Environmental Science and Pollution Research (2021) 28:66914–66929
https://doi.org/10.1007/s11356-021-15309-z

RESEARCH ARTICLE

Industrialization, urbanization, and carbon emission efficiency of Yangtze River Economic Belt—empirical analysis based on stochastic frontier model

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Received: 29 March 2021 / Accepted: 1 July 2021 / Published online: 8 July 2021

Abstract
Carbon emission efficiency directly determines the level of green economic development. Based on the panel data of China's Yangtze River Economic Belt (YEB) from 2008 to 2017, this paper uses the stochastic frontier analysis (SFA) model to analyze the overall carbon emission efficiency level, influencing factors, and changing trends, with a view to discussing the relationship between economic development and carbon emission efficiency. The results suggest, first, the overall carbon emission efficiency of the YEB is on an upward trend, but there is still much room for improvement. Second, the impact of industrialization and urbanization on carbon emission efficiency follows a U-shaped. As industrialization and urbanization progress, the impact on carbon emission efficiency shows a downward and then upward trend. Third, due to the rebound effect, technological progress has a slight negative impact on carbon emission efficiency. Energy consumption structure, government intervention, and foreign trade are all negative incentive factors. Therefore, efforts to improve carbon emission efficiency in the YEB should focus on transforming the economic growth model, adjusting the industrial structure, improving the energy consumption structure, and innovating green technology. The research results can provide a reference for the government policymakers to develop a green economy.

Keywords Carbon emission efficiency; · Industrialization; · Urbanization; · Stochastic frontier analysis; · Yangtze River Economic Belt

Introduction

Global warming has become a major global issue, and the increasingly serious greenhouse effect poses a serious threat to the survival and development of human society. Therefore, how to effectively control the emission of CO_2 and other greenhouse gases and slow down the process of global warming has received great attention from countries all over the world. Green and low-carbon development has become an inevitable option.

Industrialization and urbanization are considered to be important factors affecting carbon emissions. The mainstream view is that there is a positive correlation between industrialization and carbon emissions. Wang et al. (2020) believe that industrialization increases CO_2 emissions and leads to environmental deterioration. They found that in APEC countries, 1% development of industrialization has increased CO_2 emissions by 0.208%. Research by Liu and Bae (2018) suggests that in China, the increase is 1.1%. In the study of China's Southwest Economic Zone, the construction industry is considered the largest source of carbon emissions (Tian et al. 2019). Some scholars have come to different views. Xu and Lin (2015) believe that there is an inverted U-shaped relationship between industrialization and carbon emissions. In the early stage of industrialization, large consumption of fossil energy increased carbon emissions, but as technology advances, carbon emissions will change from rising to falling. In Nigeria, there is no significant relationship between industrialization and carbon emissions (Lin et al. 2015). There are three main views on the impact of urbanization on carbon emissions: (1) urbanization increases carbon emissions (Ali et al. 2019; Chen et al. 2020; Wang et al. 2019b. The central idea of this view is that the increase in population and energy consumption caused by urbanization

Responsible Editor: Ilhan Ozturk

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will lead to an increase in carbon emissions. (2) Urbanization reduces carbon emissions (Abdallh and Abugamos 2017; Zhao and Chen 2013). This is inconsistent with the findings of most studies. This view suggests that a higher urbanization level can promote technological advances and policy improvements in carbon abatement, thereby reducing carbon emissions to some extent. (3) There is a dynamic U-shaped relationship between carbon emission and urbanization (Shah et al. 2020; Xu et al. 2018). This view holds that different stages of urbanization have different impacts on carbon emissions.

Since China's economic reform and open up, the expansion of production by industrial enterprises has attracted the agglomeration of population and capital, thus promoting the development of urbanization. At the same time, urbanization has also created a favorable external environment for industrialization. Industrialization and urbanization promote each other and greatly contribute to economic and social development. However, over the past few decades, China's economic growth has come with a heavy environmental price tag. The extensive economic growth model has a serious impact on the sustainable development of the economy and society (Huang and Du 2020; Wen and Zhang 2020). China pledges to reach the CO_2 emission peak no later than 2030, and strive to achieve carbon neutrality by 2060. Therefore, the sustainable development of economy and environment has become a top priority and how to reduce carbon emission while promoting economic growth is a key issue (Chen et al. 2021; Fang et al. 2019).

In the context of a low-carbon economy, carbon emission efficiency has been a hot issue in recent years. As one of the vital pointers to assess carbon emissions, carbon emission efficiency can well reflect the level of green development. The research on carbon emission efficiency can be divided into three aspects: definition, measurement methods, and influencing factors. Some scholars defined carbon emission efficiency as CO_2 emissions per unit of GDP (Long et al. 2016; Vujović et al. 2018). This approach provides a good explanation of the relationship between economic development and CO_2 emissions, but ignores the important influence of energy. Wang and Zheng (2021) analyzed the energy intensity of the region and then evaluated the level of carbon emission efficiency based on the inevitable link between energy and CO_2 emissions. This indicator focuses more on the relationship between energy and economic growth, and can only qualitatively study carbon emission efficiency. Besides, some scholars have proposed other definitions (Du et al. 2018; Mohsin et al. 2019). These definition methods are easy to understand and use, but lack comprehensiveness.

Different methods are adopted for carbon emission efficiency calculations, data envelopment analysis (DEA), and stochastic frontier analysis (SFA) are the two most commonly used methods. Pérez et al. (2017) used DEA to analyze the carbon emission efficiency of Chilean manufacturing industry. Meng et al. (2016) used DEA to calculate the carbon emission efficiency of 30 provinces in China and proposed a gradual decline in efficiency from east to west. There are some defects in the DEA model, such as not considering random error interference and not being able to conduct the statistical test. SFA can solve this problem well. Sun et al. (2019) analyzed the carbon emission efficiency of China ' s industries based on SFA and concluded that there is little room for improvement in efficiency. Cui et al. (2019) applied SFA to analyze the total factor productivity of 36 industrial sectors in China. Moutinho et al. (2020) used both DEA and SFA to evaluate the ecological efficiency of Germany. Cai et al. (2019) combined these two models to analyze the carbon emission efficiency of 280 cities in China and concluded that the average efficiency is about 70–90%.

To have a more systematic and comprehensive understanding of carbon emission efficiency, various influencing factors are taken into account for research. Yan et al. (2017) researched the carbon emission efficiency of China's thermal power industry and concluded that technological advancement was the main driving force. In the analysis of manufacturing industry, Li and Cheng (2020) concluded that despite the increasing technological level, the low management efficiency still seriously hindered carbon emission efficiency. In Wang et al. (2019d)'s study, resource dependence is usually detrimental to the rationalization of industrial structure, which directly leads to lower carbon emission efficiency. Through the research on technological innovation in G20 countries, Erdoğan et al. (2020) found that innovation in the industrial sector can reduce carbon emissions, while innovation in the building sector conversely increases emissions.

Some studies have explored the impact of industrialization and urbanization on carbon emission efficiency. Huo et al. (2020) believed that for the construction industry, the increase in urban population and building area will have a negative impact on carbon emissions. Wang et al. (2019c) calculated the carbon emission efficiency of 31 provinces in China, and proposed that the improvement of urbanization level has a positive effect on efficiency. Sun and Huang (2020) found that the impact of urbanization on carbon emission efficiency is inverted U-shaped and there is a critical value for urbanization to promote carbon emission efficiency. Zhang et al. (2014) suggested that an increase in the proportion of the tertiary industry will help to reduce carbon intensity, while population urbanization will have a positive impact on carbon intensity. Li et al. (2012) analyzed the carbon emission data of 30 provinces in China from 1990 to 2010 and concluded that urbanization has the most significant impact on carbon emissions, while industrialization is not the main factor. Zhou et al. (2020) believed that there is an obvious dynamic imbalance between China ' s carbon emission efficiency and industrial structure upgrading. Furthermore, other scholars have conducted carbon emission efficiency studies on different urban agglomerations in China, such as Beijing-Tianjin-Hebei region (Wang et al. 2019a), Guangdong-Hong Kong-Macao Greater Bay area (Lin and Li 2020), etc.

Considering the above background, based on the panel data from 2008 to 2017, this paper uses the SFA model to study the 10-year data of 11 provinces in the YEB. The purpose of this paper is to discuss the relationship between economic development and carbon emission efficiency, as well as the possible influence of economic and social development, and puts forward some relevant recommendations.

The main contributions are as follows: (1) most studies on carbon emission efficiency adopt DEA, which has the disadvantage of not considering random error interference and failing to perform statistical test. This paper adopts the SFA model for empirical analysis, which can optimize the previous researches. (2) Different factors have different impacts. This paper selects industrialization level, urbanization level, technological progress, energy consumption structure, government intervention, and foreign trade as environmental variables, and quantifies the impact of each variable through the model. (3) To deeply study the impact of industrialization and urbanization on carbon emission efficiency, the square of industrialization and urbanization are introduced as new variables. (4) Most studies stick to national or provincial data. Taking the YEB as the research object, this paper can analyze regional characteristics in a more detailed way, which is conducive to adapting measures to local conditions.

Study area

Yangtze River Economic Belt (YEB), consisting of nine provinces and two municipalities[1] (Fig. 1), is a globally influential inland river economic belt that can effectively promote the coordinated development of the eastern, central, and western regions of China. As the economic center and the most densely populated region of China, the YEB has the greatest potential for economic growth, but also one of the regions with the most carbon emissions. YEB is facing the dual challenges of economic growth model transformation and carbon emission reduction. Therefore, it is necessary to know how industrialization and urbanization affect YEB's carbon emissions.

As a typical representative of watershed economy, the YEB has concentrated on a large number of major projects such as petrochemical, steel, mechanical and electrical, etc. These projects have contributed to the economic development of the YEB, but have also become a key source of environmental pollution. The industry structure of 11 provinces in the YEB in 2017 is shown in Fig. 2. The secondary industry accounts for a relatively high proportion, especially Anhui and Jiangxi, indicates that industry is an important way for the development of the YEB. Besides, Shanghai, Zhejiang, and, Jiangsu have a high proportion of the tertiary industry, with a reasonable industrial structure and a well-developed economy. This is mainly because the Yangtze River Delta gradually concentrating on the development of high-value-added emerging industries. On the whole, the YEB is in the transitional period between industrialization and post-industrialization, and the leading industries are gradually changing from heavy industries to high-tech industries and services.

Figure 3 shows the urbanization level of 11 provinces in the YEB from 2008 to 2017. The urbanization level of the YEB presents a ladder-like trend of high in the east and low in the west. The urbanization rate of the three provinces downstream is far higher than that in the midstream and upstream. Especially, Shanghai's urbanization rate is close to 90%, exceeding the average level of major developed countries in the world, Jiangsu and Zhejiang are also at a relatively high level. Besides, Hubei and Chongqing are also above the national average. Other provinces have relatively low urbanization levels, especially Guizhou, where the urbanization rate is 15% lower than the national average, the scale of urbanization is smaller and development is backward. On the whole, the YEB is in a stage of rapid urbanization, the rapid growth of the urban population and the shift in consumption structure will inevitably affect the environment.

Methods

CO_2 emissions

This paper uses the carbon emission estimation method proposed by the IPCC to calculate the CO_2 emission of different provinces in the YEB (IPCC 2006). The formula is expressed as:

$$CO_2 = \sum_{i=1}^{n} CO_{2,i} = \sum_{i=1}^{n} E_i \cdot LCV_i \cdot CC_i \cdot COR_i \cdot \frac{44}{12} \qquad (1)$$

where E_i is the consumption of energy i, LCV_i is the mean low calorific value, CC_i is the carbon content per unit calorific value, COR_i is the carbon oxidation rate, $\frac{44}{12}$ indicates the molecular weight ratio of CO_2 to carbon.

Stochastic frontier analysis model

Stochastic frontier analysis

SFA represents the deviation between actual output and optimal output. Aigner et al. (1977) and Meeusen and van

[1] In China, provinces and municipalities are all provincial-level administrative regions, so all use "province" in this paper.

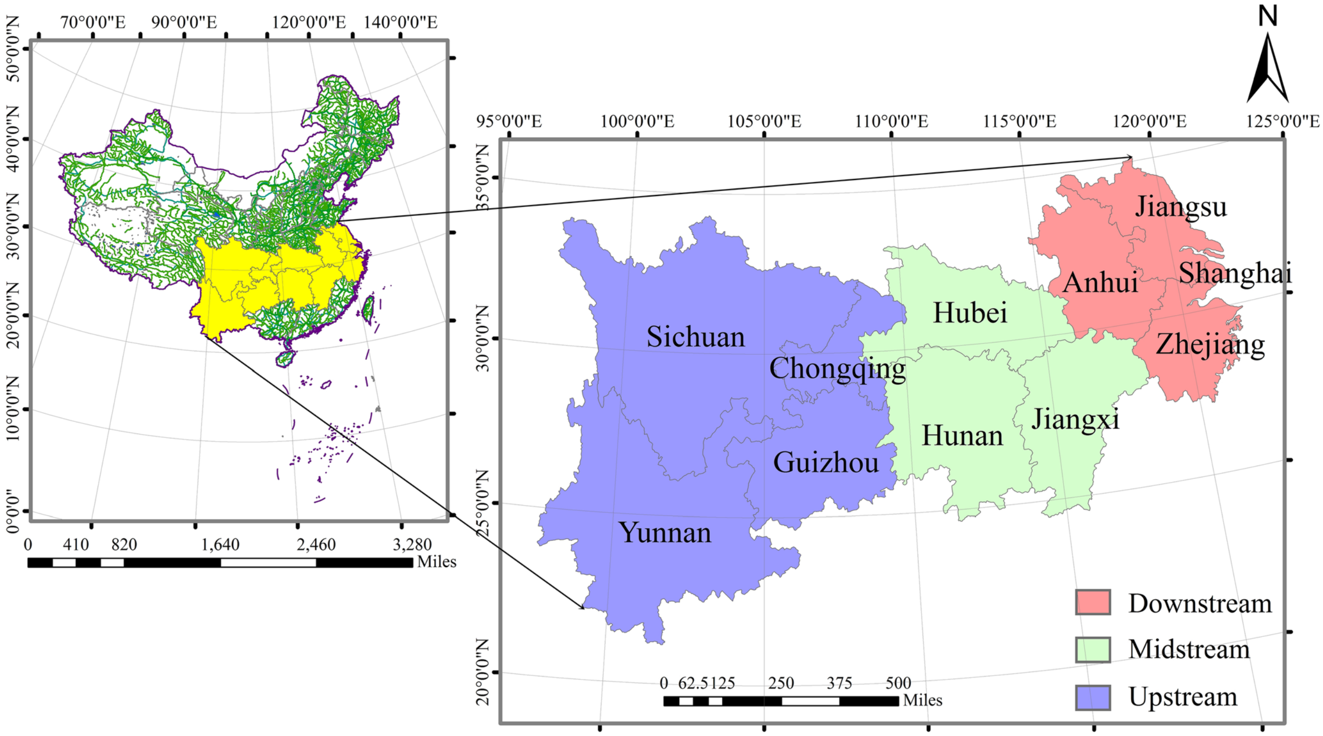


Fig. 1 Geographical location of the YEB

Den Broeck (1977) independently proposed stochastic frontier production function, the model is as follows:

$$Y_i = f(X_i, \beta)\exp(V_i - U_i), i = 1.2, \ldots, N \quad (2)$$

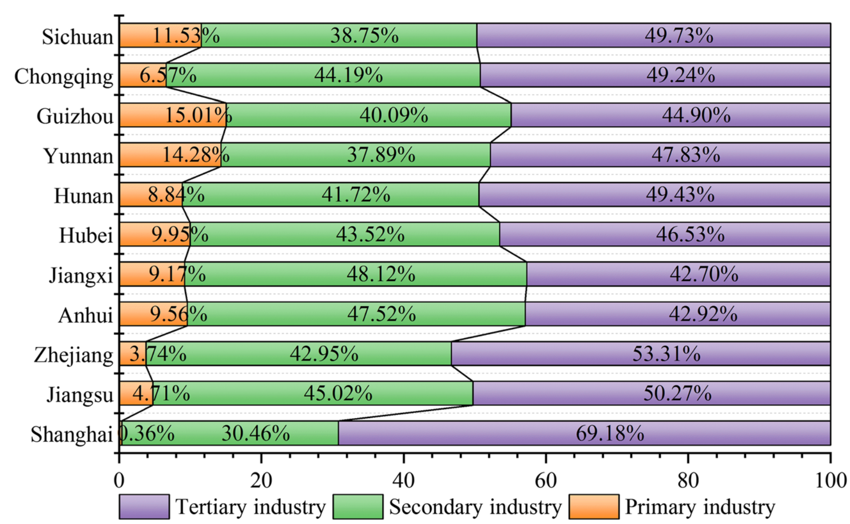
where X_i and Y_i respectively represent input and output, $f(X_i, \beta)$ is the production function, representing the frontier of production technology, β is a parameter vector, V_i is a random error term, U_i is a non-negative error term.

The above basic model has two shortcomings: (1) it does not involve time variables and is only applicable for cross-sectional data. (2) It is unable to study the influence of external factors on technical inefficiency. Two improved models Battese and Coelli (1992) and Battese and Coelli (1995) solve these problems well. This paper selects Battese and Coelli (1995) as the research model, which can not only study the carbon emission efficiency, but also analyze the influencing factors. The model is as follows:

$$\begin{cases} Y_{it} = \beta X_{it} + (V_{it} - U_{it}), i = 1, 2, \ldots, N, t = 1, 2, \ldots, T \\ V_{it} \sim N(0, {\sigma_V}^2) \\ U_{it} \sim N(m_{it}, {\sigma_U}^2) \\ m_{it} = Z_{it} \cdot \delta \end{cases} \quad (3)$$

where Z_{it} is the influencing factor of technical efficiency, δ is the parameter to be estimated, and m_{it} is the technical

Fig. 2 Industry structure of 11 provinces in the YEB in 2017



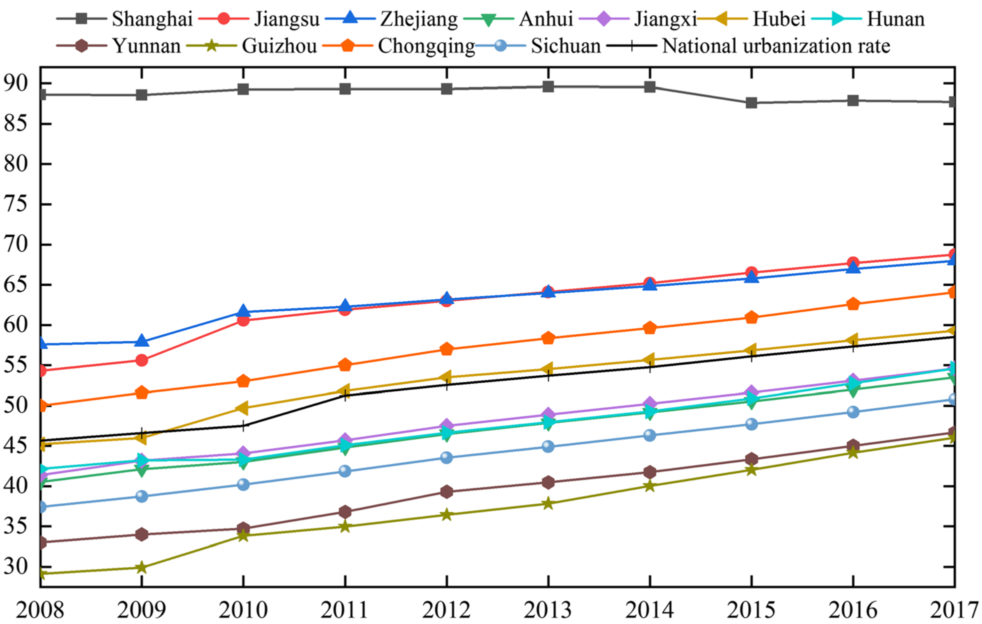


Fig. 3 The urbanization level of 11 provinces in the YEB from 2001 to 2017

inefficiency.

There are two main methods for testing the SFA model. (1) Variable-rate γ test. When γ approaches 1, the model is reasonable. (2) Unilateral likelihood ratio (LR) test. $H_0 : \gamma = 0$, $H_1 : \gamma \neq 0$, LR obeys the mixed χ^2 distribution, at the significance level α, if LR $\geq \chi^2_{\alpha, j}$, then H_0 is rejected. The formulas are as follows:

$$\gamma = \frac{\sigma_U{}^2}{\sigma_U{}^2 + \sigma_V{}^2} \quad (4)$$

$$LR = -2[lnL(H_0) - lnL(H_1)] \quad (5)$$

Variables

The output variable is the GDP. The input variables include capital, labor, and CO_2 emissions. CO_2 emissions is an undesired output, which is regarded as an input variable in this paper.

Carbon emission efficiency is influenced by various factors and the degree of influence is different. This paper selects industrialization level, urbanization level, technological progress, energy consumption structure, government intervention, and foreign trade as environmental variables.

(1) Industrialization level. The industrial structure reflects the level of economic development in a region and is closely related to carbon emission efficiency. The secondary industry, mainly industry and construction, consumes huge amounts of energy and therefore brings more carbon emissions. The tertiary industry is dominated by the service industry, with high added value and low carbon emissions.

(2) Urbanization level. The most striking feature of urbanization is the increase in urban population, which will lead to greater energy consumption. Meanwhile, the improvement of urbanization means the construction of large-scale infrastructure, both of which will generate more CO_2. On the other hand, urbanization can help reduce transaction costs and improve transaction efficiency, thereby generating agglomeration effects and improving production efficiency. Therefore, the urbanization level affects carbon emission efficiency.

(3) Technological progress. Technological progress can eliminate backward production capacity, further increase labor productivity, improve the energy consumption structure of provinces, and enhance energy efficiency.

(4) Energy consumption structure. More than 85% of China ' s CO_2 emissions are produced by fossil fuel combustion, with coal accounting for a significant portion. The carbon content of different energy sources is different, for the same amount of heat, coal has the highest carbon emissions. However, the consumption of clean energy will not produce carbon emissions. Therefore, the proportion of different energy consumption is also an important variable

(5) Government intervention. The corresponding policies proposed by the government may be beneficial to energy conservation and emission reduction. However, excessive government intervention may distort the market and affect the effective allocation of resources, thus affecting the level of production efficiency.

(6) Foreign trade. On the one hand, the development of foreign trade will result in the large-scale transfer of pollution-intensive industries to China, which will

increase carbon emissions. On the other hand, foreign trade will promote technological efficiency, which will have a positive impact on carbon emission efficiency.

Table 1 summarizes all the variables. All data are from the *China statistical yearbook*. All variable data related to the current price are adjusted to the constant price in 2008 by deflator.

Model construction

The Trans-log production function is a kind of variable elasticity production function model, which can better study the interaction between input factors. This paper selects trans-log production function to construct the following model:

$$\begin{aligned}\ln Y_{it} = {} & \beta_0 + \beta_1 lnK_{it} + \beta_2 lnL_{it} + \beta_3 ln\mathrm{CO}_{2it} \\ & + \beta_4 (lnK_{it})^2 + \beta_5 (lnL_{it})^2 + \beta_6 (ln\mathrm{CO}_{2it})^2 \\ & + \beta_7 lnK_{it} lnL_{it} + \beta_8 lnK_{it} ln\mathrm{CO}_{2it} \\ & + \beta_9 lnL_{it} ln\mathrm{CO}_{2it} + (V_{it} - U_{it}) \end{aligned} \tag{6}$$

Subtract $ln\mathrm{CO}_{2it}$ from both ends of formula (6) to obtain formula (7):

$$\begin{aligned}\ln(Y_{it}/\mathrm{CO}_{2it}) = {} & \beta_0 + \beta_1 lnK_{it} + \beta_2 lnL_{it} \\ & + (\beta_3 - 1) ln\mathrm{CO}_{2it} + \beta_4 (lnK_{it})^2 \\ & + \beta_5 (lnL_{it})^2 + \beta_6 (ln\mathrm{CO}_{2it})^2 \\ & + \beta_7 lnK_{it} lnL_{it} + \beta_8 lnK_{it} ln\mathrm{CO}_{2it} \\ & + \beta_9 lnL_{it} ln\mathrm{CO}_{2it} + (V_{it} - U_{it}) \end{aligned} \tag{7}$$

Besides, the SFA model can investigate the influence of non-efficiency factors. Put the six influencing factors mentioned above into the model to build model 1, expressed as follows:

$$\begin{aligned} U_{it} = {} & Z_0 + Z_1 lnI_{it} + Z_2 lnU_{it} + Z_3 lnT_{it} + Z_4 lnE_{it} \\ & + Z_5 lnG_{it} + Z_6 lnF_{it} \end{aligned} \tag{8}$$

The impact of each environmental variable on carbon emission efficiency is complex, which may be linear or double-sided. To explore whether industrialization and urbanization of different degrees has the same effect on output, the square of industrialization and urbanization are introduced as new influencing variables. Model 2 is shown in formula (9):

$$\begin{aligned} U_{it} = {} & Z_0 + Z_1 lnI_{it} + Z_{11} (lnI_{it})^2 + Z_2 lnU_{it} \\ & + Z_{22} (lnU_{it})^2 + Z_3 lnT_{it} + Z_4 lnE_{it} + Z_5 lnG_{it} \\ & + Z_6 lnF_{it} \end{aligned} \tag{9}$$

Results and discussion

Carbon emission assessment

First, this part analyzes the development trend of the total carbon emissions in the YEB. As shown in Fig. 4 (b), the total CO_2 emissions of the YEB showed a slow upward trend during 2008-2012, and fluctuated slightly after 2012, and then stabilized. In 2008, the total CO_2 emission of the YEB was 3.16 billion tons, reaching a peak of 4.17 billion tons in 2017, an increase of 32.23% over 2008. The CO_2 emissions of the YEB accounted for 30–40% of China ' s total CO_2 emissions, with a peak of 39.44% in 2011. In terms of per capita CO_2 emissions, the YEB increased rapidly in 2008–2011 and stabilized after 2011. In general, carbon emissions in the YEB have been effectively controlled after 2012.

Second, the development trend of carbon emissions in the provinces of the YEB is analyzed, as shown in Fig. 4 (a). In terms of total annual CO_2 emissions, Jiangsu has always been in a far leading position, and Zhejiang ranks second, which is

Table 1 Selection and definition of variables

Variables	Definition	Unit
Output	GDP	100,000,000 RMB
Capital (K)	Fixed asset investment	100,000,000 RMB
Labor (L)	Number of employees	10,000 person
CO_2 emissions (CO_2)	CO_2 emissions	10,000 tons
Industrialization (I)	The secondary industry output value/GDP	%
Urbanization level (U)	Urban population/total population	%
Technological progress (T)	Technology market turnover/GDP	%
Energy consumption structure (E)	Coal consumption/total energy consumption	%
Government intervention (G)	General public budget expenditure/GDP	%
Foreign trade (F)	Total import and export volume of foreign-invested enterprises/GDP	%

directly related to the relatively developed economy in the eastern region. In terms of CO_2 emissions growth, each province generally increased in 2008–2011, especially in Jiangsu, Zhejiang, and Hubei. After 2011, the emissions of each province were controlled, and some provinces even decreased slowly, indicating that these provinces have begun to attach importance to carbon emissions. Only Jiangsu still has a significant increase.

Third, there is spatial heterogeneity in carbon emissions, as shown in Fig. 5. Areas with higher carbon emissions are mainly distributed in the Yangtze River Delta in downstream, Hunan and Hubei in midstream, and Sichuan in upstream. The main reasons are the huge economic aggregate in the Yangtze River Delta, the developed heavy industry in Hunan and Hubei, and the vast area and large population in Sichuan.

Analysis of carbon emission efficiency and influencing factors

Measurement of carbon emission efficiency

The Frontier 4.1 program is used to calculate the carbon emission efficiency and influencing factors of the provinces in the YEB, and the results are in Table 2.

The γ is 0.626 of model 1 and 0.918 of model 2, indicating that the error of the frontier production function mainly comes from the inefficiency term, and the null hypothesis is rejected at the 1% significance level, so the SFA model is feasible. The main parameters have passed the t-test at different significance levels, so the model data fitting results are better.

Among them, the parameter estimation results of capital and labor are both greater than zero, indicating that the increase of capital and labor contributes to the improvement of carbon emission efficiency. The CO_2 emission parameter estimation result of model 1 is −1.367, and the parameter estimation result of model 2 is −1.435, both of which are less than zero, indicating that carbon emissions and efficiency move in the opposite direction.

The carbon emission efficiency of the provinces in the YEB are shown in Table 3 and Fig. 6. First, the average carbon emission efficiency of the YEB has been steadily improving, from 0.488 in 2008 to 0.571 in 2017, an increase of 17%. Meanwhile, the maximum and minimum values have also increased accordingly. Policy support, structural upgrading, and technological progress have all made great contributions. However, there is still much room for improvement, the average efficiency in 2017 was only 0.571, far below 1.

Second, large differences between provinces. Shanghai's carbon emission efficiency has always been far ahead, always greater than 0.7, and exceeded 0.9 in 2016 and 2017, which is inseparable from Shanghai's developed economy and technology. Zhejiang ranks second and can maintain above 0.6. Due to the geographical location of Yunnan and Guizhou are not dominant, the economic development and carbon emission efficiency are poor. In 2017, the carbon emission efficiency of Guizhou and Yunnan were 121.7% and 106.7% lower than that of Shanghai, respectively. The efficiency of each province varies greatly, with a tendency for the differences to increase. In 2008, the difference between the highest and lowest carbon emission efficiency was 0.351 but in 2017, this value reached 0.505.

Third, there is spatial heterogeneity in the carbon emission efficiency, as shown in Fig. 7. The eastern region

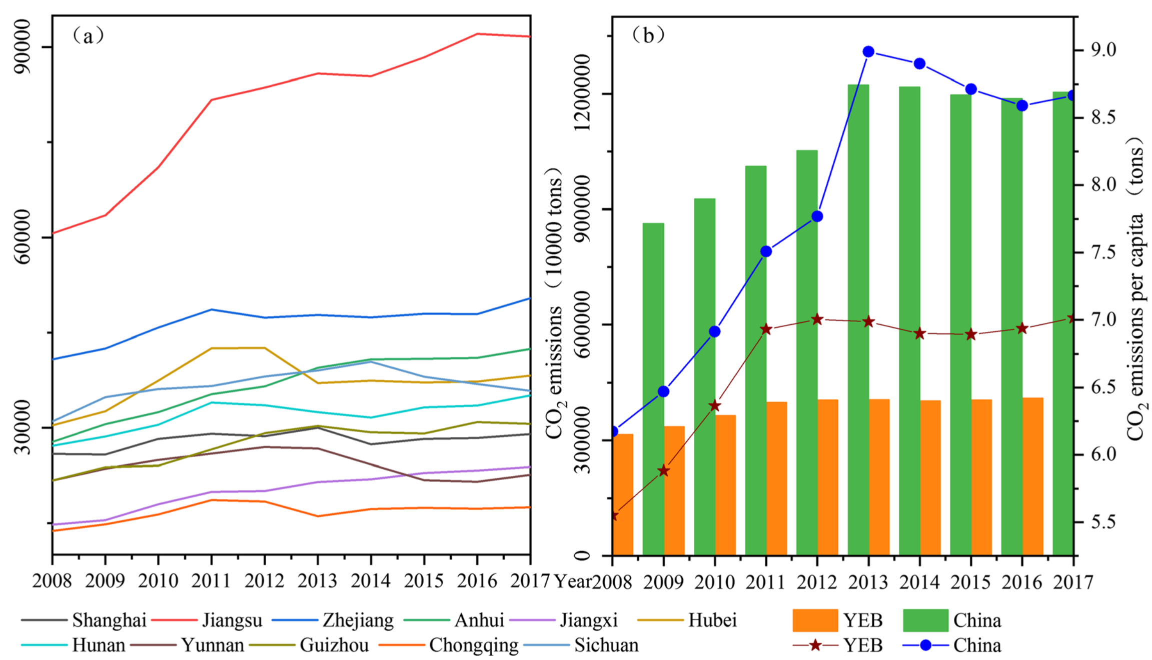


Fig. 4 Carbon emissions in the YEB from 2008 to 2017: (a) Provinces in the YEB; (b) YEB and China

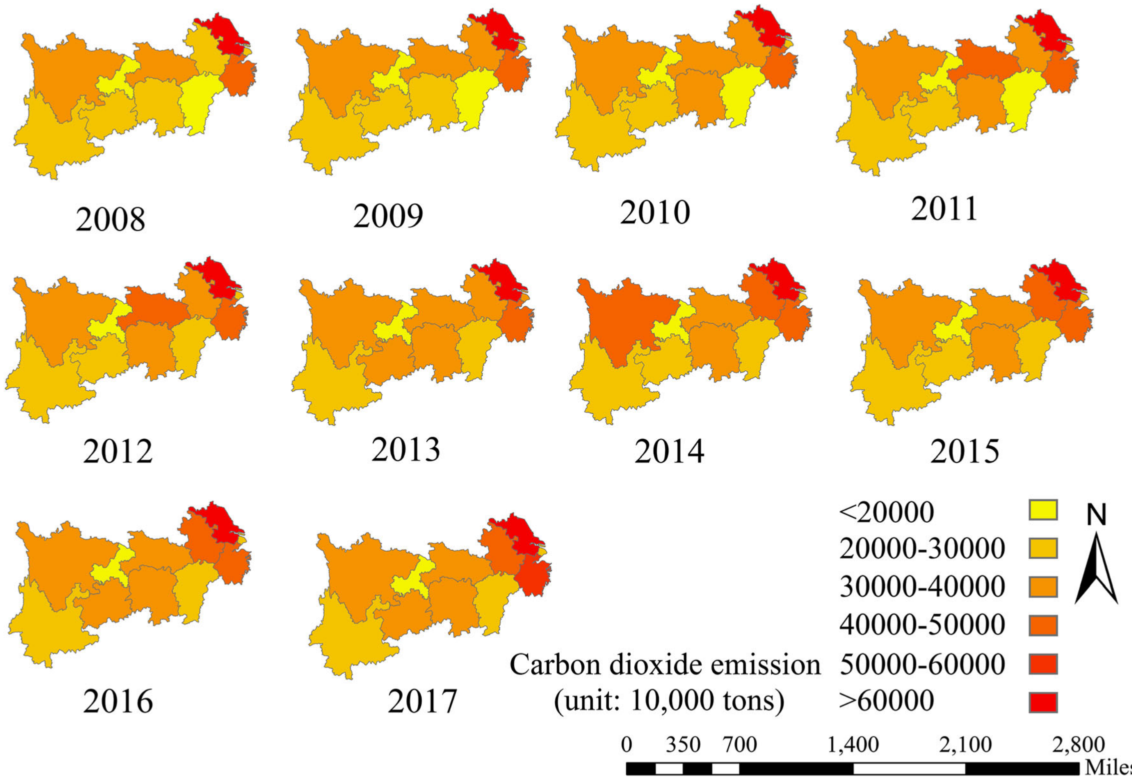


Fig. 5 Spatial distribution of carbon emissions

(downstream) is generally better than the western region (upstream), and coastal cities are generally better than inland cities, which is related to the imbalance of regional development. The economic and technological level of the eastern region and coastal cities is significantly higher than that of other regions. Since 2015, the carbon emission efficiency of the central and western provinces, Hubei, Hunan, and Sichuan, also exceeded 0.5, reaching a relatively high level, which is closely related to the rapid development of the three major provincial capitals, Wuhan (Hubei) Changsha (Hunan), and Chengdu (Sichuan) in recent years.

Analysis of influencing factors

(1) Industrialization level. The coefficient of industrialization level is 0.202 in model 1, this means that industrialization has a dampening effect on carbon emission efficiency. The secondary industry, dominated by industry and construction, is the main sector of energy consumption and also the main sector of using coal energy, which will increase carbon emissions.

To explore whether the effect on efficiency varies by industrialization level, the square of industrialization is taken as a new variable. The coefficient Z_{11} is −0.792 in model 2, indicating that the industrialization level has a U-shaped effect on carbon emission efficiency. This conclusion is different from many studies, but with the support of Xu and Lin et al. (2015). This is because the extensive industrial growth model in the early stage of industrialization has a large demand for energy consumption but low energy-saving technologies, which has led to an increase in CO_2 emissions and caused great damage to the ecological environment. However, when industrialization reaches a certain level, as people's requirements for environmental quality continue to rise, investment in environmental protection continues to increase, energy efficiency in the industrial production process is continuously improved, and the industrial structure is continuously optimized. These have a technical and structural effect on carbon emissions, resulting in improved carbon emission efficiency. Therefore, even if the proportion of the second industry increases, carbon emission efficiency can still be improved as long as the output performance of industrialization exceeds the carbon emission performance. It is suggested in model 1 that industrialization level restrains the carbon emission efficiency of the YEB, indicating that the effect of industrialization on efficiency is in the left half of the U-shaped function, and the level of industrialization still needs to be improved. YEB's economic development is on the rise, industry is still the pillar. However, as an important scientific research area in China, especially Shanghai, Zhejiang, and Jiangsu, which are located in the first echelon of scientific research, a large number of emerging technologies have been put into industrial production to create more GDP while minimizing carbon

Table 2 Parameter estimation results

Estimated variables	Parameter	Model 1		Model 2	
		Coefficient	T-statistic	Coefficient	T-statistic
Constant term	β_0	10.296***	3.022	10.133**	2.001
lnK	β_1	0.031***	5.441	0.791	0.830
lnL	β_2	2.435***	2.936	1.467	1.286
$lnCO_2-1$	β_3	−2.367***	−2.638	−2.435*	−1.869
$(lnK)^2$	β_4	0.005	0.134	0.001	0.017
$(lnL)^2$	β_5	−0.406***	−3.820	−0.339**	−2.103
$(lnCO_2)^2$	β_6	0.071	0.862	0.083	0.683
lnK*lnL	β_7	0.069	0.868	0.045	0.378
$lnK*lnCO_2$	β_8	−0.163	−0.216	−0.062	−0.482
$lnL*lnCO_2$	β_9	0.225	1.393	0.256	1.156
Constant term	Z_0	−1.467*	−1.720	−20.069***	−5.585
Industrialization	Z_1	0.202***	2.768	6.243***	4.358
	Z_{11}			−0.792***	−4.120
Urbanization	Z_2	−0.558***	−8.746	3.181**	2.290
	Z_{22}			−0.464***	−2.673
Technology	Z_3	0.046***	4.337	0.027**	2.189
Energy structure	Z_4	0.665***	6.410	0.517***	2.781
Government	Z_5	0.194***	5.694	0.263***	3.846
Foreign trade	Z_6	0.042**	2.031	0.044	1.386
σ^2		0.003***	7.563	0.003***	7.780
γ		0.626***	2.620	0.918***	10.113
log likelihood function		171.005		173.454	
LR		188.490		193.389	

Note: *, **, and *** represent significant levels at 10%, 5%, and 1% respectively

emissions. Meanwhile, in most coastal cities, the output value of the tertiary industry is gradually surpassing that of the secondary industry. With the continuous growth of the tertiary industry, carbon emission efficiency will also be increased.

(2) Urbanization level. The urbanization level coefficient of model 1 is −0.558, which indicates that for every unit increase in urbanization level, the carbon emission efficiency increases by 0.558 units. The effect of

Table 3 Results of carbon emission efficiency

Provinces	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	Average
Shanghai	0.726	0.760	0.794	0.775	0.784	0.796	0.842	0.852	0.903	0.920	0.815
Jiangsu	0.564	0.568	0.577	0.568	0.570	0.575	0.593	0.594	0.611	0.648	0.587
Zhejiang	0.593	0.597	0.631	0.652	0.646	0.642	0.645	0.638	0.653	0.671	0.637
Anhui	0.412	0.403	0.425	0.442	0.440	0.417	0.421	0.423	0.438	0.458	0.428
Jiangxi	0.457	0.452	0.462	0.482	0.476	0.460	0.459	0.459	0.472	0.483	0.466
Hubei	0.485	0.471	0.486	0.485	0.490	0.500	0.509	0.505	0.523	0.543	0.500
Hunan	0.492	0.478	0.501	0.516	0.531	0.535	0.552	0.547	0.565	0.548	0.527
Yunnan	0.389	0.371	0.374	0.402	0.397	0.397	0.418	0.427	0.435	0.445	0.406
Guizhou	0.375	0.365	0.376	0.369	0.366	0.365	0.378	0.392	0.402	0.415	0.380
Chongqing	0.444	0.445	0.453	0.452	0.472	0.485	0.483	0.504	0.538	0.566	0.484
Sichuan	0.433	0.401	0.434	0.484	0.490	0.481	0.490	0.516	0.538	0.581	0.485
Average	0.488	0.483	0.501	0.512	0.515	0.514	0.526	0.532	0.553	0.571	0.519

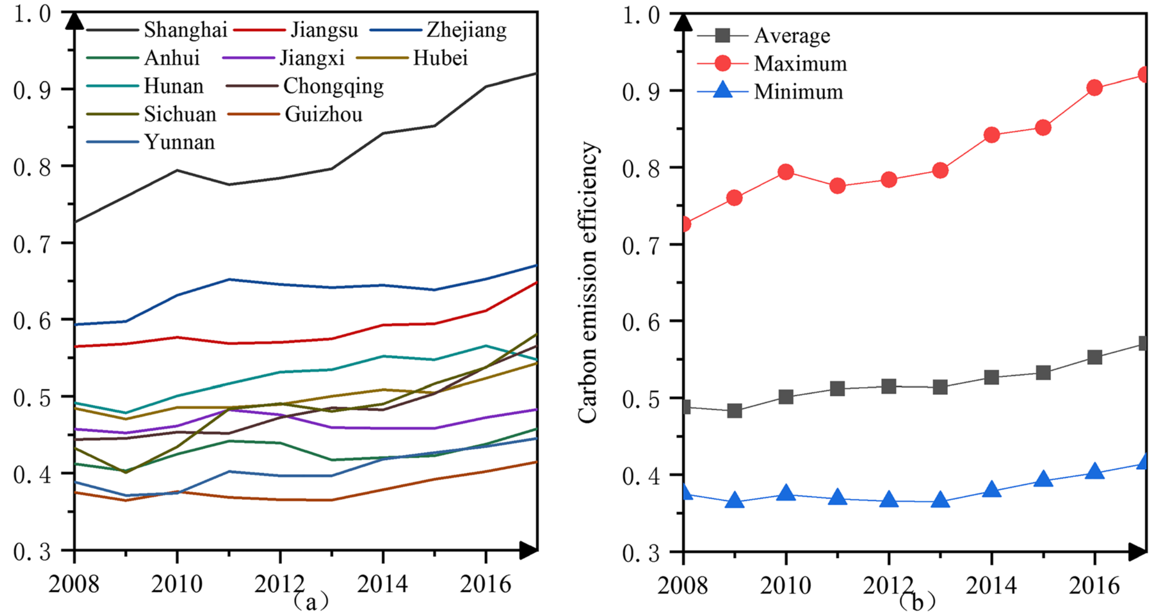


Fig. 6 Results of carbon emission efficiency

urbanization on the improvement of productivity and the optimal allocation of resources outweighs the effect of increasing carbon emissions.

To further study the impact of different urbanization levels on carbon emission efficiency, this paper takes the square of urbanization as a new variable and analyzes it through model

2. The coefficient of the square of urbanization is −0.464, indicating a U-shaped relationship between urbanization level and carbon emission efficiency. This result is different from Sun and Huang et al. (2020), but in line with Li et al. (2018). The development of urbanization is still largely driven by industrialization, which increases energy consumption and causes more carbon emissions to a certain extent. However,

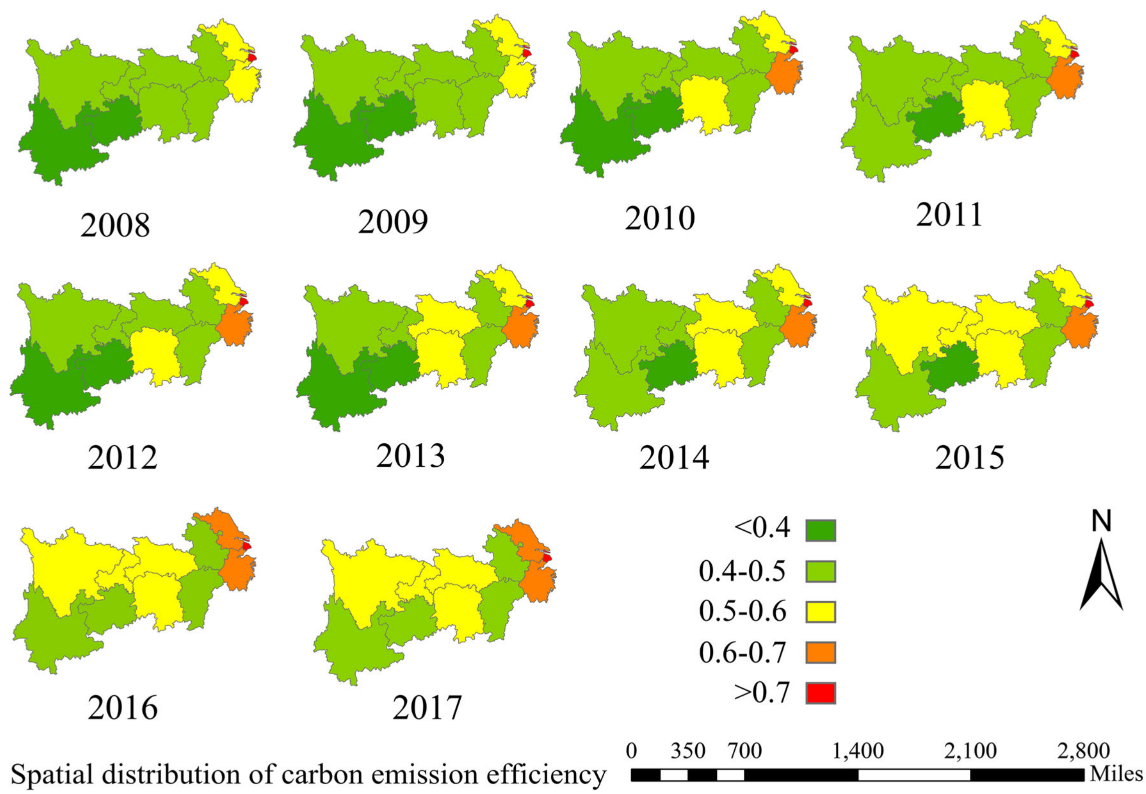


Fig. 7 Spatial distribution of carbon emission efficiency

once the urbanization reaches a certain level, urbanization will have a positive impact on carbon emission efficiency. The continuous improvement of human resources and technology level brought by the development of urbanization has led to the effect of productivity enhancement exceeding the effect of carbon emissions increase. The results of model 1 suggest that urbanization can promote carbon emission efficiency in the YEB, which indicates that the relationship between urbanization and carbon emission efficiency can be represented by the right half of the U-shaped function, and that the urbanization level has exceeded the lowest point of the U-shaped line. As an important riverine economic belt, the YEB's urbanization level is relatively mature, especially the urbanization level of the eastern provinces is at the forefront of China. Local people are also more aware of energy conservation and emission reduction, and the production process and lifestyle are also shifting to a conservation-oriented approach. Therefore, although the impact of urbanization on carbon emission efficiency is two-way, it is more positive.

(3) Technological progress. The parameter estimation result of technological progress is 0.046 in model 1 and 0.027 in model 2, which shows that technological progress has a slight negative impact on carbon emission efficiency. This result is different from Xu and Lin (2017), but in line with Wang et al. (2019e) and Huang et al. (2020). The rebound effect can explain this phenomenon well. Technological progress can improve energy efficiency and production level, and play a positive role in reducing carbon emissions. However, the reduction of the cost may lead to more production, and more production will consume more energy, which harms carbon emission reduction. Besides, technological advances have changed people ' s lifestyles. The use of a large number of household appliances and electronic products has greatly increased the consumption of electrical energy, which indirectly increases carbon emissions. At present, the YEB is in the stage of rapid development, technological progress is bound to serve larger production, so the positive effects of technological progress are offset by the rebound effect, even weaker than the rebound effect.

(4) Energy consumption structure. The coefficient is 0.665 in model 1 and 0.517 in model 2, indicating that the increase in coal consumption is not conducive to carbon emission efficiency. The unit carbon emissions of different energy sources are different. Coal belongs to the primary energy with a high carbon emission coefficient, which is 1.2 times and 1.6 times of the same amount of oil and natural gas. During the 14th Five-Year Plan period, China will set stricter carbon emission targets, strengthen coal consumption control, increase support for the development of renewable energy, and continue to accelerate the transition to a low-carbon economy and society. Therefore, the YEB needs to adjust the energy consumption structure and gradually transition from coal to clean energy, so as to improve the carbon emission efficiency.

(5) Government intervention. The parameter estimation coefficient is 0.194 in model 1 and 0.263 in model 2, indicating that the government intervention is a negative factor. China has not yet achieved a complete market economy; government intervention still has a certain impact on the allocation of resources. But sometimes the direction of government intervention is not the direction guided by the market, which causes a waste of resources and is not conducive to energy conservation and environmental protection. Therefore, excessive government intervention will reduce carbon emission efficiency. In addition, the Chinese government regards industrialization as an important means of vigorously developing the economy, and sometimes has to tolerate pollution.

(6) Foreign trade. The estimated parameter value of foreign trade is 0.042 in model 1 and 0.044 in model 2, indicating that trade openness has a slight negative impact on efficiency. This is consistent with the results of "pollution shelters" proposed by scholars in other studies. Trade openness measures the comprehensive level of imports and exports, YEB is a major component of China ' s import and export trade. When imports increase, developed countries move pollution-intensive companies to China, thereby increasing carbon emissions; when exports develop rapidly, a large amount of product production will lead to implicit energy consumption and carbon emissions.

Robust test

Adjust the study period to 2012–2017, and get the regression results shown in Table 4. The regression results show that after adjusting the study period, the coefficients of each variable have little change. In general, the estimation results in this paper are reliable.

Comparative analysis of SFA model and DEA model

The general understanding of carbon emission efficiency assumes that smaller inputs and larger outputs lead to higher carbon emission efficiency. This is consistent with the desired output, but does not meet the characteristics of the undesired output. The traditional DEA model cannot handle the efficiency measurement with undesirable output. Therefore, many scholars treat the undesired output as input in the DEA model. To explore the advantages and disadvantages of SFA model and DEA model in efficiency measurement. This paper uses the DEA-BCC model (carbon emission as input) and the SBM-DEA model (carbon emission as undesired output) to measure the carbon emission efficiency of 11 provinces and compared with the results of the SFA model. The results of BCC model and SBM model are shown in Appendix Tables 5 and 6 respectively.

Figure 8 shows the comparison of the average carbon emission efficiency of provinces under the three models. It can be seen that the calculation results of the DEA model are generally larger than the results of the SFA model. Analysis of all 110 sets of data: (1) The Wilcoxon matched-pairs signed-ranks test is used to analyze whether the DEA model will improve carbon emission efficiency compared to the SFA model. The median of the SFA model, BCC model, and SBM model is 0.485, 0.876, and 0.596 respectively. The test results show that $Z=-9.104$, $P<0.001$ (SFA and BCC), $Z=-8.954$, $P<0.001$ (SFA and SBM), rejecting the null hypothesis at the 1% significance level, indicating that the carbon emission efficiency calculation result of the DEA model is higher than that of the SFA model. Therefore, compared with the SFA model, the DEA model may overestimate the carbon emission efficiency of the YEB. (2) The coefficient of variation of the three models are calculated, which are 0.236 (SFA model), 0.177 (BCC model), and 0.337(SBM model). Compared with the BCC model, the measured results of the SFA model have a higher degree of dispersion and have a stronger ability to judge the carbon emission efficiency of each province. Compared with the SBM model, the SFA model is less likely to have extreme values.

In short, the results of the SFA model are generally lower and more stable than those of the DEA model, which is consistent with the measurement principles of the two models. Compared with the DEA model, the SFA model uses the production function to construct the production frontier, and uses the conditional expectation of the technical inefficiency term as the technical efficiency. The results are less affected by the special points, and there is no case that the efficiency values are all 1. DEA model does not take into account the impact of error, efficiency is directly determined by the input-output variables. The SFA results are absolute efficiency and the DEA results are relative efficiency. SFA model is more reliable and comparable.

Table 4 Results of robust test

Estimated variables	Parameter	Model 1		Model 2	
		Coefficient	T-statistic	Coefficient	T-statistic
Constant term	β_0	20.152***	20.290	18.060***	9.708
lnK	β_1	0.051***	−6.307	0.497***	−3.088
lnL	β_2	5.802***	4.638	5.905***	5.153
$\ln CO_2-1$	β_3	−1.442	−1.258	−3.765***	−3.900
$(\ln K)^2$	β_4	0.303***	4.734	0.390***	5.826
$(\ln L)^2$	β_5	−0.360*	−1.652	−0.038	−0.180
$(\ln CO_2)^2$	β_6	0.036	−0.283	0.364***	2.738
lnK*lnL	β_7	0.299**	−2.285	−0.304	−1.597
$\ln K*\ln CO_2$	β_8	−0.150	1.047	−0.269	−1.621
$\ln L*\ln CO_2$	β_9	0.136	0.745	0.166	−0.630
Constant term	Z_0	−4.995***	−4.197	1.260	1.074
Industrialization	Z_1	0.548***	4.878	3.824	−1.232
	Z_{11}			−0.465	1.003
Urbanization	Z_2	−0.292*	1.686	3.258**	−2.160
	Z_{22}			−0.375	1.502
Technology	Z_3	0.041**	2.044	0.125	−1.455
Energy structure	Z_4	0.142***	9.686	0.728	−1.640
Government	Z_5	0.568***	6.135	0.316	1.525
Foreign trade	Z_6	0.092**	−2.198	0.002	−0.017
σ^2		0.004***	4.549	0.007***	3.916
γ		0.999***	837081.760	0.223*	1.697
log likelihood function		96.733		71.954	
LR		58.958		94.006	

Note: *, **, and *** represent significant levels at 10%, 5%, and 1% respectively

Table 5 Carbon emission efficiency in DEA-BCC model

Provinces	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	Average
Shanghai	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
Jiangsu	1.000	1.000	1.000	1.000	1.000	1.000	0.966	0.989	1.000	1.000	0.996
Zhejiang	0.968	0.928	0.997	1.000	1.000	1.000	0.986	1.000	0.985	0.976	0.984
Anhui	0.615	0.601	0.647	0.704	0.713	0.903	0.884	0.858	0.850	0.873	0.765
Jiangxi	0.871	0.849	0.865	0.890	0.910	0.865	0.836	0.822	0.809	0.812	0.853
Hubei	0.688	0.681	0.705	0.729	0.775	0.884	0.877	0.905	0.903	0.923	0.807
Hunan	0.783	0.782	0.866	0.886	0.952	1.000	1.000	1.000	1.000	1.000	0.927
Yunnan	0.568	0.495	0.484	0.553	0.566	0.700	0.719	0.714	0.708	0.714	0.622
Guizhou	0.655	0.544	0.464	0.516	0.522	0.683	0.704	0.719	0.705	0.726	0.624
Chongqing	0.776	0.757	0.798	0.812	0.874	1.000	0.962	1.000	1.000	1.000	0.898
Sichuan	0.748	0.696	0.784	0.874	0.904	0.862	0.824	0.891	0.897	0.951	0.843
Average	0.788	0.758	0.783	0.815	0.838	0.900	0.887	0.900	0.896	0.907	0.847

Conclusion and policy recommendations

Conclusion

To study the impact of industrialization and urbanization on the carbon emission efficiency of the YEB, the data from 2008 to 2017 are selected, and first, the current status of carbon emissions in the YEB is analyzed. Second, the SFA model is used to study and measure the carbon emission efficiency of 11 provinces, and the influence of industrialization, urbanization, and other factors is analyzed. The study found:

First, the overall carbon emission efficiency of the YEB is on an upward trend, but there is still much room for improvement. There are regional differences in the carbon emission efficiency, with large and increasing differences between provinces. The difference between the highest and lowest efficiency of each province changed from 0.351 in 2008 to 0.505 in 2017. Besides, in terms of spatial distribution, the carbon emission efficiency of eastern coastal provinces is significantly higher than that of western provinces.

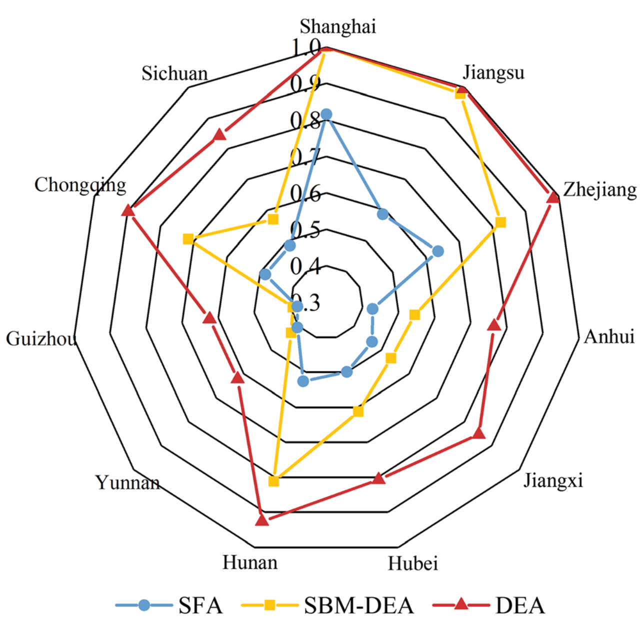


Fig. 8 Comparison of three models

Second, the impact of industrialization and urbanization on carbon emission efficiency is U-shaped, with the impact of industrialization is in the decreasing part of the U-shaped line, while the urbanization is in the increasing part. This is consistent with the staged characteristics of China ' s industrialization and urbanization process, and is compatible with the economic development of 11 provinces in the YEB. In the early stages of industrialization, economic development was the first goal, and environmental protection was ignored. In the early stage of urbanization, the population in urban areas increased sharply, resulting in a low carbon emission efficiency. With the enhancement of environmental protection awareness and the development of energy-saving and emission reduction technologies, there is a turning point in the curve, which changes from decreasing to increasing. The driving effect of industrialization and urbanization on economic development exceeds their carbon emission effect, and carbon emission efficiency is gradually increasing.

Finally, technological progress, energy consumption structure, government intervention, and foreign trade are negatively related to carbon emission efficiency. Among them, the weak negative impact brought about by technological progress can be explained by the rebound effect. The influence of these four factors on efficiency cannot be ignored. The results can provide theoretical reference for policy-makers to make reasonable emission reduction targets and plans.

Policy recommendations

The fundamental purpose of this paper is to better understand the current status of carbon emission efficiency in the YEB, find out the problems in emission reduction, and improve

Table 6 Carbon emission efficiency in SBM-DEA model

Provinces	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	Average
Shanghai	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
Jiangsu	1.000	1.000	1.000	1.000	1.000	1.000	0.871	0.929	1.000	1.000	0.980
Zhejiang	0.770	0.695	0.691	1.000	1.000	1.000	0.713	1.000	0.681	0.712	0.826
Anhui	0.472	0.448	0.454	0.546	0.547	0.611	0.614	0.602	0.572	0.584	0.545
Jiangxi	0.540	0.494	0.491	0.575	0.590	0.582	0.552	0.517	0.500	0.501	0.534
Hubei	0.576	0.532	0.513	0.553	0.615	0.660	0.701	0.687	0.617	0.667	0.612
Hunan	0.630	0.570	0.572	0.637	0.714	1.000	1.000	1.000	1.000	1.000	0.812
Yunnan	0.425	0.378	0.357	0.415	0.430	0.456	0.472	0.474	0.436	0.434	0.428
Guizhou	0.410	0.369	0.339	0.359	0.377	0.402	0.418	0.428	0.405	0.424	0.393
Chongqing	0.513	0.487	0.469	0.510	0.576	1.000	0.610	1.000	1.000	1.000	0.717
Sichuan	0.541	0.460	0.487	0.596	0.656	0.590	0.589	0.595	0.574	0.612	0.570
Average	0.625	0.585	0.579	0.654	0.682	0.755	0.685	0.748	0.708	0.721	0.674

carbon emission efficiency. To develop a low-carbon economy and achieve emission reduction targets, this paper proposes the following policy recommendations:

(1) For the industrialization

- Optimize stock and control increment. For existing enterprises, optimize the allocation of industrial production, continuously promote various new technologies, and gradually realize the intensification and clean development. For that newly added high-pollution and high-energy-consumption enterprises, the market access threshold should be raised.
- Optimize the industrial structure. First, phase out high-polluting industries. Second, continuously optimize capital-intensive and technology-intensive industries. Then, promote industrial innovation and absorption of advanced technologies. Finally, accelerate industrial transformation, take the road of new industrialization, and vigorously develop high-tech industries and services.
- Optimize energy consumption structure. The proportion of coal consumption in the YEB is not high, but there is still room for improvement. As the world ' s largest water energy river, the provinces in the YEB have abundant water resources, and the government should make full use of the regional advantages. Meanwhile, coastal provinces, Shanghai, Jiangsu, and Zhejiang also have abundant ocean and wind resources. The use of these clean energy sources can promote carbon emission efficiency.

(2) For the urbanization

- Optimize population structure. YEB has a large population and a high proportion of urban population. It is necessary to pay attention to the changes in the urban population, promote the movement of the urban and rural populations within a reasonable range. Besides, in the process of urbanization, huge population resources should be transformed into more effective human capital, therefore, the government should invest more in education to improve the quality of citizens.
- Rational urban layout planning. Pay attention to low-carbon transportation development, accelerate the construction of a green public transportation system, and promote the use of new energy vehicles. Focus on low-carbon building development, use environmentally friendly materials in buildings, avoid blind expansion, and preserve urban green spaces.

(3) Increase technical research and development support. The government should increase investment in low-carbon technologies through special funds, financial allocations, etc. Promoting technological innovation and development through key technology research, to improve energy efficiency.

(4) In addition, reasonably develop foreign trade and scientifically introduce foreign capital can also improve carbon emission efficiency. The government should reduce intervention and give full play to the role of the market. The 14th Five-Year Plan mentions that building a national carbon market is an important step in implementing the CO_2 peak target and the vision of carbon neutrality. Therefore, a carbon trading market should be gradually established and improved to facilitate the rationalization of carbon emissions.

At the same time, this study also has some limitations. (1) Due to the lag of data, this paper cannot reflect the current status of carbon emission efficiency in the YEB with the latest data. (2) Only six influencing factors are selected in this paper, which cannot fully reflect the effects of all influencing factors on YEB ' s carbon emission efficiency. The impact on carbon emission efficiency is complex, and there may be other factors. (3) Some limitations of the SFA model may affect the results to a certain extent. In the future, different estimation methods can be selected for research and comparison.

Acknowledgements This work was supported by the National Natural Science Foundation of China (No. 71471061). Thanks to Ms. Qianqian Xu for her help on the data.

Author contribution Caiqing Zhang: methodology, resources, writing—review & editing. Panyu Chen: conceptualization, software, validation, investigation, data curation, writing—original draft.

Data availability All data are from the *China statistical yearbook.*

Declarations Not applicable.

Ethics approval and consent to participate Not applicable.

Consent for publication Not applicable.

Competing interests The authors declare no competing interests.

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