319***(0.022)	0.336(0.140)
Year FE	Yes	Yes	Yes	Yes
City FE	Yes	Yes	Yes	Yes
Control variables	No	Yes	No	Yes
N	680	680	680	680
R^2	0.133	0.235	0.175	0.253

Standard errors are in parentheses; *, **, *** represent 10%, 5%, and 1% significance levels, respectively; control variables are the same as the benchmark regression.

(treatment group) and cities without one (control group) do not differ significantly or share a common trend in energy-environmental efficiency before policy implementation, and we use Eq.(11) to test the common trend assumption:

$$Y_{it} = \alpha_0 + \sum_{k=-8, k \neq -2}^{3} \alpha_k D_{it}^k + \lambda Z_{it} + \nu_i + \mu_t + \varepsilon_{it} \qquad (11)$$

where D_{it}^k are a set of dummy variables, indicating the city i in year t whether the year is the kth year of the approved national new zone (negative numbers indicate the year before approval). According to Fig. 6, we can find the variables before the establishment of national new zones($D_{it}^k, k < 0$) are not significant, which indicates there is no significant difference in the energy-environmental efficiency between the treatment group and the control group before the establishment of national new zones, which satisfies the common trend assumption.

Bacon decomposition

Goodman-Bacon (2021) proposes a method to decompose the two-way fixed effects estimates of the difference-in-difference model (TWFE-DID) into the weighted average of

all 2×2 DID coefficients[4], whose decomposition is shown in Fig. 7. It can be found that the estimated coefficients with larger weights are all coefficients from the never-treated group as the control group regressed with the treatment group for the DID model[5], which is related to the fact that the number of cities in the never-treated group (262) is much larger than the cities in the treatment group (22) in this paper. In addition, the sum of the coefficients' weights accounted for by the never-treated group is larger than 0.95, and the coefficients are all around the overall DID estimates.

On the other hand, Goodman-Bacon (2021) argues that if policy effects are likely to vary over time, the TWFE-DID model should not be used for the estimation of effects, and

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[4] All 2×2 DID models in this paper refer to (1) the untreated group as the control group with the treatment group for DID model regression ; (2) samples treated in year t before t as the control group with the treatment group treated in year [2003, t-1] for DID model regression; (3) samples treated in year t after year t as the control group with the treatment group treated in year [t+1, 2019] for DID model regression. The weighted mean refers to the weighted mean of the DID coefficients in category (1)(2)(3). In Fig. 6, the "ever-treated" group includes category (2) and (3), and the "never-treated" group includes case (1).

[5] Goodman-Bacon (2021) argues that most econometric textbooks and survey articles use this traditional DID structure.

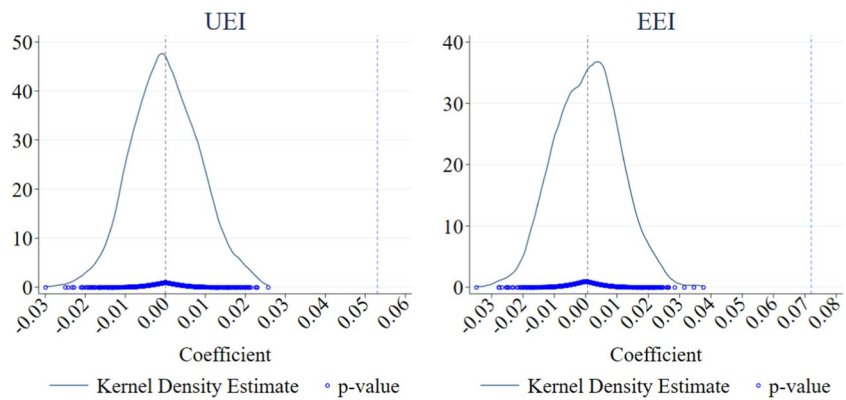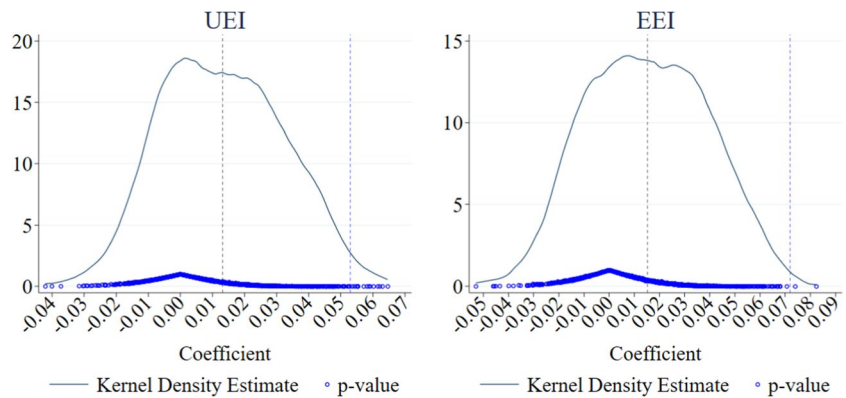**Fig. 8** Placebo test 1: randomly select the control group and the treatment group.

Fig. 9 Placebo test 2: randomly advance the year of the establishment of national new zones.

from Section 4.3.1, we can find the regression coefficients in the common trend assumption test change less over time after policy implementation, so this study is suitable for estimation using the TWFE-DID model and the obtained DID coefficients provide meaningful results for causal inference.

Using the PSM-DID model

Next, using the propensity score matching (PSM) model to reduce the sample's selective bias. Due to the multi-period establishment of national new zones, taking the 23 cities that established the national new zone during our sample period as the treatment group, we use the PSM model to combine the control group for each year after matching the treatment group year by year through the 1:1 nearest neighbor matching with the put-back sampling method. After matching, the p-values of the differences between the treatment and control group samples of the control variables and energy-environmental efficiency are not significant at the 10% level, so the treatment and control group samples are balanced. Table 11 shows the results of the DID model regression for the new samples after the PSM method matching, and it can be found that the coefficient of the variable DID is still significant at the 1% level.

Placebo test

The following two placebo tests are performed next.

First, randomly select the control group and the treatment group. One year is randomly selected in every sample city as the year of implementation of the policy (establishing national new zones), using the cities before the year as the control sample, and re-estimating the DID coefficient in the benchmark regression Eq. (1), which is one placebo test. We repeat 1000 times, and the estimated coefficients and p-value distributions of the 1000 DIDs obtained are shown in Fig. 8. The mean values of the simulated DID coefficients (black dashed line) are all close to 0, much smaller than the DID coefficients in the actual model (blue dashed line). There are no simulated estimates of the DID variables near the true value, indicating that the significant impact of the establishment of national new zones on the energy-environmental efficiency is robust.

Second, randomly advance the year of the establishment of national new zones. For every city i in the treatment group, if it established a national new zone in year t, then any one year from [2003,t-1] is randomly selected as the time when city i established a national new zone, and similarly re-estimate the DID coefficient in the benchmark

Table 12 Exclude the impact of other special zones.

	UEI (1)	UEI (2)	UEI (3)	EEI (4)	EEI (5)	EEI (6)
DID (National New Zone)	0.057***(0.012)	0.054***(0.012)	0.057***(0.012)	0.074***(0.015)	0.074***(0.014)	0.076***(0.015)
DIDc (CSRPZ)		-0.008(0.012)	-0.007(0.012)		-0.030**(0.015)	-0.029**(0.015)
DIDf (FTPZ)	-0.022*(0.012)		-0.022*(0.012)	-0.015(0.016)		-0.014(0.016)
_Cons	0.629***(0.038)	0.643***(0.033)	0.630***(0.038)	0.462***(0.048)	0.474***(0.047)	0.466***(0.048)
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
City FE	Yes	Yes	Yes	Yes	Yes	Yes
Control variables	Yes	Yes	Yes	Yes	Yes	Yes
N	4828	4828	4828	4828	4828	4828
R^2	0.177	0.176	0.177	0.141	0.142	0.142

Standard errors are in parentheses; *, **, *** represent 10%, 5%, and 1% significance levels, respectively; control variables are the same as the benchmark regression.

Table 13 Reset DID strictly according to the year of approval.

	UEI (1)	UEI (2)	EEI (3)	EEI (4)
New DID	0.072***(0.012)	0.052***(0.012)	0.090***(0.015)	0.070***(0.015)
_Cons	0.460***(0.006)	0.642***(0.037)	0.349***(0.008)	0.471***(0.047)
Year FE	Yes	Yes	Yes	Yes
City FE	Yes	Yes	Yes	Yes
Control variables	No	Yes	No	Yes
N	4828	4828	4828	4828
R^2	0.115	0.176	0.097	0.140

Standard errors are in parentheses; *, **, *** represent 10%, 5%, and 1% significance levels, respectively; control variables are the same as the benchmark regression.

regression Eq. (1), which is one placebo test. Similarly, we repeat 1000 times, and the estimated coefficients and p-values of the 1000 DIDs are distributed in Fig. 9. The mean values of the simulated DID coefficients are 0.015 (UEI) and 0.015 (EEI), lower than the DID coefficients in the actual model (0.053 and 0.072, respectively). Therefore, randomly advancing the year of establishing national new zones leads to a decrease in the impact on the energy-environmental efficiency, confirming from a counterfactual perspective that the establishment of national new zones does improve the energy-environmental efficiency.

Excluding the impact of other special zones

In this part, we exclude the impact of other special zones the central government has approved in some prefecture-level cities. During the sample time, in addition to the national new zones, the central government has also established other high-impact pilot zones[6], including "comprehensive supporting reform pilot zones"(CSRPZ) and "free trade pilot zones"(FTPZ). Regarding specific distinctions, national new zones are multifunctional zones that undertake major national development and reform and opening-up strategies, with the objectives of promoting regional transformation and upgrading, advancing ecological civilization construction, etc. CSRPZ is a pilot zone established to explore the construction of a harmonious society and innovative regional development model, with an administrative level lower than that of the national new zone. FTPZ mainly provides more foreign trade preferences. However, many cities where

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[6] Most of the prefecture-level cities have established high-tech zones (HIDZ) and the economic and technological development zone (ETDZ), and the establishment time is earlier than the sample time, which does not facilitate the setting of difference-in-difference models, and we only exclude the effect of other special zones here.

national new zones are located also have these two special zones. In the robustness test, to exclude their influence, corresponding DID variables are added in the regression model separately, as well as at the same time:

$$Y_{it} = \beta_0 + \beta_1 DID_{it} + \beta_2 DIDc_{it} + \lambda Z_{it} + v_i + \mu_t + \varepsilon_{it} \quad (12)$$

$$Y_{it} = \beta_0 + \beta_1 DID_{it} + \beta_3 DIDf_{it} + \lambda Z_{it} + v_i + \mu_t + \varepsilon_{it} \quad (13)$$

$$Y_{it} = \beta_0 + \beta_1 DID_{it} + \beta_2 DIDc_{it} + \beta_3 DIDf_{it} + \lambda Z_{it} + v_i + \mu_t + \varepsilon_{it} \quad (14)$$

where if CSRPZ exists in city i in year t, the variable $DIDc_{it}$ equals to 1, otherwise it equals to 0. Similarly, if FTPZ exists in city i in year t, the variable $DIDf_{it}$ equals to 1, otherwise it equals to 0. From the results (Table 12), the coefficients of DID_{it} are all significantly positive and have a small increase over the benchmark regression, indicating that the improvement of energy-environmental efficiency in the cities of the treatment group is indeed brought by national new zones. On the contrary, from UEI and EEI, respectively, show that the FTPZ and CSRPZ have the effect of suppressing the cities' energy-environmental efficiency, and the specific reasons remain to be further explored, but for another index the impact is not significant, may meaning an unstable effect.

Reset DID$_{it}$ strictly according to the year of approval

In the analysis of Section 4.1 and Section 4.2, when defining DID_{it}, we consider the impact of national new zones may be advanced in practice. Next, the new DID_{it} is defined strictly according to the year of approval by the central government (the approval both in the first half and the second half of the year is taken as in the current year), and re-estimating the DID coefficient in the benchmark regression Eq. (1). As shown in Table 13, the coefficients and significance of the new DID_{it} are generally consistent with the benchmark regression, indicating that the benchmark regression results are robust.

Conclusion and policy implications

We first measure the energy-environmental efficiency of 284 prefecture-level cities based on the non-radial directional distance function and data envelopment analysis method (NDDF-DEA). Overall, the level of energy-environmental efficiency in China is low and there is still much space for improvement. Secondly, based on the panel data of 284 prefecture-level cities in China from 2003 to 2019, the multi-period difference-in-difference model is used to estimate the impact of establishing national new zones on

energy-environmental efficiency. Three main conclusions are as follows: First, establishing national new zones significantly improves the energy-environmental efficiency of the cities in which they are located by 13% to 25%. The impact mechanisms include from the efficiency decomposition perspective, national new zones improve cities' technical efficiency and scale efficiency, and from the micro-foundation perspective, national new zones improve the innovation and green innovation level, the amount of foreign capital employed, and the degree of cities' economic agglomeration. Second, establishing a national new zone has both negative and positive spillover effects on the energy-environmental efficiency of its neighboring cities. Specifically, it has a negative effect on the energy-environmental efficiency of cities within 50 km of the city where the national new zone is located, while it has a positive effect on the energy-environmental efficiency of cities around 300 km. Third, in terms of heterogeneity, the impact of the establishment of national new zones on energy-environmental efficiency increases with larger quantile of the latter, which may indicate the national new zones do not promote the convergence of energy-environmental efficiency to a uniform level across regions; meanwhile, the impact of one-city layout national new zones on the energy-environmental efficiency is significant and higher than the average level, while the two-city layout one is not significant, which may indicate the green synergistic development effect between two cities is not significant.

Based on the above conclusions, the following policy recommendations are proposed: First, the central government needs to guide the national new zones to improve further the support measures for the energy and environment sector. Second, pay attention to the issue of resource allocation between the city where the national new zone is located, and neighboring cities when setting policies for national new zones. In particular, when improving scale efficiency, we need to reduce unnecessary redistribution of stock resources between cities. Third, for cities with high energy-environmental efficiency, they need to continue to improve the existing policies; for those with low energy-environmental efficiency, it's crucial to strengthen the central government's financial support in the field of energy and environment when constructing national new zones. In addition, strengthen the cooperation in energy and environment between the two cities involved in the national new zone with a two-city layout, and promote green synergistic development. Since urban agglomerations have become an important spatial form of urbanization in China, cities belonging to the same urban agglomeration should be more closely connected, but the national new zones with two-city layouts are more concerned with economic development, and the coordination and attention between the cities in energy and

environment are insufficient. Therefore, it is suggested to improve further the green synergistic development of two-city layout national new zones, and guide national new zones to use tax incentives and other autonomy to motivate enterprises to improve energy-environmental efficiency through green innovation, use of foreign investment, and agglomeration development.

In this paper, the impact of national new zones on the energy-environmental efficiency of the cities in which they are located and the surrounding cities is explored from a relatively macro perspective using city-level samples, while more detailed mechanisms and welfare effects of this impact can be analyzed in depth using firm-level data in future studies. On the other hand, the impact of national new zones on green innovation, energy consumption, and environmental protection may be further quantitatively assessed through textual quantitative analysis of relevant policy documents of national new zones.

Data availability Data and code will be made available on reasonable request.

Declarations

Ethical Approval Not applicable.

Consent to Participate Not applicable.

Consent to Publish Not applicable.

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