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Unpacking multidimensional effects of economic restructuring and technological progress on carbon emission performance: the moderating role of environmental regulation

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The growth in carbon emissions poses a severe challenge to global sustainable development, making it imperative to explore the impacts of economic restructuring and technological progress on Carbon Emission Performance (CEP). However, existing studies often lack an integrated analysis of economic restructuring and technological progress, while giving limited attention to the indirect role of Environmental Regulation (ER). This study constructs a multidimensional theoretical framework, breaking down economic restructuring into four dimensions—industrial structure, factor input, ownership, and new-type urbanization (NTU), and refining technological progress into technological innovation and energy efficiency. It uncovers the complex interplay among CEP, economic restructuring, technological progress, and ER. The findings reveal critical insights: (1) industrial structure suppresses CEP, whereas adjustments in factor input and ownership structure significantly enhance it; (2) the relationship between NTU and CEP exhibits a non-linear pattern; (3) compared to the technological innovation, energy efficiency provide a more substantial boost to CEP; and (4) ER positively moderates the impacts of factor input, ownership structure, and NTU. Finally, the study proposes recommendations for holistic economic restructuring and diversified ERs.

Keywords Carbon emission performance, Economic restructuring, Technological progress, Environmental regulation, Moderating effects

Carbon emissions present a universal challenge for the sustainable economic growth of nations worldwide. The 2023 Emissions Gap Report by the United Nations Environment Programme (UNEP) highlighted a critical alert, stating that temperatures hit new highs, yet the global failure to reduce emissions persists. This document accentuates the critical need for a worldwide shift towards a low-carbon economy, advocating for a 28% reduction in greenhouse gas emissions by 2030 to align with the Paris Agreement's 2015 warming thresholds[1].

China was the main emitter of carbon globally in 2021, according to the latest report, with its per capita emissions being the third highest after the United States and Russia[2]. This positions China under immense pressure to curb its carbon output. In response, China has shown a firm dedication to fostering a low-carbon economic framework, setting targets in September 2020 to reach a carbon emissions peak by 2030 and to attain carbon neutrality by 2060, now essential pillars of its national economic strategy[3].

Initially, investigations concentrated on diverse methodologies for measuring carbon emissions. Yet, the escalating industrial economy's energy demand necessitates a focus on maximizing resource utilization and economic output without increasing carbon emissions. Thus, in recent years, a comprehensive approach to assessing carbon emissions has surpassed single metrics like per capita emissions, offering better insights into the nexus between economic gains and environmental strains. This is because performance reflects various factors

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from the input–output perspective, rooted in neoclassical economic principles[4]. Therefore, Carbon emission performance (CEP) serves as an effective instrument to evaluate the balance between economic productivity growth and environmental impacts by treating carbon emissions as undesirable outputs in production processes[5]. Existing literature provides abundant discussions on CEP[6,7], with similar concepts termed as total factor productivity (TFP) of carbon, green TFP, and eco-efficiency[8,9]. Variations in findings mainly stem from diverse input–output indicators. Some studies consider CO_2 as an input indicator, whereas others view it as an undesired byproduct[10]. DEA is a widely recognized method for evaluating performance, valued for its scientific approach in assessing DMUs with multiple inputs and outputs, devoid of subjective bias[11]. This research classifies carbon emissions as an undesirable output, better reflecting actual production scenarios[12].

Another vital research focus investigates the determinants of carbon emissions reduction. Economic restructuring is crucial for reducing carbon emissions[13]. Initial inquiries into restructuring focus on the transition from secondary to tertiary sectors[14], this shift is typically reflected the proportion of industrial sectors, while overlooking the importance of maintaining a balanced industrial structure. Therefore, the rationalization of industrial structure applied in this research becomes increasingly important, as it reflects the balanced allocation of resources among different industrial sectors and avoids biases that overly emphasize the proportion of the tertiary sector.

The influence of urbanization on emission reduction has garnered extensive attention[15]. Previous research emphasized demographic urbanization, indicated by the ratio of urban population to total population. However, this type of urbanization, which solely reflects population growth, is no longer suitable in the face of social and environmental challenges[16]. In 2012, China introduced the concept of "new-type urbanization" (NTU), which emphasizes sustainable development and improved quality of urbanization[17]. Yet, studies on its effects on emission reduction are insufficient.We find that current literature often focuses on a single aspect of structural adjustment, lacking a holistic understanding. It is worth noting that economic restructuring is a multifaceted strategic effort involving various economic activities, such as ownership patterns, factor input structures, and urbanization. Therefore, this study conducts an integrated analysis of these major adjustments, which is essential for a multidimensional understanding of economic restructuring.

Technological progress, a well-acknowledged driver of economic growth[18,19], plays a critical role in enhancing productivity. However, its effect on emission reduction is debated[20,21], with the dual nature of technology's impact being a focus of discussion. On one hand, technological advancements drive economic expansion and help lower emissions[22]. On the other, the path dependence on technological evolution[23] introduces uncertainty in its environmental outcomes. Moreover, we found that previous studies overlooked an issue: not all technological advancements are beneficial for energy conservation and carbon reduction, as their impact depends on the emphasis placed on eco-friendly innovations.

Environmental regulation (ER), a governmental mechanism to guide economic activities towards environmental improvement, predominantly adopt mandatory type in China, exemplified by the 2015 Environmental Protection Law[24]. While incentive type and voluntary type ER are emerging, such as the Interim Rules For Carbon Emissions Trading Management[25] and the Environmental Information Legal Disclosure System Reform Plan[26]. Though grounded in Porter's hypothesis[27], empirical findings on ER's influence on innovation or competitiveness present a mixed picture[28,29]. We found that while the role of ER has been a topic of ongoing debate[30], its potential indirect effects on carbon emissions through other variables have received little attention.

Addressing these research gaps, our study poses the following research questions:

First, could economic restructuring and technological progress bolster CEP?

Secondly, could ER impact these interactions indirectly?

This study makes three contributions: Firstly, it integrates multiple dimensions of economic restructuring, incorporating industrial structure, factor input structure, ownership structure, and urban–rural structure into a unified framework, offering a comprehensive perspective beyond single-dimensional analyses. Secondly, it quantifies the multi-level effects of technological progress by combining innovation and energy efficiency, addressing the limitation of existing studies that over-rely on patent indicators while neglecting energy efficiency's direct impact on carbon reduction. Thirdly, it examines the moderating role of ER, revealing its indirect influence on the effects of economic restructuring and technological progress on CEP, providing valuable insights into regulatory impacts.

Theoretical mechanisms

Economic restructuring promotes CEP

The impact of industrial structure on CEP

The industrial structure is a critical component of economic optimization. Reducing the share of high-carbon-emission industries while expanding the scale of low-carbon-emission industries is often considered a key pathway to reducing emissions. Therefore, the tertiary industry is often given greater emphasis, as it is more likely to have lower energy consumption and carbon emissions compared to the secondary industry. However, focusing exclusively on industrial structure changes may overlook the emission reduction opportunities available in the secondary sector through technological advancements.

The impact of factor input on CEP

A higher capital-labor input ratio typically indicates a shift from labor-intensive industries to capital-intensive industries. Comparatively speaking, capital-intensive industries leverage automated production, which not only reduces resource waste caused by human error but also significantly enhances resource utilization efficiency. Moreover, these industries provide strong capital support for technological upgrades, enabling the advanced technologies to further lower carbon emissions, thereby positively contributing to CEP.

The impact of ownership structure on CEP
Ownership structure serves as an essential aspect of economic restructuring, particularly due to the differences in emission reduction responsibilities between state-owned enterprises (SOEs) and non-state-owned enterprises (non-SOEs), which significantly impact CEP. SOEs, being subject to stricter policy regulations, typically place greater emphasis on social responsibility and demonstrate more proactive efforts in energy conservation and emission reduction. In contrast, non-SOEs prioritize cost–benefit considerations and are more inclined to balance economic interests with environmental goals. Therefore, changes in ownership structure provide diverse impacts for enhancing CEP.

The impact of NTU on CEP
Traditional urbanization mode, characterized by excessive resource consumption and environmental pollution, can no longer meet the demands of sustainable development. NTU, by promoting environmentally friendly urban infrastructure, can significantly improve urban energy efficiency. This new mode offers innovative solutions for achieving coordination between economic growth and carbon emission reduction.

Technological progress promotes CEP
The impact of technological innovation on CEP
Technological innovation is regarded as a pivotal driver for enhancing productivity. Through the R&D of green technologies, it can significantly reduce energy consumption and carbon emissions, providing critical support for the green transformation of the economy. Additionally, the spillover effects of technological innovation enable green technologies to spread rapidly across regions and industries, further amplifying emission reduction outcomes. However, the actual impact of technological innovation on emission reduction depends on whether its focus is directed toward clean energy and environmental technologies.

The impact of energy efficiency improvements on CEP
Improving energy efficiency is a vital manifestation of technological progress and can effectively lower energy consumption per unit of output by optimizing energy utilization methods. However, the positive effects of energy efficiency may be constrained by the rebound effect, where the expansion of the production scale offsets part of the emission reduction benefits. Therefore, energy efficiency affects CEP through multiple channels, with the key point being whether it can genuinely translate into substantial improvements in CEP.

Based on the above analysis, the study introduces its first hypothesis:

Hypothesis 1: Economic restructuring and technological progress can enhance CEP.

The moderating role of ER
According to the Porter Hypothesis (Porter, 1991), a well-designed ER can boost corporate innovation and competitiveness. While ER might increase environmental costs, potentially deterring innovation investment, innovation could offset these costs[31]. For example, Palmer and Jaffe[32] observed a positive link between ER and innovation spending. Moreover, stronger environmental policies have been correlated with an uptick in patent filings[33]. The applicability of the Porter Hypothesis in China is debated. Some studies highlight the predominant "cost effect" of ER on industrial productivity over the "innovation compensation effect"[34], suggesting a downturn in productive performance. Others, like Wang and Shen[35] observe that the positive impacts of ER on productivity may not be immediate, suggesting a lag that could impede short-term productivity enhancements. Conversely, some research supports the Porter Hypothesis, finding that ER fosters innovation or TFP[36]. Given the mixed evidence, the validity of the Porter Hypothesis in China remains open for discussion.

Adopting effective environmental policies significantly influences the synergy between economic restructuring, technological progress, and enhanced CEP.

First, ER accelerates the flow of resources from high-pollution industries to cleaner industries through mandatory standards, reducing market inertia in industrial structure and making the green transition more efficient. Second, ER increases the environmental costs of traditional labor-intensive production, encouraging enterprises to adopt more capital-intensive production methods. This enables the allocation of capital and labor factors to better align with the demands of a low-carbon economy. Regarding ownership structure, ER imposes stricter constraints on state-owned enterprises through rigorous green assessment mechanisms, ensuring their exemplary role in energy conservation and emission reduction. In the context of NTU, ER promotes the adoption of green building and low-carbon transportation standards by local governments, thereby aligning urbanization more closely with environmental goals. Furthermore, in technological innovation, ER facilitates the industrial application of green technologies through tax incentives and dedicated funding, enhancing the contribution of technological innovation to CEP. Finally, ER promotes the adoption of energy-efficient equipment through mandatory efficiency standards and subsidy mechanisms, reducing energy waste and further amplifying the positive impact of energy efficiency on CEP.

From the foregoing analysis, this study examines ER's role in the CEP framework and formulates our second research hypothesis:

Hypothesis 2: ER positively influences the impacts of economic restructuring and technological progress in promoting CEP.

The following Fig. 1 shows the theoretical framework and research hypotheses of this study.

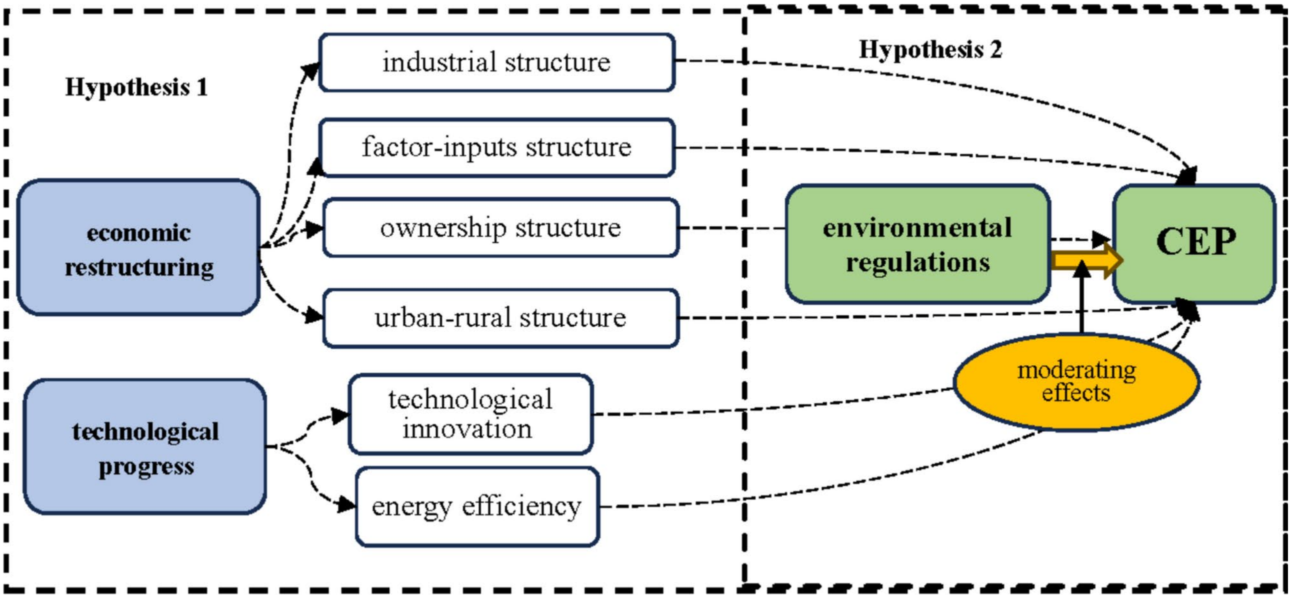

Fig. 1. Theoretical framework.

Methodology

CEP evaluation by DEA with undesirable output

The primary aim of this study is to quantify CEP using the SBM-DEA model with undesirable output, as presented in Eq. (1)

$$\begin{aligned} &\text{Minimize:} \quad \rho = \frac{1-\frac{1}{m}\sum_{i=1}^{m} s_i^-/x_{io}}{1+\frac{1}{s+b}\left(\sum_{r=1}^{s} s_r^+/y_{ro}+\sum_{u=1}^{b} s_u^b/b_{uo}\right)} \\ &\text{Subject to:} \quad x_{io} = \sum_{j=1}^{n} \lambda_j x_{ij} + s_i^-, i = 1,2,\ldots,m \\ &y_{ro} = \sum_{j=1}^{n} \lambda_j y_{rj} - s_r^+, r = 1,2,\ldots,s \\ &b_{uo} = \sum_{j=1}^{n} \lambda_j b_{uj} + s_u^b, u = 1,2,\ldots,b \\ &\sum_{j=1}^{n} \lambda_j = 1 \\ &\lambda_j \geq 0, j = 1,2,\ldots,n \\ &s_i^- \geq 0, i = 1,2,\ldots,m \\ &s_r^+ \geq 0, r = 1,2,\ldots,s \\ &s_u^b \geq 0, u = 1,2,\ldots,b \end{aligned} \tag{1}$$

$\rho\,(cep)$: efficiency score; x_{io}: i_{th} input variable; y_{ro}: r_{th} desirable output variable; b_{uo}: u_{th} undesirable output variable; s_i^-: input slack variable; s_r^+: desirable output slack variable; s_u^b: undesirable output slack variable; λ_j: weight of the j_{th} DMU; m: number of input variables; s: number of desirable output variables; b: number of undesirable output variables; n: number of DMUs.

Interpretations of measurements are delineated as follows. The input indicators encompass labor, quantified by the number of employees; energy input, defined by overall energy consumption; and the undesired output gauged by Carbon Dioxide (CO_2) emissions. Following the method advocated by the Intergovernmental Panel on Climate Change (IPCC), this study utilizes carbon emissions data provided by China Emission Accounts and Datasets (CEADs)[37,38]. The rationale behind this choice lies in the research team's recalculation of carbon emissions factors, aligning with China's actual circumstances and the scientific accuracy of the method proposed by the IPCC. The evaluation results have gained wide recognition in the academic community and have been published in key studies on carbon emissions[39,40]. The specifics of how input and output indicators are set in the DEA model are illustrated in Table 1.

Empirical model designation

To check the effects of economic restructuring and technical progress on CEP, the regression model is constructed as Eq. (2):

$$cep_{it} = \beta_1 instr_{it} + \beta_2 klstr_{it} + \beta_3 owner_{it} + \beta_4 ntu_{it} + \beta_4 ntu2_{it} + \beta_5 paten_{it} + \beta_6 eneff_{it} + Z_{it} + \varepsilon_{it} \tag{2}$$

Indicators	Name	Description	Data source	Unit
Economic input	Capital	The capital stock	China Statistical Yearbook	100 million CNY
	Labor	The employment at the end of the year	China Population & Employment Statistics Yearbook	10 thousand people
	Energy	total energy consumption	China Energy Statistical Yearbook	10,000 tons of standard coal equivalent
Output	Desired output	GDP	China Statistical Yearbook	100 million CNY
	Undesired output	CO_2 emission	China Emission Accounts and Datasets (CEADs)	mt

Table 1. The description of input and output indicators in the DEA model.

cep refers to carbon emission performance. instr refers to industrial structure, klstr refers to the structure of capital and labor inputs, owner refers to the ownership structure, ntu refers to new-type urbanization, paten refers to technical innovation, eneff refers to energy efficiency, Z_{it} refers to the control variable dataset, ε_{it} refers to the error term.

Variables explanation

The variables of the empirical model are illustrated as follows:

Explanatory variable: CEP (cep), which is calculated by the DEA with undesired output.

Core explanatory variable

The first core explanatory variable is economic restructuring, which is elaborated by the following four aspects in this study.

Industrial structure (instr), as mentioned earlier, this study uses the rationalization of industries to describe industrial restructuring, it is represented by the reciprocal of the Theil Index.

In several studies, the rationalization of industrial structure is gauged by the Theil index, with a smaller index indicating a more rational industrial structure[41]. In this study, the reciprocal of the Thiel index is employed to depict the rationalization of industrial structure, following the approach proposed by Sun et al.[42]. A higher value in this context corresponds to improved industrial structure rationalization, which facilitates a better understanding from an economic perspective. The positive impact of a rational industrial structure on energy management and emission reduction, thereby enhancing CEP, aligns with theoretical expectations.

The calculation method is outlined as Eq. (3):

$$instr = \frac{1}{\text{Theil Index}} = \frac{1}{\sum_{i=1}^{N} \left(\frac{V_i}{V}\right) * \ln\left(\frac{V_i}{L_i} / \frac{V}{L}\right)} \tag{3}$$

where V represents the added value of the industry, L represents industrial employment, n represents the industrial types, which are divided into primary, secondary, and tertiary industries in this study.

The factor structure (klstr), is defined by the ratio of capital stock to employment[43]. A higher capital-to-labor ratio reflects the transition of industries from labor-intensive to capital-intensive, where capital investment can drive industrial upgrading, potentially improving CEP. Therefore, the expected sign is positive.

Ownership structure (owner), is expressed as the ratio of state-owned fixed investment to total fixed asset investment[44]. It is widely assumed that state-owned enterprises are more proactive in energy conservation and emission reduction since they are more likely to receive government policy support. Therefore, the expected signs are positive.

The urban and rural structure is explained by NTU (ntu). It can be observed that the framework for NTU put forth by the Chinese government encompasses various components, this study accesses the NTU by the entropy method and sets comprehensive evaluation indicators from five aspects, namely population, economic efficiency, urban function, urban–rural coordination, and environmental friendliness[45,46], Table 2 provides the evaluation indexes and weights.

A high degree of NTU implies the accrual of resources and advanced infrastructure, fostering economies of scale and elevated economic productivity. Nevertheless, the swift expansion of urban areas may result in a notable upsurge in energy consumption and carbon emissions. Following this train of thought, the correlation between urbanization and carbon emissions or productivity may exhibit nonlinearity. Hence, the model incorporates quadratic terms of NTU.

Unlike previous studies, this study uses two variables to describe technological progress. On one hand, the number of patents (paten) represents a region's technological innovation capability[47], on the other hand, energy efficiency (eneff) is closely related to the CEP, which is explained by the ratio of GDP to energy consumption[48]. With the same energy consumption, the higher GDP output means higher energy utilization efficiency, which helps reduce carbon emissions. Therefore, the expected sign is positive.

General layer	Objective layer	Indicator layer	Unit	Indicator type	Weights
New-type urbanization (NTU)	Population development	Urban population ratio	%	+	0.0420
		Urban population density	persons/km^2	+	0.0410
		Urban population quality	persons	+	0.0413
		Natural population growth rate	%	+	0.0423
	Economic efficiency	GDP per capita	yuan/person	+	0.0395
		Tertiary industry value added per capita	yuan/person	+	0.0387
		Local financial income per capita	yuan/person	+	0.0366
		Total retail sales of consumer goods per capita	yuan/person	+	0.0390
	Urban function	Urban road area per capita	m^2/person	+	0.0414
		Public vehicles per 10,000 people	pcs/10,000 persons	+	0.0416
		Health technicians per 10,000 people	persons	+	0.0411
		Urban gas penetration rate	%	+	0.0426
		Urban water penetration rate	%	+	0.0430
	Urban–rural coordination	The ratio of disposable income per capita of urban and rural residents	%	–	0.0427
		The ratio of consumption expenditure per capita of urban and rural residents	%	–	0.0427
		Urban–rural income gap	yuan	–	0.0431
	Environmental friendliness	The green coverage rate of areas	%	+	0.0425
		Green space per capita	m^2/person	+	0.0422
		Harmless treatment rate of domestic garbage	%	+	0.0421
		Carbon dioxide emissions per capita	tons/person	–	0.0431
		Sulfur dioxide emissions per capita	tons/person	–	0.0428
		Domestic garbage removal per capita	tons/person	–	0.0429
		Electricity consumption per unit of the GDP	kwh/person	–	0.0430
		Water consumption per unit of GDP	m^3/yuan	–	0.0432

Table 2. Comprehensive evaluation indicators and weights of NTU.

Moderating variable
This study aims to further examine how the ER (lnregul) affects improving CEP through economic restructuring and technical progress, which is expressed as the proportion of industrial pollution control investment to GDP, in the form of the logarithm[49].

Control variables are illustrated as follows:

Government intervention (gover) is measured by the proportion of fiscal expenditure to regional GDP[50]. Fiscal expenditure can reflect the government's intervention in the economy and its ability to provide public services. High fiscal expenditure indicates that the local government is more able to support energy saving and emission abatement, so the expected sign is positive. Economic development (pgdp). It is explained by the ratio of the per capita GDP of a region to its maximum value based on the year 2000[51]. Economically developed regions have more investment in environmental protection, so the expected sign is positive. FDI (fdi), is measured by the proportion of total imports and exports to regional GDP[52].

The description of variables is displayed in Table 3.

Data processing and data source
The data set is panel data from 30 provinces in China from 2007 to 2019. Due to a lack of data, Tibet, Hong Kong, Macao, and Taiwan are not included in this study. Data sources are the national Statistical Yearbook, Environmental Statistical Yearbook, Industrial Statistical Yearbook, Science and Technology Statistical Yearbook in China, the provincial Statistical Yearbook, the EPS database, CEADs, and other official databases. GDP value is deflated taking the 2000 as the base period to reduce the influence of inflation on variables. Several incomplete data were supplemented by linear interpolation.

Descriptive statistics
The descriptive statistics provided in Table 4 indicate the dataset's relative stability without the presence of outliers. As depicted in Table 5, the majority of the variables have successfully passed the correlation test at a 1% confidence level, affirming the rationality of the chosen explanatory variables. The Variance Inflation Factor (VIF) indices for all variables remain below 10, signifying the absence of noticeable multicollinearity among the variables.

Empirical results
The spatial and temporal variation of CEP
As described in the methodology, this investigation applies the DEA model with undesirable outputs to assess the CEP at the provincial level in China. Table 6 displays the average CEP for 30 provinces. From the evaluation, it's observed that Shanghai, Beijing, and Guangdong, situated along China's eastern coast, top the CEP rankings

Types	Variable	Description	Unit	Symbol	Expected sign
Explained variable	Carbon emission efficiency (CEP)	Calculated by undesirable output dea	/	cep	/
Core explanatory variable (economic restructuring)	Industrial structure	The reciprocal of the Theil Index	/	instr	+
	Structure of capital and labor factors	The ratio of the capital stock to the employment	/	lnklstr	+
	Ownership structure	The ratio of state fixed investment to total fixed asset investment	/	owner	+
	New-type urbanization (NTU)	it is measured by comprehensive indicators calculated using the entropy method	/	ntu	nonlinear
Core explanatory variable (technological progress)	Technological innovation	patents per 10,000 people	pcs	paten	+
	Energy efficiency	The ratio of GDP to energy consumption	10,000 CNY/ton standard coal	eneff	+
Moderating variable	Environmental regulation (ER)	The proportion of industrial pollution control investment to GDP	/	lnregul	+
Control variables	Government intervention	The proportion of fiscal expenditure to regional GDP	/	gover	+
	Economic development	The ratio of per capita GDP to its maximum value	/	pgdp	+
	FDI	The proportion of total imports and exports to regional GDP	USD/CNY	fdi	+

Table 3. Variable description.

Variable	Obs	Mean	Std. Dev.	Min	Max
cep	390	0.656	0.194	0.314	1.000
instr	390	1.841	0.790	0.223	4.056
lnklstr	390	4.179	0.469	3.039	5.327
owner	390	0.283	0.106	0.101	0.560
ntu	390	0.586	0.068	0.399	0.726
paten	390	8.134	10.517	0.350	60.144
eneff	390	0.950	0.483	0.200	2.502
gover	390	0.373	0.190	0.110	1.155
pgdp	390	0.694	0.206	0.286	1.000
fdi	390	0.479	0.521	0.006	2.300

Table 4. Descriptive statistics.

Variables	VIF	(cep)	(instr)	(lnklstr)	(owner)	(ntu)	(paten)	(eneff)	(gover)	(pgdp)	(fdi)
cep	/	1.000									
instr	4.830	0.641***	1.000								
lnklstr	3.710	− 0.029	0.165***	1.000							
owner	2.130	− 0.438***	− 0.506***	− 0.246***	1.000						
ntu	6.190	0.632***	0.723***	0.438***	− 0.592***	1.000					
paten	3.260	0.603***	0.758***	0.136***	− 0.391***	0.693***	1.000				
eneff	4.180	0.825***	0.698***	0.052	− 0.514***	0.769***	0.740***	1.000			
gover	2.590	− 0.601***	− 0.301***	0.360***	0.492***	− 0.271***	− 0.248***	− 0.443***	1.000		
pgdp	5.950	0.172***	0.343***	0.788***	− 0.295***	0.669***	0.423***	0.381***	0.287***	1.000	
fdi	2.470	0.526***	0.698***	− 0.132***	− 0.247***	0.329***	0.531***	0.458***	− 0.273***	− 0.036	1.000

Table 5. Pairwise correlations. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$

with Shanghai leading at 0.990. Conversely, Shanxi, Qinghai, and Ningxia, located in China's western territories, show the lowest CEP values, with Ningxia at 0.323, highlighting substantial regional CEP disparities within the nation.

Figure 2 delineates the average CEP's temporal variation from 2007 to 2019, showing a steady increase from 2007 to 2012. During this period, China's government launched energy efficiency and pollutant reduction strategies as part of the 11th Five-Year Plan (During China's 11th five-year plan, which covered 2006 to 2010, the Chinese government developed an extensive plan for national economic and societal progress. Launched in 2005, this strategy targeted a 20% decrease in energy intensity per GDP unit relative to the previous tenth five-year plan. To achieve this goal, the plan detailed a range of measures focused on enhancing energy efficiency and reducing emissions. These measures included industrial restructuring, transforming the economic growth model, and creating a society that emphasizes efficient use of resources and environmental sustainability. Hence,

Ranking	Province	Mean cep	Ranking	Province	Mean cep
1	Shanghai	0.990	16	Liaoning	0.643
2	Beijing	0.980	17	Henan	0.614
3	Guangdong	0.972	18	Tianjin	0.609
4	Jiangsu	0.947	19	Heilongjiang	0.605
5	Zhejiang	0.837	20	Guangxi	0.549
6	Fujian	0.829	21	Yunnan	0.546
7	Anhui	0.803	22	Hebei	0.534
8	Inner Mongolia	0.781	23	Gansu	0.530
9	Hunan	0.768	24	Shaanxi	0.517
10	Chongqing	0.754	25	Jilin	0.450
11	Jiangxi	0.725	26	Guizhou	0.443
12	Sichuan	0.696	27	Xinjiang	0.428
13	Hainan	0.690	28	Shanxi	0.391
14	Hubei	0.672	29	Qinghai	0.371
15	Shandong	0.670	30	Ningxia	0.323

Table 6. The mean CEP in 30 provinces.

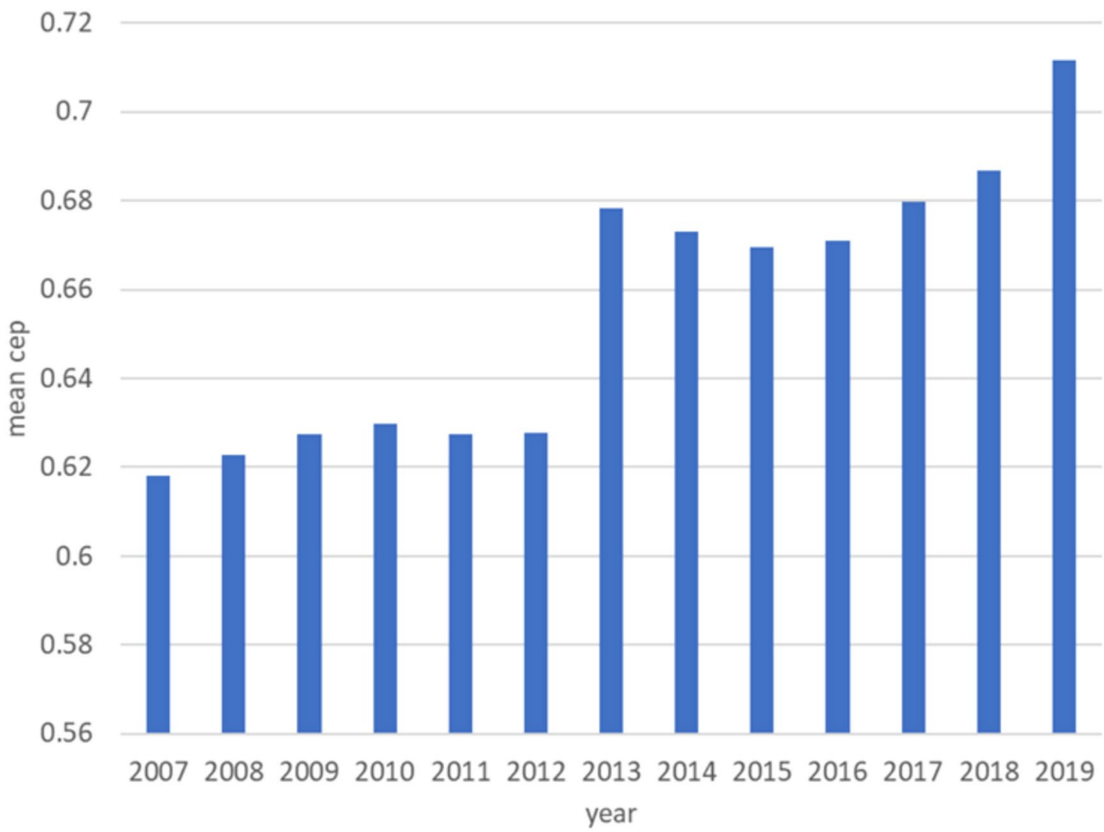

Fig. 2. Reginal average CEP from 2007 to 2019.

the 11th five-year plan marked a significant step towards promoting an energy-conserving and environmentally friendly economic framework in China.), aiming to decrease per GDP unit energy consumption by 20% and reduce key pollutants' total emissions by 10% within five years. A noticeable rise in CEP since 2013 aligns with the 12th Five-Year Plan's more rigorous energy and emission reduction standards, introducing policies such as fiscal incentives for energy-efficient products and market-based pricing for resources. These results validate the Chinese government's initiatives in energy conservation and carbon mitigation, though further enhancements are possible.

Yet, focusing solely on CEP's temporal changes doesn't fully capture the scenario, considering the tight spatial linkage of carbon emissions. Hence, it's crucial to also consider CEP's spatial connections. Figure 3 presents the

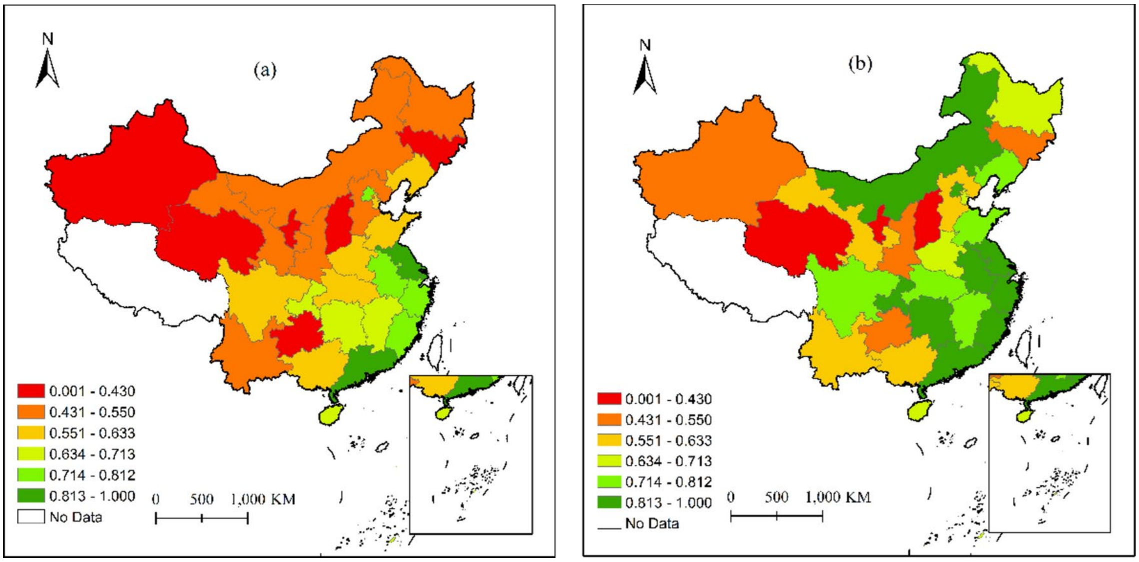

Fig. 3. Spatial distribution of CEP in 2007 and 2019. Created using ArcGIS Desktop (Version 10.7.0.10450), developed by Esri. For details, see: https://desktop.arcgis.com/en/arcmap/latest/map/main/what-is-arcmap-.htm.

provincial CEP distribution in 2007 and 2019, while Fig. 4 categorizes China into four economic zones as per the National Statistics Bureau. Areas greener in color indicate higher CEP and redder tones suggest lower CEP. The 2019 data shows a general CEP improvement across most provinces since 2007, indicating regional growth potential.

Spatial analysis reveals pronounced CEP disparities at the provincial level. High CEP regions mainly cluster in the eastern coastal provinces, correlating with the most developed economic zones. Except for Sichuan and Chongqing in the west, with relatively high CEPs, other provinces face lower CEPs due to factors like sparse population and limited resources. The central region, though lagging behind the east, shows a positive CEP trajectory, especially notable in Hunan. Given the central region's later industrial start and smaller scale compared to the east, it might be more suited for industrial green transitions and phasing out obsolete capacities.

Empirical results discussion

Given that the CEP's dependent variable ranges between 0 and 1, this analysis adopts the panel TOBIT model for regression to address the potential truncation in data[53]. Table 7 summarizes the regression results, with columns (1)–(4) outlining four dimensions of economic restructuring: industrial structure, factor input, ownership, and NTU. Column (5) offers an in-depth evaluation of how economic restructuring and technological progress influence CEP enhancement, establishing the groundwork for this research's economic examination.

This study now analyzes the results of the four dimensions of economic restructuring on CEP. The industrial structure's coefficient (instr) is negatively correlated and significant at a 1% level, suggesting that industrial structure refinement does not necessarily boost CEP, diverging from anticipated outcomes.

This result is consistent with the findings of Huang and Wang[54], indicating that structural imbalances in China's economic development may lead to stagnation. Similarly, Chen et al.[55] pointed out that industrial structure optimization and economic growth might lack synergy. A possible explanation is that while resource balance among industries has improved, energy-intensive sectors within the secondary industry still occupy a significant share. Moreover, although the tertiary industry is generally considered low-carbon, some economically underdeveloped regions remain heavily reliant on low-value-added traditional services rather than high-tech service industries. This study further suggests that policymakers should focus on enhancing inter-industry coordination, particularly in optimizing resource allocation among industries, to achieve comprehensive improvements in CEP.

The factor input structure's coefficient (lnklstr) shows a positive and significant effect at a 1% level, indicating its promotive effect on CEP. This study interprets factor structure as the ratio of capital to labor intensity, with its beneficial impact on CEP contingent on the green direction of capital investments. This finding supports the conclusions of Shao et al.[56], while this study highlights that the reorganization of factor input structures, driven by the combined effects of capital and labor transformation, will have a broader impact on the regional CEP.

The ownership structure's coefficient (owner) is positively significant at a 1% level, signifying its contribution to CEP enhancement. This finding aligns with those of Dong et al.[57], indicating that state-owned enterprises (SOEs) are more willing to engage in corporate environmental responsibility activities. Furthermore, we argue that the government exerts stronger environmental supervision over SOEs, thereby highlighting their substantial potential value in the field of carbon reduction.

NTU's association with CEP is confirmed to be an inverted U-shaped curve, validated using a U-test [58], signifying a promotion followed by a restraint on CEP, interpretable through NTU's developmental phases. This

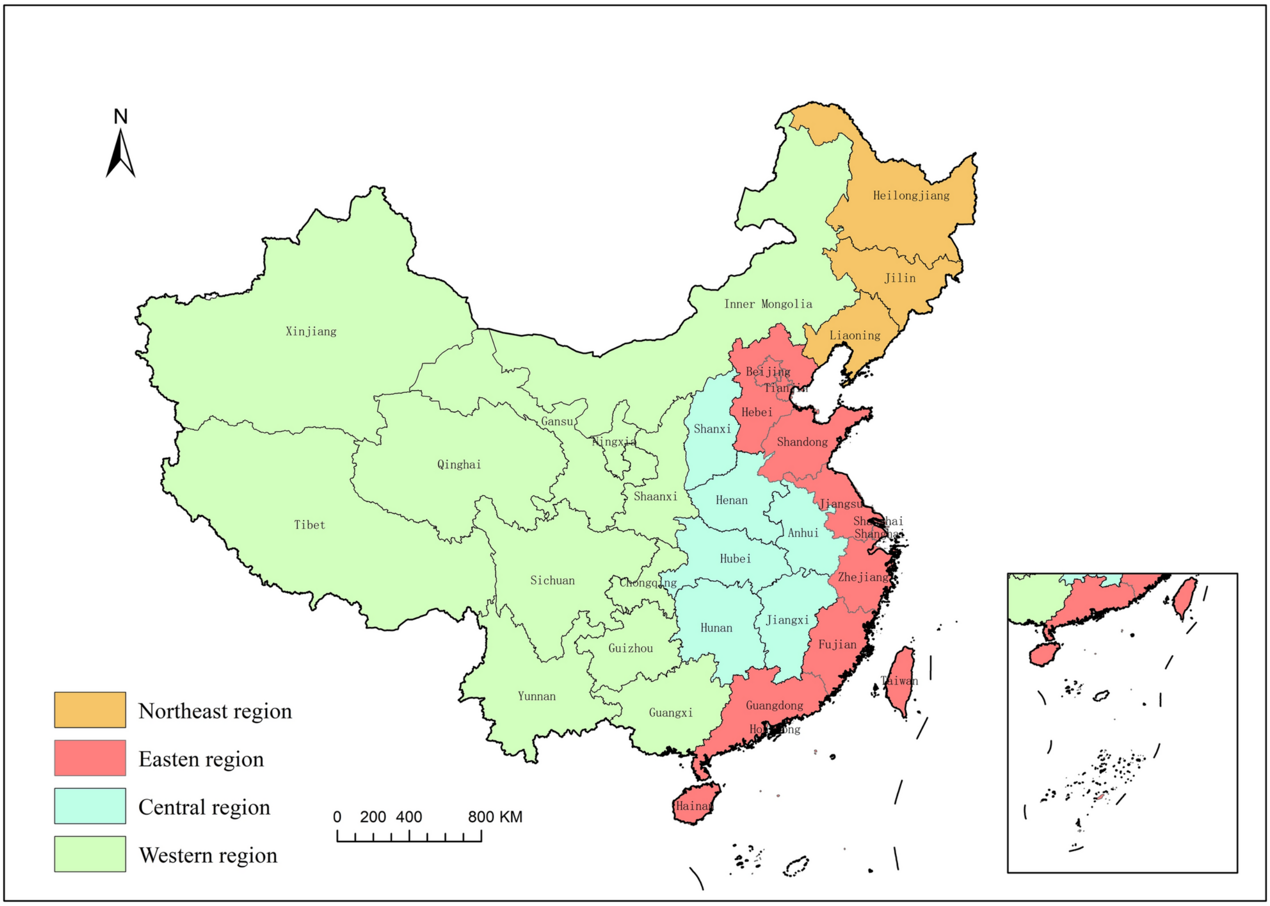

Fig. 4. Four economic regions in China. Created using ArcGIS Desktop (Version 10.7.0.10450), developed by Esri. For details, see: https://desktop.arcgis.com/en/arcmap/latest/map/main/what-is-arcmap-.htm.

inverted U-shaped relationship aligns with the findings of Wang et al.[59], indicating that urbanization initially enhances CEP by increasing employment and improving infrastructure. However, in later stages, the scarcity of resources and environmental pressures brought about by urbanization led to a slowdown in the growth rate of CEP. The challenges faced by megacities in developed countries, such as congestion, resource limitations, and pollution stress, serve as cautionary examples[60]. This finding highlights the critical importance of planning greener and more efficient development pathways in the later stages of urbanization.

Technological progress's dual impact on CEP is complex. The coefficient for technological innovation (paten) lacks significance, potentially because prevailing patents prioritize production efficiency and cost reduction over environmental and clean technology applications. Despite this, the significant positive coefficient for energy efficiency (eneff) underscores its direct positive influence on CEP, emphasizing the need for technological advancements to focus on energy conservation. This is consistent with the findings of Zhong et al.[61], further pointing out that the carbon reduction effects of technological progress require greater emphasis on the practical application of energy-saving and new energy technologies.

Moreover, the analysis of control variables provides additional insights:

Economic development (pgdp), shows a negative impact, suggesting that the current phase of economic advancement may be a hindrance to CEP improvement, a result contrary to expectations. This could be due to the varied engines of economic growth; specifically, if the growth is predominantly driven by industries characterized by high pollution and emission, this could result in economic progress being tied to environmental degradation[62].

Foreign direct investment (fdi), appears to enhance CEP, consistent with China's increasing standards for foreign investments. Reflecting the government's commitment to sustainable development, FDI is expected to be directed preferentially towards sectors that are not only high in value-addition but also low in emissions, thereby contributing to CEP advancement.

The above results validate the first research hypothesis, revealing that economic restructuring and technological progress promote CEP, albeit with heterogeneity. These findings underscore the importance of formulating carbon reduction policies from multiple dimensions.

Variables	(1)	(2)	(3)	(4)	(5)
instr	− 0.0115				− 0.0392***
	(− 0.854)				(− 3.086)
lnklstr		0.1059***			0.0742***
		(4.242)			(3.113)
owner			0.1470*		0.2076***
			(1.926)		(2.911)
ntu				4.0406***	3.5177***
				(4.515)	(3.937)
ntu2				− 2.7589***	− 2.0534**
				(− 3.201)	(− 2.400)
paten	− 0.0016*	− 0.0013	− 0.0018**	− 0.0003	0.0004
	(− 1.816)	(− 1.461)	(− 2.084)	(− 0.323)	(0.441)
eneff	0.1732***	0.2110***	0.1840***	0.1672***	0.1988***
	(4.950)	(6.152)	(5.272)	(5.142)	(6.090)
gover	− 0.1552***	− 0.1862***	− 0.1651***	− 0.2058***	− 0.2257***
	(− 2.705)	(− 3.324)	(− 2.872)	(− 3.772)	(− 4.236)
pgdp	0.1078***	− 0.1301**	0.1114***	− 0.1050*	− 0.2661***
	(2.627)	(− 1.981)	(2.824)	(− 1.928)	(− 3.765)
fdi	0.1115***	0.1130***	0.1065***	0.0989***	0.1113***
	(5.164)	(5.603)	(5.054)	(5.213)	(5.857)
_cons	0.4610***	0.1345*	0.3930***	− 0.8005***	− 0.9586***
	(13.477)	(1.685)	(9.231)	(− 3.288)	(− 4.019)
sigma_u	0.1023***	0.0943***	0.1000***	0.0864***	0.0861***
	(6.264)	(6.825)	(6.388)	(7.308)	(7.255)
sigma_e	0.0572***	0.0563***	0.0570***	0.0538***	0.0519***
	(24.091)	(24.354)	(24.109)	(24.512)	(24.550)
N	390	390	390	390	390
aic	-790	-810	-790	-840	-860
bic	-760	-770	-760	-800	-810
likelihood	404.7423	413.2499	406.2241	428.6903	442.2298
U test					2.5100***

Table 7. Empirical results of the Tobit panel model. t statistics in parentheses. $^{*}p<0.1$, $^{**}p<0.05$, $^{***}p<0.01$.

Robustness test

We conducted robustness checks using three methods[63] presented in Table 8: First, we applied a 1% winsorization to the data, shown in column (1); Second, we supplemented the analysis with both fixed effects and random effects models, shown in the column (3) and (4); Third, we included a cubic term for NTU (ntu3) to verify the non-linear relationship between NTU and CEP, presented in the column (2). The robust test results consistently align with our core conclusions.

To further verify the reliability of the nonlinear relationship between NTU and CEP, we would like to provide additional explanations. Firstly, we plotted a scatter diagram of NTU and CEP as shown in Fig. 5, which shows an overall positive relationship, indicating that NTU may have a positive impact on CEP. However, the scatter plot cannot directly reveal a nonlinear relationship. To verify this, we added quadratic and cubic terms (ntu3) to the model as presented in column (2) of Table 8. The regression results indicate that the directions of the core variables are consistent and significant, with the quadratic term(ntu2) being negative and the cubic term(ntu3) being positive, further confirming the nonlinear relationship between NTU and CEP. However, the turning point in the cubic term model does not yield a real solution, suggesting that the data characteristics are insufficient to support a more complex higher-order relationship, such as an "N" shaped curve, so there may be issues of model overfitting. In contrast, the quadratic term model captures the inverted U-shaped relationship between NTU and CEP, with a calculated turning point at 0.856, which falls within the range of NTU values (0–1) and holds more realistic economic significance. Therefore, this model primarily introduces the quadratic term, using the cubic term as a robustness check to ensure the reliability and interpretability of the conclusions.

This study further considers the issue of endogeneity by conducting a lagged variable analysis, introducing a one-period lag for all key explanatory variables. The findings, detailed in Table 9, reveal that the signs and significances of the majority of the critical explanatory variables align with the initial observations, demonstrating statistical significance at various levels of confidence.

variables	(1)	(2)	(3)	(4)
lntaile	− 0.0388***	− 0.0381***	− 0.0443***	− 0.0325***
	(− 3.056)	(− 3.022)	(− 3.658)	(− 2.823)
lnklstr	0.0742***	0.0759***	0.0941***	0.0622***
	(3.114)	(3.209)	(3.909)	(2.942)
owner	0.2076***	0.2213***	0.1953***	0.1959***
	(2.912)	(3.112)	(2.612)	(3.074)
ntu	3.4974***	20.8188***	3.1664***	3.5597***
	(3.892)	(3.007)	(3.748)	(4.447)
ntu2	− 2.0355**	− 33.3678***	− 1.6739**	− 2.1917***
	(− 2.364)	(− 2.679)	(− 2.133)	(− 2.900)
ntu3		18.6619**		
		(2.520)		
paten		− 0.0004	0.0006	0.0002
		(− 0.431)	(0.647)	(0.235)
eneff	0.1991***	0.1936***	0.1765***	0.1860***
	(6.153)	(5.945)	(5.219)	(6.454)
gover		− 0.2585***	− 0.1564**	− 0.2380***
		(− 4.740)	(− 2.440)	(− 4.925)
pgdp	− 0.2629***	− 0.2355***	− 0.2669**	− 0.2128***
	(− 3.718)	(− 3.303)	(− 2.166)	(− 3.364)
fdi		0.1244***	0.0945***	0.0946***
		(6.293)	(4.018)	(5.785)
paten_wins	0.0003			
	(0.287)			
gover_wins	− 0.2332***			
	(− 4.311)			
fdi02_wins	0.1099***			
	(5.785)			
_cons	− 0.9518***	− 4.1212***	− 0.9616***	− 0.9100***
	(− 3.969)	(− 3.226)	(− 3.706)	(− 4.256)
sigma_u	0.0860***	0.0868***		
	(7.252)	(7.275)		
sigma_e	0.0519***	0.0514***		
	(24.549)	(24.561)		
N	390	390	390	390
aic	-860	-860	-130	
bic	-810	-810	-120	
likelihood	442.3083	445.3875	669.3272	
Hauman test (Prob > chi2)			0.1899	

Table 8. Robustness test results. t statistics in parentheses. *$p<0.1$, **$p<0.05$, ***$p<0.01$.

Examining ER's moderating influence

Investigating whether ER has a moderating role in CEP enhancement, the study explores ER's moderating mechanisms based on the above empirical findings. Results presented in Table 10, which include ER as a moderating factor in the model, indicate that the interaction term between ER and industrial structure (instr#lnregul) is not significant. In contrast, the interaction terms between ER and both factor structure (lnklstr#lnregul) and ownership structure (owner#lnregul) align with the primary regression variables, signifying that ER reinforces the positive impacts in these domains. Specifically, the failure of ER to moderate the effect of industrial structure on CEP may be attributed to the previously discussed issue of structural imbalances. Addressing these imbalances should be prioritized, as merely strengthening ER proves to be insufficient. Meanwhile, ER intensifies the propitious effect of factor input restructuring on CEP, as stricter ER deters investment in highly polluting industries and encourages capital flows towards sustainable energy and emission reduction initiatives. Similarly, ER's positive moderating impact on ownership restructuring is observed; SOEs, facing higher ER compliance costs and under stricter governmental scrutiny, exhibit a more pronounced commitment to emission reduction, substantially aiding CEP improvement.

Additionally, ER's interaction with NTU reveals a complex, nonlinear modulation effect. When the interaction term between ER and the NTU term (ntu#lnregul) is considered alone, the coefficient isn't significant. However,

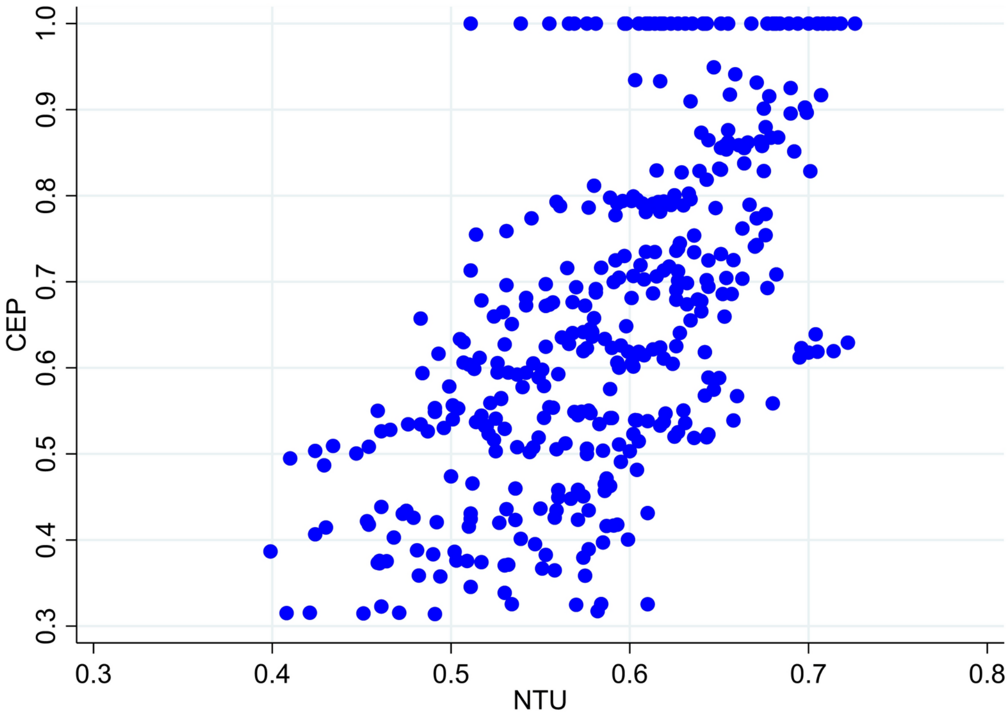

Fig. 5. The scatter diagram of NTU and CEP.

when the quadratic interaction term (ntu2#lnregul) is included, the coefficient becomes positive and significant, suggesting that ER's moderating effect distinctly influences the inverted U-shaped relationship between NTU and CEP.

Specifically, as ER strengthens (from weak regulation to strong regulation) as shown in Fig. 6, the inverted U-shaped curve becomes flatter, indicating that the decline in CEP is significantly mitigated. This suggests that ER may effectively alleviate the negative impact of resource consumption and environmental pressures caused by NTU on CEP. In summary, ER demonstrates a positive moderating effect on NTU.

Regarding the moderating effect of ER on technological progress, we found that the interaction terms between ER and the two indicators were not significant, indicating that strengthened ER cannot amplify the positive effects of technological progress. A possible reason is that the ER indicator used in this study primarily reflects mandatory type regulations, such as pollution treatment costs, which deter enterprises from engaging in environmentally harmful activities by increasing compliance costs. However, it does not serve as incentive-type regulations, such as tax incentives or subsidies, which encourage enterprises to adopt green technological innovations and improve energy efficiency, thus failing to significantly enhance the positive effects of technological progress.

The above analysis partially confirms the second research hypothesis, indicating that ER plays a positive moderating role in the process where economic restructuring promotes CEP. However, its moderating effect on industrial structure and technological progress is not significant.

Conclusion

This study explores the complicated relationship between economic restructuring, technological progress, and CEP, revealing key insights:

First, industrial structure does not significantly enhance CEP, which can be attributed to structural imbalances, as the rationalization of industrial structure is not aligned with the green economic transition. Therefore, this study proposes the following recommendations: it is vital to promote technological upgrading and structural adjustments within the secondary industry to phase out outdated production capacities in high-energy-consuming sectors. For example, the "Air Pollution Prevention and Control Action Plan" issued by the State Council in 2013 has driven the green transformation of industries. Meanwhile, the government should implement incentive policies to promote high-tech service industries to enhance the high-quality development of the service sector. For instance, the "Outline for the Innovation-Driven Development of the Service Industry (2021–2025)" emphasizes the modern service industries such as information technology, fintech, and green logistics. These measures are essential to fostering the synergy between industrial restructuring and a green economy.

The factor input structure and ownership structure play a positive role in enhancing CEP, while the relationship between NTU and CEP exhibits an inverted "U-shaped" curve. Based on these findings, this study recommends promoting high-tech, capital-intensive industries through green financial policies to transition capital factors toward low-carbon and efficient directions. Additionally, SOEs should strengthen their role as

	(1)	(2)	(3)	(4)	(5)
L.instr	− 0.0098				− 0.0375***
	(− 0.706)				(− 2.884)
L.lnklstr		0.0964***			0.0602**
		(3.961)			(2.568)
L.owner			0.0823		0.1275*
			(1.086)		(1.784)
L.ntu				3.9641***	3.6382***
				(4.507)	(4.098)
L.ntu2				− 2.6068***	− 2.1535**
				(− 3.074)	(− 2.539)
L.paten	− 0.0025**	− 0.0021**	− 0.0026***	− 0.0011	− 0.0004
	(− 2.541)	(− 2.208)	(− 2.762)	(− 1.110)	(− 0.400)
L.eneff	0.1619***	0.2088***	0.1694***	0.1611***	0.1942***
	(4.336)	(5.652)	(4.520)	(4.613)	(5.422)
gover	− 0.2260***	− 0.2298***	− 0.2337***	− 0.2244***	− 0.2348***
	(− 3.428)	(− 3.603)	(− 3.537)	(− 3.645)	(− 3.891)
pgdp	0.1482***	− 0.0880	0.1478***	− 0.1132*	− 0.2461***
	(3.379)	(− 1.259)	(3.490)	(− 1.950)	(− 3.337)
fdi	0.1196***	0.1168***	0.1162***	0.1088***	0.1143***
	(5.134)	(5.355)	(5.071)	(5.227)	(5.534)
_cons	0.4771***	0.1868**	0.4350***	− 0.7687***	− 0.8907***
	(12.569)	(2.396)	(9.605)	(− 3.192)	(− 3.756)
sigma_u	0.1084***	0.0999***	0.1051***	0.0947***	0.0938***
	(6.056)	(6.613)	(6.204)	(7.158)	(7.095)
sigma_e	0.0542***	0.0533***	0.0542***	0.0506***	0.0493***
	(23.139)	(23.381)	(23.175)	(23.573)	(23.601)
N	360	360	360	360	360
aic	-760	-770	-760	-800	-820
bic	-720	-740	-720	-760	-770
likelihood	387.6080	395.0450	387.9467	411.7467	420.7668

Table 9. Results of lagged explanatory variable analysis. t statistics in parentheses. *$p < 0.1$, **$p < 0.05$, ***$p < 0.01$.

models in energy conservation and emission reduction, while non-SOEs can be encouraged to adopt cleaner production practices through tax exemptions and subsidies, achieving a balance between economic benefits and environmental goals. For urbanization, excessive expansion should be reasonably controlled in the later stages, with a focus on developing third- and fourth-tier cities. By decentralizing resource and population distribution, environmental pressures can be alleviated, fostering the synergy between NTU and CEP.

The two dimensions of technological progress have differing effects on CEP: technological innovation has failed to improve CEP, while energy efficiency plays a significant role in promoting it. This confirms that the ability of technology to reduce emissions depends on its green orientation.

This study proposes the following recommendations: the government should prioritize support for clean energy and energy-saving technologies, encourage enterprises to focus their R&D efforts on green technologies through dedicated funding and tax incentives and ensure that technological progress contributes to CEP.

As a key moderating variable, ER strengthens the beneficial impacts of the factor input structure, ownership structure, and NTU on CEP, yet shows minimal influence on industrial structure, technological innovation, and energy efficiency.

Based on the findings above, we believe that fully leveraging the three types of ERs, can enable targeted and precise adjustments in different areas. Command-type regulations should focus on high-energy-consuming industries by implementing stricter environmental standards and energy consumption limits, such as the industry entry thresholds outlined in the Benchmark Levels of Energy Efficiency in 2022 Edition, to promote the green transformation of energy-intensive enterprises[64]. Incentive-type regulations should play a stronger role in advancing technological progress. Given the high investment and long-term nature of technological innovation, which is often undertaken by large SOEs, incentives should encourage them to continue leading in green technology development through mechanisms such as carbon emissions trading systems, green finance, and green subsidies. Voluntary-type regulations, on the other hand, should emphasize public participation and are particularly applicable to NTU projects. Through environmental awareness campaigns and reward mechanisms, green lifestyles such as waste sorting, energy-efficient appliances, and eco-friendly commuting

	(1)	(2)	(3)
instr	− 0.0392***	− 0.0422***	− 0.0400***
	(− 3.086)	(− 3.388)	(− 3.239)
lnklstr	0.0742***	0.0807***	0.0808***
	(3.113)	(3.438)	(3.466)
owner	0.2076***	0.1791**	0.2008***
	(2.911)	(2.556)	(2.862)
ntu	3.5177***	3.5395***	2.3980**
	(3.937)	(3.141)	(2.003)
ntu2	− 2.0534**	− 2.1690**	− 1.2207
	(− 2.400)	(− 2.148)	(− 1.147)
paten	0.0004	0.0003	0.0002
	(0.441)	(0.291)	(0.189)
eneff	0.1988***	0.1949***	0.1855***
	(6.090)	(5.341)	(5.077)
gover	− 0.2257***	− 0.2937***	− 0.3080***
	(− 4.236)	(− 5.499)	(− 5.770)
pgdp	− 0.2661***	− 0.2124***	− 0.1986***
	(− 3.765)	(− 3.021)	(− 2.832)
fdi	0.1113***	0.1183***	0.1329***
	(5.857)	(6.162)	(6.603)
lnregul		0.0140**	0.0123**
		(2.465)	(2.168)
instr#lnregul		− 0.0079	− 0.0059
		(− 0.775)	(− 0.575)
lnklstr#lnregul		0.0216*	0.0213*
		(1.809)	(1.780)
owner#lnregul		0.1111**	0.1195**
		(2.036)	(2.199)
paten#lnregul		0.0002	0.0009
		(0.301)	(1.182)
eneff#lnregul		− 0.0218	− 0.0117
		(− 1.210)	(− 0.641)
ntu#lnregul		0.1071	2.6302***
		(0.630)	(2.726)
ntu2#lnregul			− 2.2985***
			(− 2.652)
_cons	− 0.9586***	− 0.8662***	− 0.5489*
	(− 4.019)	(− 2.817)	(− 1.678)
sigma_u	0.0861***	0.0843***	0.0849***
	(7.255)	(6.970)	(6.979)
sigma_e	0.0519***	0.0500***	0.0495***
	(24.550)	(24.428)	(24.438)
N	390	390	390
aic	− 860	− 870	− 880
bic	− 810	− 790	− 790
likelihood	442.2298	455.1457	458.6592

Table 10. Empirical results of the moderating model. t statistics in parentheses. $^{*}p < 0.1$, $^{**}p < 0.05$, $^{***}p < 0.01$.

should be promoted. In summary, the coordinated efforts of these three types of ERs will effectively amplify their regulatory impact, supporting the achievement of low-carbon and sustainable development goals.

Limitations and future research

Although this study reveals the multi-faced relationship between economic restructuring, technological progress, and CEP, it has certain limitations. First, the research is based on provincial-level data, which makes it difficult to capture the heterogeneous characteristics at the city or firm level. Future studies could incorporate micro-level data to further explore the mechanisms through which different economic entities influence CEP. Second,

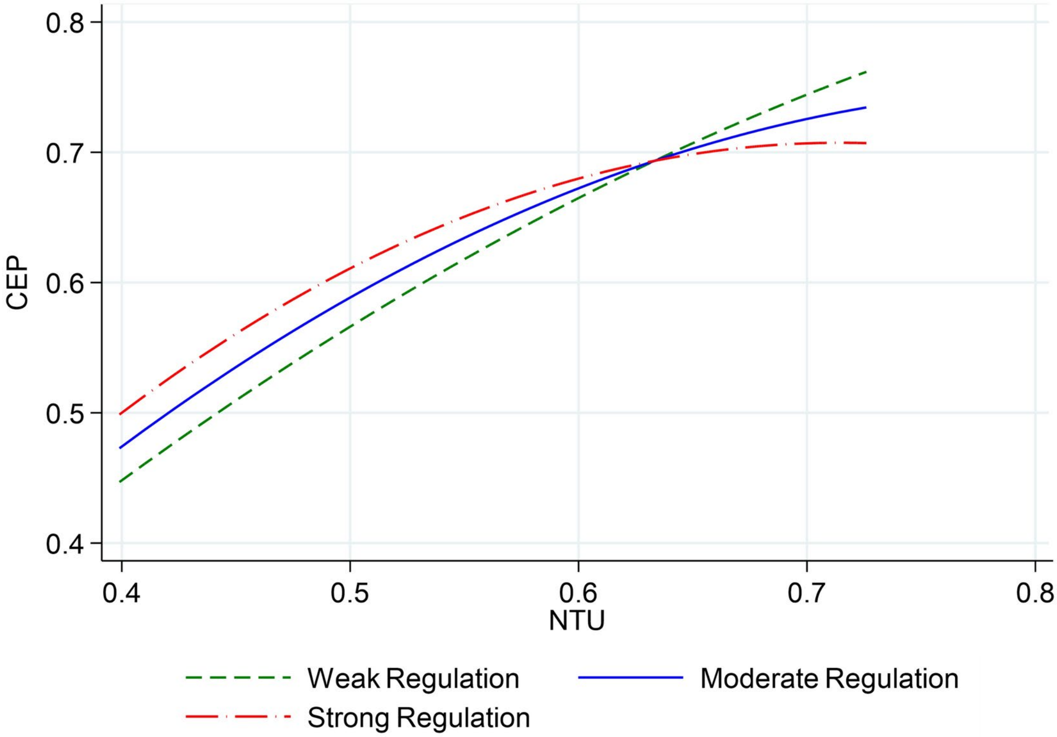

Fig. 6. The moderating effects at different ER intensities.

the model design may overlook the dynamic relationships between variables, such as potential bidirectional causality between CEP and technical progress. Future research could employ causal inference methods, such as instrumental variables, to further validate the conclusions. Additionally, this study treats ER as a single type of regulation; future research could classify ER into different types (e.g., command type, incentive type, and voluntary type) to examine their distinct effects. These limitations provide valuable directions for future research and may support more effective carbon reduction policies.

Data availability

Data cannot be shared openly but are available on request from corresponding author.

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Author contributions

All authors contributed to the study design. The research framework was completed by S.I. and X.M. Data collection, analysis, and the first draft of the manuscript were completed by J.Y. and C.Z. Revision and proofreading were done by N.N.A.M. And all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

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Consent to participate and publication

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Additional information

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