

Industrial Energy Efficiency with CO₂ Emissions in the Yangtze River Delta, China: A Nonparametric Analysis

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Abstract. As one of the most developed regions in China, the Yangtze River Delta (YRD) is experiencing rapid industrialization and urbanization, which is accompanied by huge energy consumption and CO₂ emissions. Moreover, Chinese government has recently redefined the scope of YRD to include 8 cities in Anhui province. In this case, it is crucial to evaluate new-YRD's sustainability by studying industrial energy efficiency (IEE) with CO₂ emissions at city level. To this end, we evaluate IEE of 26 cities in YRD and its space-time distribution during 2006-2015 based on Shephard energy distance function and GIS visualization method, respectively. The findings reveal that IEE in YRD shows an ascending trend during the study period. Moreover, the spatial distribution of the IEE presents the characteristics of low in south, high in north, indicating the existence of a spatial cluster. Finally, a couple of suggestions are concluded.

1. Introduction

As the largest energy consumer and CO₂ emitter, China is faced by great challenges of resource and environment from home and abroad. To safeguard its energy security and mitigate global climate change, China has to find ways to control its fossil energy use and CO₂ emissions. It is accepted that improving energy efficiency is one of the most cost-effective ways to increase energy security, improve industrial competitiveness and mitigate climate change [1]. Due to the fact that industrial sector is the largest energy end-user of China, improving industrial energy efficiency plays a significant role for China to enhance energy security and promote low-carbon development. In this context, the analysis of industrial energy efficiency performance in China may provide empirical and condensed information for policy makers to assess the effectiveness of energy efficiency policies and measures.

As one of the six largest urban agglomerations in the world, Yangtze River Delta (YRD) urban agglomeration accounted for 19.78% of China's GDP in 2016. In 2014, the State Department has incorporated Anhui Province as a part of YRD, and the scope of YRD has been expanded accordingly. According to the "Development Plan of Urban Agglomeration in the Yangtze River Delta" approved by the State Council in May 2016, YRD urban agglomeration was extended to include 26 cities [2]. In this sense, it is of great theoretical and practical value to study the (IEE) of the 26 cities in new-YRD. YRD has been the concerns of many scholars due to its irreplaceable economic status. Gu et al [3]. Pointed out that it is among the most developed, densely populated and industrialized areas in China, and it is developing into a competitive world-class metropolitan area. Sun and Li [4] measured the



total-factor energy efficiency of the YRD region during 1992-2010 based on the DEA-Malmquist model. Yang et al [5]. Estimated the total-factor energy efficiency 14 representative cities in YRD from 2000 to 2009 by using a stochastic frontier production function.

However, IEE with CO₂ emissions in the new-YRD urban agglomeration has not been investigated, and this paper is conducted to fill the gap in this field. The reminder of this paper proceeds as follows. Section 2 introduces methods and materials. Section 3 presents the results and discussions. Section 4 draws conclusions and provides policy implications.

2. Methods and Materials

2.1. Environmental Production Technology

Consider a productive process in which capital stock (K), labor force (L) and energy (E) are utilized to jointly produce gross industrial output (Y) and CO₂ emissions (C) as the single desirable output and undesirable output, respectively. Mathematically, the joint production can be presented as Eq. (1), which is so-called environmental production technology.

$$T = \{(K, L, E, Y, C) : (K, L, E) \text{ can produce } (Y, C)\} \quad (1)$$

Notably, in the joint-production process, inputs and the desirable output are usually assumed to be strongly disposable, while the undesirable output is weakly disposable.

2.2. Industrial Energy Efficiency Index

To measure the industrial energy efficiency performance, we first define a Shephard sub-vector input distance function for energy use (hereafter referred to as the Shephard energy distance function) as follows:

$$D_e(K, L, E, Y, C) = \sup \{\beta : (K, L, E/\beta, Y, C) \in T\} \quad (2)$$

Eq. (2) seeks to measure the maximal possible reduction in energy use, while keeping the resulting input-output combination within the production technology set as defined by Eq. (1).

The Shephard energy distance function $D_e(K, L, E, Y, C)$ measures the degree to which energy use can be reduced. As such, its reciprocal may be taken as an energy efficiency index that can be used to compare the industrial energy efficiency performance. Here we refer to the reciprocal of the Shephard energy distance function as the industrial energy efficiency (IEE):

$$IEE = \frac{1}{D_e(K, L, E, Y, C)} \quad (3)$$

The Shephard energy distance function can be measured by solving the following DEA model exhibiting constant returns:

$$\begin{aligned} & \left[D_e(K_j, L_j, E_j, Y_j, C_j) \right]^{-1} = \min \theta \\ \text{s.t.} \quad & \sum_{j=1}^n \lambda_j K_j \leq K_j; \sum_{j=1}^n \lambda_j L_j \leq L_j; \sum_{j=1}^n \lambda_j E_j \leq \theta E_j; \\ & \sum_{j=1}^n \lambda_j Y_j \geq Y_j; \sum_{j=1}^n \lambda_j C_j = C_j; \lambda_j \geq 0, j = 1, 2, \dots, n \end{aligned} \quad (4)$$

2.3. Regions and Data

The research object in this paper is urban agglomeration in YRD which contains 26 cities located in three provinces of Jiangsu, Zhejiang, Anhui and one municipality of Shanghai. Specifically, cities in Jiangsu Province contain Nanjing (NJ), Suzhou (SZ), Wuxi (WX), Changzhou (CAZ), Zhenjiang (ZJ), Yangzhou (YZ), Taizhou (TZ), Nantong (NT) and Yancheng (YC); cities in Zhejiang Province contain Hangzhou (HZ), Ningbo (NB), Jiaxing (JX), Huzhou (HUZ), Shaoxing (SX), Jinhua (JH), Zhoushan (ZS), Taizhou (TAZ); cities in Anhui Province contain Hefei (HF), Wuhu (WH), Maanshan (MAS), Tongling (TL), Anqing (AQ), Chuzhou (CUZ), Chizhou (CIZ), Xuancheng (XC).

The data of capital stock (K), average number of employees (L), energy consumption (E), gross industrial output value (G) and CO₂ emissions (C) are gathered and calculated from the relevant City Statistical Yearbooks.

Table 1. IEE of 26 cities in YRD during 2006-2015.

<i>Region</i>	<i>2006</i>	<i>2007</i>	<i>2008</i>	<i>2009</i>	<i>2010</i>	<i>2011</i>	<i>2012</i>	<i>2013</i>	<i>2014</i>	<i>2015</i>	<i>Mean</i>
Shanghai	0.813	0.969	0.908	0.971	0.944	0.872	0.773	0.816	0.828	0.781	0.868
Nanjing	0.733	0.849	0.796	0.981	0.802	0.749	0.700	0.929	0.951	0.845	0.834
Suzhou	0.858	0.861	0.823	0.850	0.812	0.772	0.719	0.668	0.615	0.630	0.761
Wuxi	0.805	0.869	0.801	0.819	0.766	0.750	0.651	0.669	0.639	0.669	0.744
Changzhou	0.860	0.839	0.860	0.986	0.978	0.981	0.912	1.000	0.944	1.000	0.936
Zhenjiang	0.298	0.461	0.462	0.744	0.655	0.639	0.682	0.782	0.797	0.779	0.630
Yangzhou	0.574	0.574	0.595	1.000	1.000	1.000	1.000	1.000	1.000	1.000	0.874
Nantong	0.777	0.880	0.842	1.000	0.857	0.810	0.809	0.809	0.819	0.827	0.843
Taizhou	0.769	0.828	0.748	1.000	1.000	1.000	1.000	1.000	1.000	1.000	0.934
Yancheng	0.644	0.785	0.796	1.000	1.000	1.000	1.000	0.831	0.781	0.798	0.863
Hangzhou	1.000	1.000	1.000	1.000	1.000	1.000	1.000	0.957	0.887	0.911	0.976
Ningbo	0.600	0.614	0.552	0.583	0.702	0.536	0.515	0.547	0.541	0.504	0.569
Jiaxing	0.421	0.540	0.522	0.545	0.664	0.563	0.489	0.514	0.512	0.525	0.530
Huzhou	0.336	0.461	0.457	0.758	0.677	0.609	0.634	0.680	0.674	0.634	0.592
Shaoxing	0.699	0.807	0.858	0.847	0.831	0.968	0.980	1.000	0.910	0.976	0.888
Jinhua	0.723	0.571	0.543	0.608	0.618	0.577	0.541	0.586	0.568	0.657	0.599
Zhoushan	0.146	0.342	0.340	0.978	0.720	0.661	0.505	0.926	1.000	0.902	0.652
Tai'zhou	0.989	0.712	0.457	0.548	0.576	0.501	0.500	0.472	0.457	0.429	0.564
Hefei	0.636	0.842	0.992	1.000	0.967	0.817	0.874	0.884	0.801	0.894	0.871
Wuhu	0.451	0.531	0.556	0.795	0.616	0.652	0.583	0.769	0.429	0.771	0.615
Maanshan	0.267	0.394	0.499	0.856	0.728	0.591	0.530	0.721	0.267	0.668	0.552
Tongling	0.284	0.371	0.284	0.885	0.951	1.000	0.611	1.000	0.324	1.000	0.671
Anqing	0.288	0.355	0.305	0.865	0.877	0.902	0.856	0.781	0.183	0.716	0.613
Chuzhou	0.578	0.616	0.600	0.737	0.879	1.000	0.771	0.781	0.145	0.961	0.707
Chizhou	1.000	1.000	1.000	0.577	0.590	0.599	0.577	0.588	0.095	0.661	0.669
Xuancheng	0.479	0.561	0.478	0.710	0.802	0.821	0.670	0.674	0.091	0.626	0.591
Shanghai	0.813	0.969	0.908	0.971	0.944	0.872	0.773	0.816	0.828	0.781	0.868
Jiangsu	0.702	0.772	0.747	0.931	0.875	0.856	0.830	0.854	0.838	0.839	0.824
Zhejiang	0.614	0.631	0.591	0.733	0.724	0.677	0.646	0.710	0.694	0.692	0.671
Anhui	0.498	0.584	0.589	0.803	0.801	0.798	0.684	0.775	0.292	0.787	0.661
YRD	0.616	0.678	0.657	0.832	0.808	0.783	0.726	0.784	0.625	0.776	0.729

3. Results and Discussion

3.1. Industrial Energy Efficiency Estimates

We computed the IEE scores for 26 cities by solving Eq. (4) with MaxDEA Ultra. The results were listed in Table 1. At city level, average efficiency of Hangzhou, Changzhou and Taizhou is at high levels with scores of more than 0.9. In contrast, the average IEE of Jiaxing (0.530) is the lowest, followed by Maanshan with the value of 0.552. At province level, Shanghai is found with the highest average IEE of 0.868, followed by Jiangsu (0.824). Moreover, the average IEE of Anhui (0.661) and Zhejiang (0.671) is much lower than the average level of YRD (0.729).

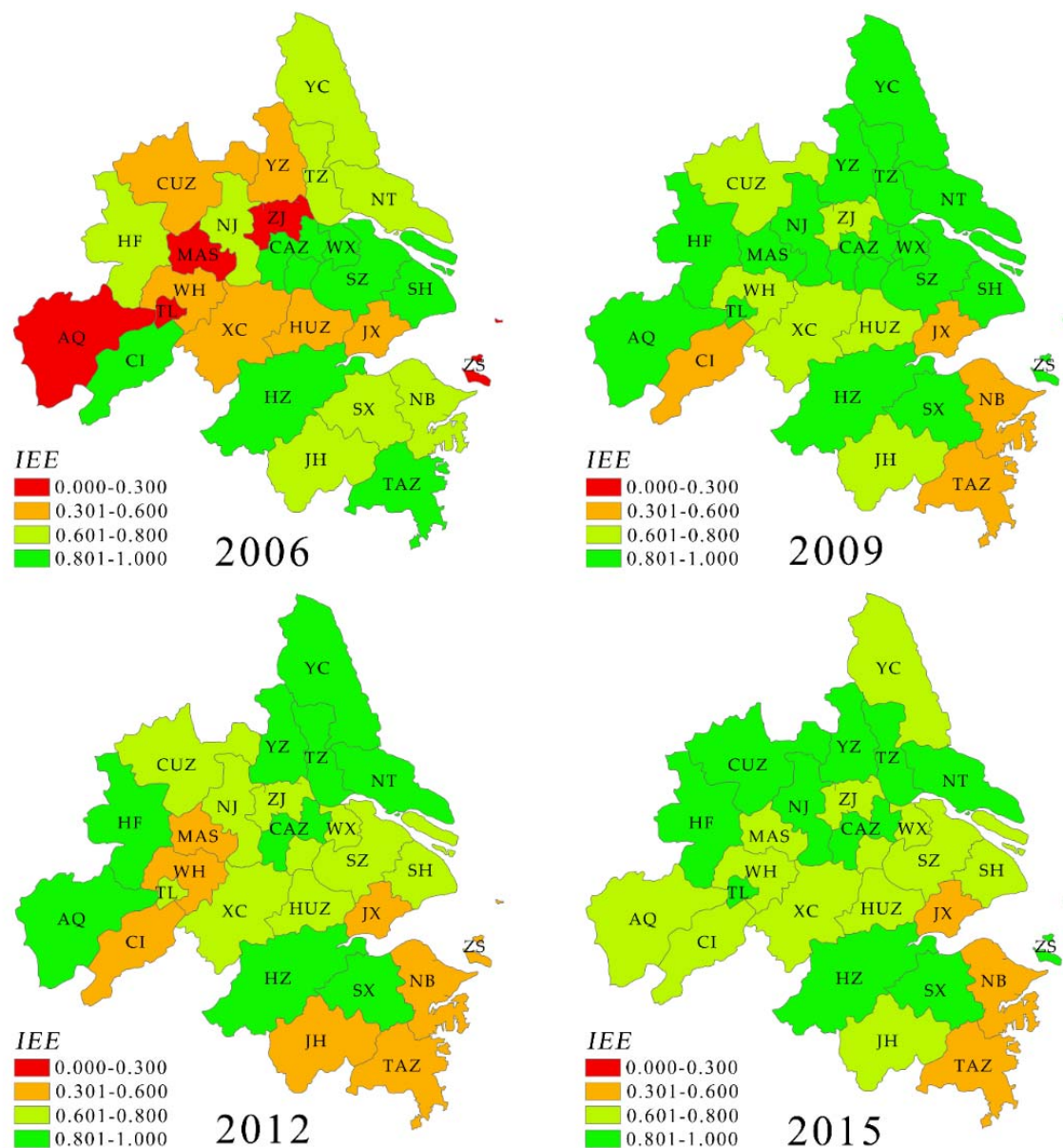


Figure 1. Spatial distribution of IEE in YRD.

3.2. Space-time Distribution of IEE

Figure 1 illustrates the distribution patterns of IEE in 2006, 2009, 2012 and 2015, which can help us to analyze the space-time distribution of IEE more intuitively. From this figure, we can observe that the

IEE scores in YRD generally show an upward trend. From the distribution of 2006, IEE is generally found with a descend tendency from east to west. As for 2009, 2012 and 2015, the distribution of IEE presents the characteristics of low in south, high in north. Obviously, the higher efficiencies are mostly concentrated in Yangzhou, Taizhou, Changzhou, Hangzhou and Shaoxing, while the lower ones are primarily concentrated in Anqing, Chizhou, Xuancheng, Maanshan, Zhenjiang, Taizhou and Ningbo, indicating the existence of a spatial cluster. More specifically, Changzhou and Hangzhou are the two cities with IEE above 0.8 throughout the period of 2006 to 2015. Yangzhou, Taizhou, Zhoushan, Tongling and Chuzhou are found with considerable growth during the study period. On the contrary, Taizhou and Chizhou both have decreased significantly in the same period, which may be the causes of the low efficiency in Zhejiang and Anhui.

4. Conclusions and Policy Implications

Based on the panel data of a municipality and 25 prefecture-level cities in YRD during 2006-2015, we investigate IEE and its space-time distribution by using the Shephard energy distance function and GIS visualization method, respectively. Our main conclusions are as follows: First, efficiency varies greatly due to the differences of economic development, government policy, energy consumption and other aspects in terms of the spatial distribution of the IEE. Additionally, from the distribution of regions with high IEE and low IEE, it can be seen that there is a spatial cluster. In terms of the trend of IEE changing with time, overall, efficiencies in YRD increase slowly in fluctuation during our study period.

On the base of above conclusions, the following suggestions are provided to improve IEE:

- Firstly, to guarantee a smooth and effective implementation of all measures taken to enhance IEE, it is necessary to develop relevant laws and regulations. While maintaining momentum in economy, YRD can improve its overall IEE, and achieve government's commitment to saving energy by taking appropriate measures.
- As mentioned above, there are disparities of IEE between various regions in YRD. The key to improve IEE is to balance economic growth and energy consumption. In this case, it is necessary to develop differentiated energy saving policies for different regions. Cities with higher levels of industrialization such as Ningbo and Suzhou, should develop high-technology industries energetically to promote the transformation of economic growth modes. Whereas cities with lower levels, such as Maanshan and Wuhu should enhance the level of industry concentration, which plays a positive role in forming scale effect and upgrading technological level. Additionally, cities with backward production technology should accelerate technology replacement to narrow disparities in industrial low-carbon technology.

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