Research on Carbon Emission Efficiency in the Core Cities of the Yangtze River Delta

Yanli Sun[a*], Zhanxu Yu[b], Yuchu Wu[c]

Shenyang Jianzhu University, Shenyang, 110168, China

[a*]yanlisun7108@163.com, [b]1310410192@qq.com, [c]1478044684@qq.com

Abstract. This study focuses on the core cities of the Yangtze River Delta, constructing a carbon emission efficiency evaluation system and using the SBM-DDF model to quantitatively assess the carbon emission efficiency of each city. The results indicate that the overall carbon emission efficiency of the core cities in the Yangtze River Delta is relatively low, with significant regional differences. Cities such as Shanghai and Hangzhou perform better in carbon emission efficiency, while cities like Jiaxing and Shaoxing lag behind, facing substantial pressure for green transformation. Since the implementation of the "Dual Carbon" policy in 2020, some cities have seen improvements in carbon emission efficiency, but fluctuations remain, indicating issues with the sustainability of short-term policy effects. Based on these findings, this paper suggests policy recommendations such as enhancing green technology innovation, promoting the green upgrading of industrial structures, and fostering regional collaboration to improve carbon emission efficiency and facilitate a green low-carbon transition in the Yangtze River Delta region.

Keywords: Carbon emission efficiency; Core cities of the Yangtze River Delta; SBM-DDF model

1 Introduction

As global climate change intensifies, carbon emission control is crucial for sustainable development. China's "dual carbon" goals—reaching carbon peak by 2030 and carbon neutrality by 2060—are essential for overcoming resource and environmental constraints and promoting high-quality economic growth. The construction industry, one of the three major energy-consuming sectors [1], plays a key role in achieving these goals. The "2022 Building Energy Consumption and Carbon Emission Research Report" [2] states that in 2020, the construction industry accounted for 45% of the country's total energy consumption, making its low-carbon transformation essential for meeting the "dual carbon" targets. The core cities of the Yangtze River Delta, among China's most developed regions, face significant carbon emission pressures despite their advanced construction sectors. The region has promoted green development through policies for green buildings, energy-saving renovations, and low-carbon

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technologies. However, balancing economic growth with carbon reduction remains challenging, especially in improving carbon emission efficiency while maintaining construction industry growth. Carbon emission efficiency, a key measure of emissions per unit of economic output, is crucial for evaluating low-carbon development. Research on carbon emission efficiency in the Yangtze River Delta's core cities can reveal the spatial distribution and evolution of carbon emissions in the construction industry and identify factors influencing efficiency, providing support for precise carbon reduction policies. This paper focuses on carbon emission efficiency in these cities, using quantitative methods to measure efficiency and explore key influencing factors, offering theoretical and policy recommendations for the region's green low-carbon development.

2 Literature Review

Carbon emission efficiency evaluation is a key research topic, typically divided into single-factor and multi-factor efficiency. Single-factor efficiency measures the ratio of carbon emissions to a specific input, such as carbon emission intensity (emissions per unit GDP) or carbon productivity (emissions per unit of energy consumption). However, this method overlooks the substitution relationships between factors, limiting its applicability. Consequently, multi-factor methods, particularly Data Envelopment Analysis (DEA), have become the standard for assessing carbon emission efficiency in complex systems with multiple inputs and outputs. For example, Niu Jianguang et al. [3] applied the super-efficiency EBM model to assess efficiency in China's construction industry. Zhang Mingdou et al. [4] used the super-efficiency SBM model to evaluate efficiency in resource-based cities and explore carbon reduction optimization paths. Li Zhonggen et al. [5] studied the Yangtze River Economic Belt, finding that the eastern region outperformed the central and western regions in carbon emission efficiency. Xiang Yinghui et al. Current research focuses on measuring and analyzing influencing factors across regions and industries, with methods evolving from single-factor to multi-factor efficiency, often incorporating spatial econometrics and threshold regression models. However, further research is needed on regional heterogeneity, dynamic evolution, and policy optimization. Studies on carbon emission efficiency in the Yangtze River Delta's construction industry are limited. This paper uses the super-efficiency SBM-DDF model to assess carbon emission efficiency in the region's construction industry, providing theoretical support and policy recommendations for green low-carbon development. Moreover, recent literature has begun to explore the integration of environmental regulation and digital innovation into efficiency analysis frameworks. Some scholars have proposed hybrid models that combine DEA with machine learning or stochastic frontier analysis (SFA) to improve estimation robustness and predictive accuracy. For instance, hybrid DEA-SFA models allow for a better separation of inefficiency and statistical noise, enhancing the explanatory power of carbon efficiency assessments. In addition, the role of government environmental governance, green credit, and eco-labeling policies is increasingly being recognized as a non-negligible external factor influencing regional disparities in emission efficiency. These studies highlight that beyond technical inputs and outputs, institutional and policy environments are vital in shaping carbon performance outcomes across cities.

Despite these advancements, challenges remain in data quality, dynamic modeling, and incorporating behavioral and market factors into efficiency assessments. Therefore, there is a growing call for interdisciplinary approaches combining economics, environmental science, and data analytics to deepen the understanding of low-carbon transitions. Building on this foundation, the present study contributes to the field by applying an advanced SBM-DDF model to evaluate the performance of key urban economies in one of China's most vital regions.

3 Carbon Emission Efficiency Indicator System

Carbon emission efficiency measures the carbon emissions per unit of output (e.g., GDP), reflecting the relationship between economic development and carbon emissions. Higher efficiency indicates fewer emissions per unit of output, signifying more environmentally friendly production. This study develops a carbon emission efficiency system for the construction industry (Table 1), using energy consumption as an input and carbon emissions as an undesirable output, based on Fare et al.'s [6] environmental production and directional distance functions. The input variables include labor, capital, and energy, with GDP as the desired output. Traditional SBM models may result in multiple cities having an efficiency value of 1, complicating comparisons. To address this, the study uses Andersen's [7] super-efficiency model, developing a super-efficiency SBM model that incorporates undesirable outputs for efficiency measurement.

Table 1. Carbon Emission Efficiency Indicator System for the Construction Industry

Indicator Type	Primary Indicator	Secondary Indicator	Unit
Input Indicators	Capital Input	Fixed Capital Stock	10,000 yuan
	Energy Input	Total Energy Consumption (Standard Coal)	10,000 tons of standard coal
	Labor Input	Number of Employees	10,000 persons
Output Indicators	Desired Output	Actual GDP	10,000 yuan
	Undesired Output	CO2 Emissions	10,000 tons

4 Carbon Emission Efficiency Model

This study uses the SBM-DDF model to assess carbon emission efficiency in the core cities of the Yangtze River Delta. Developed by Fukuyama and Weber [8], the model integrates the directional distance function into SBM, overcoming traditional DEA's limitations. It accounts for input-output asymmetry and slack variables, providing a more accurate efficiency depiction. Suitable for low-carbon transition assessments, the model considers both economic output and carbon emissions. This study evaluates city performance under carbon emission constraints using this model. The calculation formula is as follows:

$$\overrightarrow{S_v^t}(x_i^t, y_i^t, b_i^t, g^x, g^y, g^b) = \frac{1}{3} max(\frac{1}{N}\sum_{n=1}^{N}\frac{s_n^x}{g_n^x} + \frac{1}{M}\sum_{m=1}^{M}\frac{s_m^y}{g_m^y} + \frac{1}{K}\sum_{k=1}^{K}\frac{s_k^b}{g_k^b}) \quad (1)$$

$$s.t. \vec{\lambda} Y - S_m^y = y_{im}^t, \forall m, \vec{\lambda} B + S_k^b = b_{ik}^t, \forall k; \vec{\lambda} X + S_n^x = x_{in}^t, \forall b; \vec{\lambda} \geq 0, \vec{\lambda} l = 1; S_n^x \geq 0, S_m^y \geq 0, S_k^b \geq 0; eff = 1 - \overrightarrow{S_v^t} \quad (2)$$

In the formula: X represents the input; y represents the output; b represents the undesirable output; (x_i^t, y_i^t, b_i^t)represents the input-output data for the i th region and t period; (g^x, g^y, g^b)represents the direction vector;(s_n^x, s_m^y, s_k^b) represents the slack variable for the distance between the input-output data of each decision-making unit and the efficiency frontier; eff represents the carbon emission efficiency.

This study covers the 10 core cities of the Yangtze River Delta, using statistical data from 2013 to 2022. The data sources include the China City Statistical Yearbook, China Energy Statistical Yearbook, China Industrial Statistical Yearbook, China Environmental Statistical Yearbook, provincial and municipal statistical yearbooks, and statistical bulletins from prefecture-level cities.

5 Research Results

The carbon emission efficiency of the 10 cities in the core cities of the Yangtze River Delta was measured using the SBM-DDF model constructed in MATLAB software. The results are shown in Table 2:

Table 2. Calculation Results of the Carbon Emission Efficiency Index

City	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	Average
Shanghai	0.412	0.369	0.298	0.303	0.278	0.287	0.288	0.289	0.301	0.310	0.313
Nanjing	0.310	0.312	0.293	0.261	0.246	0.243	0.255	0.273	0.308	0.343	0.284
Hangzhou	0.480	0.515	0.532	0.526	0.503	0.536	0.741	1.036	0.864	0.693	0.643
Suzhou	0.310	0.305	0.288	0.243	0.188	0.190	0.198	0.218	0.253	0.287	0.248
Ningbo	0.256	0.246	0.250	0.243	0.238	0.151	0.168	0.215	0.261	0.306	0.233
Wuxi	0.196	0.193	0.200	0.194	0.214	0.229	0.226	0.235	0.263	0.290	0.224
Hefei	0.203	0.199	0.199	0.209	0.212	0.232	0.240	0.262	0.217	0.171	0.214
Jiaxing	0.596	0.635	0.657	0.641	0.671	0.661	0.594	0.405	0.388	0.372	0.562
Shaoxing	0.295	0.296	0.321	0.332	0.390	0.390	0.401	0.433	0.403	0.410	0.367
Wuhu	0.279	0.285	0.117	0.137	0.217	0.343	0.349	0.351	0.338	0.326	0.274
Average	0.334	0.335	0.316	0.309	0.316	0.326	0.346	0.372	0.360	0.351	0.336

Based on carbon emission efficiency indices of the core cities in the Yangtze River Delta from 2013 to 2022, the overall average efficiency was low at 0.336, indicating significant room for improvement in green and low-carbon development. Notable disparities were found across cities. Shanghai's efficiency decreased from 0.412 in 2013 to 0.310 in 2022, maintaining a high level due to its advanced industrial structure and effective green policies. In contrast, Jiaxing's efficiency dropped from 0.596 to 0.372, reflecting over-reliance on traditional manufacturing and lagging innovation. Jiaxing needs to accelerate its green transformation, especially in upgrading traditional industries. Hangzhou's efficiency rose from 0.480 to 0.693, driven by the digital economy's rapid growth, while Wuhu's efficiency remained low, from 0.279 to 0.326, due to insufficient green technology investment. Wuhu should accelerate digital transformation and adopt green technologies. Suzhou averaged 0.248, benefiting from advancements in manufacturing and high-tech industries, while Ningbo's efficiency averaged 0.233, still reliant on traditional industries. Ningbo must invest more in green technologies and promote intelligent industry upgrades. In summary, industrial structure, technological innovation, and policy support are key to improving carbon emission efficiency. Cities like Shanghai, Hangzhou, and Suzhou, leading in innovation and transformation, show better efficiency, while cities like Jiaxing, Wuhu, and Ningbo must accelerate digital transformation, green technology, and industrial upgrading to catch up and promote higher-quality development.

This study reveals significant disparities in carbon emission efficiency across the core cities of the Yangtze River Delta, indicating the need for differentiated and targeted policy strategies. Cities in this region can be classified into three typologies based on their carbon emission efficiency trends and industrial characteristics: These cities exhibit relatively high carbon emission efficiency due to advanced service-oriented industrial structures, significant investment in green innovation, and early adoption of digital technologies. Policy emphasis should focus on consolidating their leadership role through international cooperation, promoting green finance, and accelerating zero-carbon building technologies. These cities can serve as demonstration zones for other urban areas.

With moderate efficiency levels and signs of improvement, these cities require policy support to accelerate the transformation of their traditional manufacturing sectors. Policies should include subsidies for clean production technologies, industrial digitalization support, and workforce training for green construction practices.

These cities face structural challenges, including dependence on carbon-intensive industries and insufficient investment in green infrastructure. For them, tailored policy interventions are essential, such as stricter emission regulation, incentives for industrial restructuring, and dedicated green technology funds. These cities should also strengthen cooperation with leading cities to absorb best practices and technological spillovers.

Moreover, this classification approach enables policymakers to design spatially coordinated policies across the Yangtze River Delta. Instead of a one-size-fits-all approach, inter-city collaboration mechanisms—such as joint carbon trading platforms, shared green R&D labs, and regional carbon emission databases—can help reduce regional disparities and improve overall efficiency.In addition, dynamic carbon efficiency monitoring systems should be established using big data and AI to provide real-time tracking of progress. The digital economy, particularly in Hangzhou and Shanghai, proves to be a major driver of green performance. Other cities can emulate this transformation through digital infrastructure investments and green entrepreneurship incubation.

Ultimately, to ensure the sustainability of the “Dual Carbon” strategy, a multi-level governance model is necessary—where national, provincial, and city-level policies are harmonized and responsive to empirical data like those generated in this study.

In addition, it is crucial to recognize the role of public awareness and community participation in enhancing carbon emission efficiency... These social aspects, often overlooked in technical analyses, play a fundamental role in ensuring long-term success and acceptance of low-carbon strategies across the region.

6 Conclusions

This study focuses on the 10 core cities of the Yangtze River Delta, using the SBM-DDF model to evaluate carbon emission efficiency and analyze regional differences and trends. The results show relatively low efficiency with significant disparities. Cities like Shanghai and Hangzhou perform well due to advanced industrial structures and policy support, while Jiaxing and Shaoxing face greater green transformation pressures, with slower improvements. Since the "Dual Carbon" policy in 2020, some cities have seen modest improvements, but fluctuations suggest the need for stronger, long-term policy support, especially for industrial transformation and technological innovation. Limitations include limited data availability, potential inaccuracies, and the model’s inability to account for dynamic socio-economic factors, such as economic growth and technological progress, which may affect long-term efficiency. Regional differences in resources and industrial structures may also limit broader applicability. Refine carbon emission accounting methods, integrating lifecycle assessments (LCA) and real-time monitoring using big data and AI to improve efficiency and sustainability, and enable accurate predictions. Strengthen international cooperation to accelerate green development in China, sharing low-carbon innovation and supporting global green goals. Expand regional comparisons and cross-regional research to tailor policies and improve coordination, boosting carbon emission efficiency and supporting green transformation. Future studies may expand the analysis to include the role of foreign direct investment (FDI), environmental regulation stringency, and the impact of inter-provincial carbon trading mechanisms. Moreover, integrating life-cycle emissions of construction materials could provide a more granular evaluation of the sector’s carbon footprint.

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2. Fund Project: Key Commissioned Project of the Liaoning Provincial Social Science Planning Fund(L24AWT012).

References

1. LAMB W. F. A review of trends and drivers of greenhouse gas emissions by sector from 1990 to 2018. Environmental Research Letters, 2021, 16: 073005.
2. Tsinghua University Building Energy Efficiency Research Center. China Building Energy Efficiency Annual Development Report 2022. Beijing: China Building Industry Press, 2022.
3. NIU J., XIN B., WANG M., et al. Research on carbon emission efficiency and the coordinated development of urbanization in the construction industry. Journal of Hebei University of Engineering, 2023, 33(4): 7-12.
4. ZHANG M., XI S. Carbon emission efficiency evaluation of resource-based cities and its policy implications. Journal of Natural Resources, 2023, 38(1): 220-237.
5. LI G., ZHU H. A study on the carbon emission efficiency of the Yangtze River Economic Belt based on a three-stage SM-DEA-Malmquist index. Operations Research and Management Science, 2022, 31(6): 161-167.
6. FARE R., GROSSKOPF S., PASURKA C. A. Environmental production functions and environmental directional distance functions. Energy, 2007, 32(7): 1055-1066.
7. ANDERSEN P., PETERSEN N. C. A procedure for ranking efficient units in data envelopment analysis. Management Science, 1993, 39(10): 1261-1265.
8. FUKUYAMA H., WEBER W. L. A directional slacks-based measure of technical inefficiency. Socio-Economic Planning Sciences, 2009, 43(4): 274-287.