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Original Research

An Investigation on Measuring Carbon Emission Efficiency and Its Influencing Elements in the Yangtze River Economic Belt —Based on the SBM-Malmquist-Tobit Model

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Abstract

First, this paper adopts the SBM-Malmquist model, which includes undesired output indicators, to examine the carbon emission efficiency of 11 provinces and municipalities in the Yangtze River Economic Belt from 2004 to 2021 in both a static and dynamic way. Subsequently, this paper utilizes the Tobit regression model to investigate the variables that impact carbon emission efficiency. The empirical results indicate that: (1) Although the data indicates a gradual rise in the carbon emission efficiency of the provinces and municipalities within the Yangtze River Economic Belt, the total level of carbon emission efficiency remains relatively low. (2) Urbanization level and technological progress contribute significantly to carbon efficiency, while two factors, the opening-up level and energy structure, reduce it.

Keywords: carbon emission efficiency, SBM-Malmquist, Tobit regression model, Yangtze River Economic Belt

Introduction

As human society continues to develop, the demand for energy gradually increases in all countries. Against the backdrop of deepening economic globalization, the increasingly serious problem of energy security and the pressure of economic transformation and upgrading are forcing countries to promote energy transformation to accomplish sustainable development within the energy industry. However, energy technology breakthroughs and energy structure transitions are not achieved in one fell swoop. The existence of uncertainties, such as intensified global energy competition and changes in the energy supply pattern, has made it more difficult for countries to establish efficient, secure, clean, and low-carbon energy supply and consumption systems. At present, fossil energy is still the main source of energy consumed by countries around the world. Data from the 2023 Statistical Yearbook of World Energy shows that the consumption of energy is growing in the vast majority of countries around the world. In 2022, total global coal power generation was 10.32 trillion kWh, an increase of one percentage point from last year. China, India, and the United States were the top three energy-consuming countries. Coal-fired power generation in mainland China was 5.4 trillion kWh, up 1.3% year-

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on-year, and accounted for 52.3% of the world's share, ranking first globally.

The Yangtze River Economic Belt is an important part of the "three supporting belts" that are reshaping China's economic geography. This region not only shoulders the burden of economic transformation and upgrading but also plays a pioneering role in promoting environmentally friendly development models. Its practical effects have important reference value for sustainable development practices in other regions of China. Between 2016 and 2023, Chinese leaders organized four important meetings on the development of the Yangtze River Economic Belt. These meetings emphasized the dual strategic responsibility of synchronizing environmental protection and economic and social development. As a result of this series of high-level meetings, the strategic blueprint for the Yangtze River Economic Belt has become clearer and more solid, with its core focus on achieving sustainable economic and social development while ensuring a steady improvement in ecological and environmental quality.

The Yangtze River Economic Belt has the dual advantages of a high population and a large economy. The region is not only an important driver of China's economic growth but also a key area for promoting a low-carbon transition [1]. However, with the acceleration of urbanization, the region is facing unique and severe pressure. The Yangtze River Economic Belt has high energy consumption for industrial production and high carbon emission intensity. At the same time, the imbalance of internal development and differences in industrial structure exacerbate carbon emission pressures. In addition, the Yangtze River Economic Belt spans several provinces and municipalities, making inter-regional synergistic development more difficult. In terms of carbon emission reduction, increasing interregional policy coordination and responding to the pressure on carbon emissions are critical problems that have to be addressed immediately. Therefore, based on measuring carbon emission efficiency, further analyzing the multifaceted influencing factors behind it will not only help to promote the synergistic development of the Yangtze River Economic Belt in a green and low-carbon manner but also provide empirical evidence and decision-making references for China to effectively achieve the "dual carbon" goal.

Literature Review

Carbon efficiency is the amount of carbon dioxide emitted per unit of economic output. It reflects the carbon intensity of economic activity and the efficiency of energy use. In areas such as industrial production and energy consumption, carbon efficiency can assess the impact of environmental externalities on economic activities. Improving carbon efficiency means that while reducing the environmental load, it can reduce production costs and promote the transformation of enterprises to an environment-friendly production model. Therefore, improving carbon emission efficiency is one of the important conditions for realizing sustainable regional development.

The majority of early studies were aimed at estimating the overall carbon dioxide emissions from a given area, with some scholars successively proposing the concepts of "carbon index", "energy intensity", "energy productivity", and "energy efficiency" on the basis of thermodynamics, physics, and economics [2]. However, earlier studies were mostly based on an analysis of "single-factor energy efficiency indicators", such as measuring carbon efficiency using the "gross domestic product/carbon emissions" ratio as an indicator. This approach is straightforward to compute and comprehend and offers an estimate of a nation's or region's energy efficiency. However, due to the overly homogeneous measurement indicators, neglecting the linkage with carbon emissions and external factors such as economic development and resource inputs, some scholars have questioned the validity of the efficiency levels derived from this methodology [3, 4]. To address the shortcomings of the above studies, researchers have gradually included GDP, energy inputs, and other factors into the scope of indicators, trying to evaluate carbon emission efficiency from a variety of angles to make the data more objective.

To optimize resource allocation, some researchers have used "total factor" indicators to assess carbon emission efficiency. Farrell first introduced carbon emissions into the input and output indicators of the DEA model, defining the technical efficiency of production in terms of total factor inputs and optimal outputs, in that case, as carbon emission efficiency [5]. Iftikhar et al. developed a system of total factor indicators with undesired outputs (carbon emissions) and used the DEA-SBM model to analyze the efficiency of energy and carbon emissions in major economies [6]. In the radial model of DEA, inputs and outputs need to be adjusted in equal proportions. This approach ignores the optimization potential of slack variables, which are effectively compensated by the SBM model. This not only involves the improvement of slack variables but also incorporates the optimization objective of undesired output reduction into the function construction [7-9]. This method has been widely used in environmental and energy efficiency evaluation scenarios [10-14]. With the deepening of research, scholars have combined the SBM model with the Malmquist index analysis method, analyzing efficiency from both dynamically and statically oriented perspectives, which makes the research on efficiency more comprehensive [15-17].

With the acceleration of urbanization and industrialization, China's demand for energy has been growing rapidly, and traditional fossil energy sources have reached large-scale consumption, which has resulted in a slew of environmental pollution issues. Therefore, regional energy issues have progressively been the attention of Chinese researchers [18, 19].

However, most of the existing studies conducted by Chinese scholars have focused on the more developed coastal regions, better resource endowment, and similar dependence on energy consumption, and the findings are not universally applicable to other regions [20-23]. The vastness of the Yangtze River Economic Belt, which has uneven regional economic growth and highly diverse industrial structures, makes measuring energy consumption and carbon emission efficiency more difficult.

Materials and Methods

Econometric Models

SBM Model

First, the DEA-SBM model must generate a production possibility set. Presuming that n decision-making units (DMUs) exist, i.e., DMU_j (j=1,2, …, n). Each DMU has m inputs, s_1 types of outputs, and s_2 undesirable outputs; then the matching vector can be shown as follows: $x \in R_m, y^g \in R_{s1}, y^b \in R_{s2}$. The relevant matrix is defined as follows: $X=(x_{ij}) \in R_{m*n}$, $Y^g=(y_{ij}^g) \in R_{s1*n}$, and $Y^b=(y_{ij}^b) \in R_{s2*n}$, where X, Y^g, and Y^b are all greater than zero.

The set of production possibilities of the model satisfies the bounded and closed sets, and the desired outputs and inputs are freely disposable, assuming a zero combination of desired and undesired outputs, as well as the joint weak disposability of outputs. To express the efficiency of any $DMU(x_0,(y_0^g,y_0^b))$, the SBM model is constructed using indicator ρ:

$$\min \rho = \frac{1-\frac{1}{m}\sum_{i=1}^{m}\frac{s_i^-}{x_{i0}}}{1+\frac{1}{s_1+s_2}\left[\sum_{r=1}^{s_1}\frac{s_r^g}{y_{r0}^g}+\sum_{r=1}^{s_2}\frac{s_r^b}{y_{r0}^b}\right]}$$

$$s.t.\begin{cases} x_0 = X\lambda + s^- \\ y_0^g = Y^g\lambda - s^g \\ y_0^b = Y^b\lambda + s^b \\ s^-, s^g, s^b, \lambda \ge 0 \end{cases} \tag{1}$$

In Equation (1), the weight vector is λ; s^- denotes the excessive input of factors; s^g denotes insufficient desirable outputs; and s^b denotes excessive undesired outputs. ρ is the DMU's efficiency value, which is between 0 and 1. The objective function ρ is strictly monotonically decreasing where s^-, s^g, s^b are concerned. When $\rho=1$, the DMU is most efficient and reaches the efficient frontier, where s^-, s^g, s^b are all 0. That is, there isn't any redundancy in the inputs or outputs. If $\rho<1$ implies a loss of efficiency in the DMU, the orientation of the efficiency improvement can be analyzed by calculating the ratio of the slack values to the corresponding raw data values, i.e., the input-output redundancy ratio.

Malmquist Index Model

Carbon emissions show significant dynamic change characteristics. To deeply analyze the trajectory of its efficiency evolution, this paper adopts the Malmquist index model as an analytical tool, aiming to accurately reveal the dynamic evolution of carbon emission efficiency over time. This method was used in conjunction with the DEA approach by Fare et al. to assess the dynamic productivity of the decision unit across time, i.e., the Malmquist index value [24]. Later, Chung et al. integrated the index model with the directional distance function that included undesired outputs, making the model even more applicable [25]. This paper will employ the notion of the directional distance function to define the input vector, desired output vector, and undesirable output vector as x, y, and b, accordingly. With variable returns to scale, (x^t, y^t, b^t) and $(x^{t+1}, y^{t+1}, b^{t+1})$ denote the input and output combinations of DMUs in period t and period t+1, respectively, while D_0^t and D_0^{t+1} denote the distance function between period t and period t+1.

$$TFP = M_t^{t+1} = \left[\frac{1+D_0^t(x^{t+1},y^{t+1},b^{t+1})}{1+D_0^t(x^t,y^t,b^t)} \times \frac{1+D_0^{t+1}(x^{t+1},y^{t+1},b^{t+1})}{1+D_0^{t+1}(x^t,y^t,b^t)}\right]^{\frac{1}{2}} \tag{2}$$

Total factor productivity (TFP) represents changes in the efficiency of decision-making units from period t to period t+1. In the event that TFP is greater than 1, it means an upward trend in carbon emission efficiency, and vice versa, it indicates a downward trend in efficiency. TFP consists of two core elements: the technical efficiency change index (EC) and the technical progress change index (TC). To further refine it, the EC can be decomposed into the pure technical efficiency change index (PEC) and the scale efficiency change index (SEC), which together reflect the changes in technical efficiency in different dimensions. The relationship between the indexes is expressed in Equations (3) and (4).

$$EC_t^{t+1} = \left[\frac{1+D_0^{t+1}(x^{t+1},y^{t+1},b^{t+1})}{1+D_0^t(x^t,y^t,b^t)}\right] = PEC * SE \tag{3}$$

$$TC_{\mathrm{t}}^{t+1}=\left[\frac{1+D_0^t(x^t,y^t,b^t)}{1+D_0^{t+1}(x^t,y^t,b^t)}\times\frac{1+D_0^t(x^{t+1},y^{t+1},b^{t+1})}{1+D_0^{t+1}(x^{t+1},y^{t+1},b^{t+1})}\right] \quad (4)$$

Tobit Model

The Tobit regression model is mainly aimed at models with truncated or restricted dependent variables. The use of traditional linear regression models when there are upper or lower bounds on the dependent variable can lead to biased and inaccurate findings. The carbon emission efficiency values that have been measured above are all in the range of 0-1, which qualifies for the use of the Tobit regression model. The model is constructed as in Equation (5).

$$Y_{\mathrm{it}}=\begin{cases}Y_{\mathrm{it}}^*=\beta_0+\sum_{k=1}^{n}\beta_k X_{\mathrm{it}}+\varepsilon_{\mathrm{it}},Y_{\mathrm{it}}^*>0\\ 0,Y_{\mathrm{it}}^*<0\end{cases} \quad (5)$$

Y_{it} is the dependent variable; β_0 denotes a constant term; β_{k} represents the estimated coefficients for the independent variables; X_{it} is the independent variable; and $\varepsilon_{\mathrm{it}}$ is the random error term.

Indicators and Data Sources

Efficiency Indicator System

Regional development varies significantly due to factors such as geographical location, resource endowment, and governmental support. Therefore, there is no uniform measurement standard for regional carbon emission efficiency, and different indicators can lead to large differences in the evaluation results. However, as research has progressed, it has become a consensus among researchers to consider environmental pollutants as undesired outputs, and they have argued that energy consumption is usually accompanied by emissions of environmental pollutants, i.e., desired and undesired results coexist. Based on the consideration of various social and economic factors, this paper selects the following series of input and output indicators, aiming to accurately assess the performance of carbon emission efficiency within the Yangtze River Economic Belt region (see Table 1).

(1) Capital stock. Given that direct access to capital stock data is not possible, the relevant studies can only measure or draw on the data in the existing literature. Based on Goldsmith (1951) and Zhang (2004), the capital stock of the decision unit is calculated at constant prices in this study using the perpetual inventory method [26, 27]. The specific formula is shown in Equation (6).

$$Q_{\mathrm{it}}=Q_{\mathrm{it-1}}(1-\delta_{it})+I_{\mathrm{it}} \quad (6)$$

Current and prior period capital stocks are denoted by Q_{it} and $Q_{\mathrm{it-1}}$, respectively. The rate of capital stock depreciation is indicated by δ_{it}, where δ_{it} = 9.6%. I_{it} is the gross fixed capital formation in year t.

(2) Human capital. The human capital variable is affected by several factors, and since data on labor time inputs and labor remuneration are not accurately available, in this paper, the number of people employed at the end of the year is used as an indicator of labor inputs.

(3) Energy consumption. Different kinds of energy with different heat contents have been converted into "10,000 tons of standard coal" to determine the energy usage of different regions with a uniform caliber. Energy consumption is used as an input indicator for carbon emission efficiency measurement.

(4) Gross Domestic Product (GDP). GDP is a crucial indicator for evaluating a nation's or region's economic status and degree of development, and GDP is used as the desired output in the majority of studies on carbon emission efficiency.

(5) CO_2 emissions. CO_2 is the main pollutant produced by energy consumption, and in this paper, we use CO_2 emissions as the undesired output. Currently, it is not possible to obtain data directly on CO_2 emissions. The IPCC country Greenhouse Gas Inventory, issued by the IPCC, is by far the most generally acknowledged and utilized guide to GHG emission inventories at the country level, encompassing six primary GHG categories, the majority of which are CO_2. The formula is shown in Equation (7).

$$E_{CO_2}=\sum_{i=1}^{n}E_{CO_2}=\sum_{i=1}^{n}E_i\times NCV_i\times CC_i\times COF_i\times\frac{44}{12} \quad (7)$$

Where E_{CO_2} denotes the CO_2 emissions of each type of fossil energy, E_{i}, NCV_{i}, CC_{i}, and COF_{i} are the consumption of the ith type of fossil energy, using the average low-level heat production, the carbon content of energy, and the carbon oxidation factor, respectively. In this paper, seven fossil energy sources, namely coal, coke, petrol, paraffin, diesel, fuel oil, and natural gas, are used to calculate CO_2 emissions.

Influencing Factor Index System

In light of the economic and social context, economic theories, and data accessibility of the provinces and municipalities situated along the belt, this paper has selected measured carbon emission efficiency as the dependent variable, with six variables, including government intervention and urbanization level, as the independent variables (see Table 2).

The industrial structure rationalization index (IND) is an index reflecting the coordination between

Table 1. Definition and description of indicators.

Indicator type	Indicator	Unit	Mean	Std. Dev.	Min	Max
Input	Capital stock	Hundred million yuan	56333	47002	5019	246249
	Human capital	Ten thousand persons	3067	1153	837	4998
	Energy consumption	Ten thousand tons	12702	6274	3009	32672
Desirable output	Gross domestic product	Hundred million yuan	23642	19885	1678	116364
Undesirable output	CO2 emissions	Ton	21743	10346	6806	56248

Table 2. Variables and symbolic meaning.

Variable type	Variable	Symbol	Definition
Dependent variable	Carbon emission efficiency	TE	Efficiency values measured above
Independent variable	Government intervention	GOV	Fiscal expenditure/regional GDP
	Urbanization level	URB	Urban population/year-end total population
	The opening-up level	OPE	Foreign direct investment/ regional GDP
	Energy structure	ES	Carbon dioxide consumption/ total energy consumption
	Technological progress	TP	Number of patent authorizations/regional GDP
	Industrial structure	IND	Industrial structure rationalization index

industries in a region, which can be used to reflect the degree of dependence between industries and assess the allocation of resources between different industries. This paper adopts the calculation method based on the Theil Index to construct this index to measure the degree of rationalization of the industrial structure. The expression is:

$$TL = \sum_{i=1}^{n} \left(\frac{Y_i}{Y} \right) \ln \left(\frac{Y_i}{L_i} \Big/ \frac{Y}{L} \right) \tag{8}$$

TL is the Theil Index that measures the degree of industrial rationalization. The larger the value of *TL*, the more the industrial structure deviates from equilibrium and the more irrational it becomes. *i* denotes industry; *n* denotes industry sector; *Y* denotes output value; and *L* denotes the number of employed persons.

Data Sources

The relevant data for the 2004–2021 sample period were gathered from national economic and social development statistical bulletins, provincial and local statistical yearbooks, and the China Energy Statistical Yearbook.

Results and Discussion

Efficiency Analysis

Static Efficiency Analysis

The efficiency values of various types of carbon emissions in 11 provinces and municipalities along the belt are shown in the Table 3.

The Yangtze River Economic Belt can be divided into three economic development regions: the eastern region, represented by Shanghai, Jiangsu, and Zhejiang, which has a strong economy; the central region, consisting of four provinces represented by Anhui Province, which has the second strongest economy; and the western region, represented by Chongqing, which has a weaker economy. As shown in Table 3, from 2004 to 2021, the average values of TE, PTE, and SE in the Yangtze River Economic Belt are 0.2939, 0.5194, and

Table 3. The average carbon emission efficiency along the Yangtze River Economic Belt.

Province	Technical efficiency (TE)	Pure technical efficiency (PTE)	Scale efficiency (SE)
Shanghai	0.5133	0.8791	0.5814
Jiangsu	0.3788	0.5219	0.7541
Zhejiang	0.3521	0.4677	0.7680
Downstream Average	0.3705	0.5634	0.6867
Anhui	0.2378	0.3849	0.6432
Jiangxi	0.2657	0.5881	0.4862
Hubei	0.2773	0.4002	0.6961
Hunan	0.2860	0.4108	0.7083
Midstream Average	0.2764	0.4664	0.6302
Chongqing	0.2799	0.6684	0.4282
Sichuan	0.2562	0.3796	0.6972
Guizhou	0.1816	0.5575	0.3684
Yunnan	0.2039	0.4550	0.4660
Upstream Average	0.2304	0.5151	0.4899
Overall Average	0.2939	0.5194	0.5997

0.5997. As may be observed, the overall carbon emission efficiency remains rather poor. Shanghai has the highest mean values of all 11 provinces and municipalities.

From a basin perspective, the downstream region shows higher average values of TE, PTE, and SE. This reflects that the downstream provinces and municipalities have optimized their resource allocation more significantly, achieved lower CO_2 emission intensities, and occupied a more cutting-edge position in the process of low-carbon transition.

Fig. 1 illustrates the overall changes in carbon emission efficiency indicators in the Yangtze River Economic Belt from 2004 to 2021, showing a steady upward trend amidst fluctuations. From this trend, it can be seen that the efficiency of carbon emission management in the region is gradually improving, and despite fluctuations in the process, it is generally moving in the direction of greater efficiency. Specifically, the technical efficiency (TE) of the upstream shows a steady increase over time; the pure technical efficiency (PTE) displays a "U"-shaped shift, with a modest drop followed by a constant gain; and the scale efficiency (SE) is maintained at a relatively stable level after a certain period of increase. Trends in individual efficiency values are more similar in the midstream and downstream regions, with technical efficiency and pure technical efficiency showing a gentle increase, while scale efficiency fluctuates and decreases and then remains at a more stable level.

Dynamic Efficiency Analysis

The dynamic efficiency results are summarized in Table 4.

Table 4 shows that from 2004 to 2021, the calendar year average of the TFP is 1.1068, indicating that the total factor ecological rate is on an upward trend with increasing returns to scale. Concerning other indices, the technical efficiency index fell by 1.65%, the technical progress index rose by 13.31%, the pure technical efficiency index fell by 1.29%, and the scale efficiency index rose by 0.1 %. This demonstrates that the Yangtze River Economic Belt's increased carbon emission efficiency is mostly attributable to technological innovation.

Regression Results Analysis

The Tobit regression findings are presented in Table 5.

The regression coefficient of government intervention (GOV) is 0.171; however, this coefficient does not meet the statistical test of a 10% significance level. This indicates that although government intervention shows some positive tendency to improve carbon emission efficiency, its actual effect is not enough to constitute a statistically significant effect. This is because reducing carbon emissions and improving environmental standards is a long process. In the past few years, although local governments have increased their intervention in energy saving and emission reduction, the effect is not obvious due to the late start

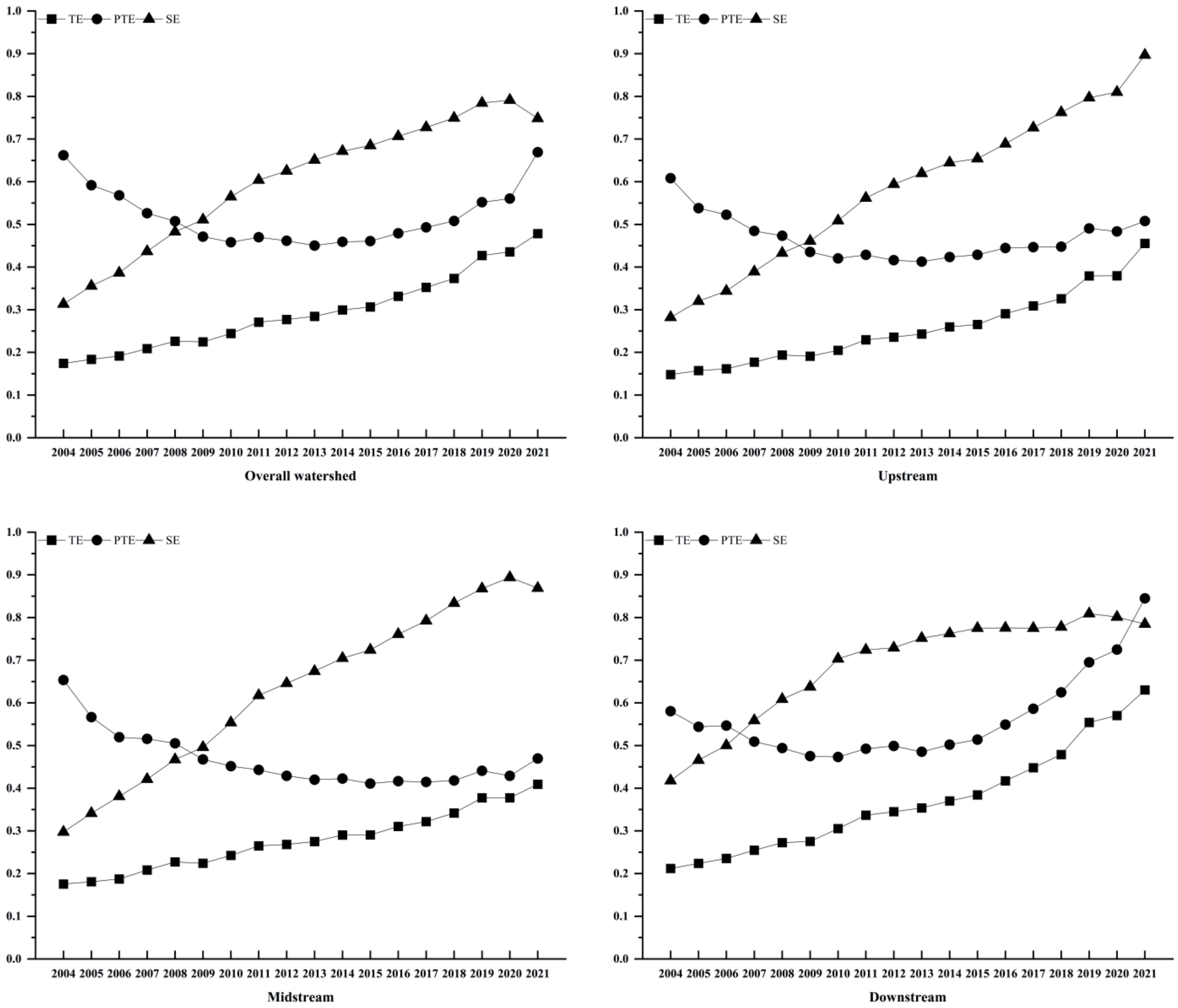

Fig. 1. Decomposition chart of carbon emission efficiency in various watersheds of the Yangtze River Economic Belt.

and imperfect funding/policy system. Additionally, the non-significance of the variable is due to limitations in the choice of indicators. Government intervention in carbon emissions is reflected not only in financial support but also in the legal system, policy guidance, and tax support for the management of carbon emissions trading, which cannot be quantified for the time being.

The variable of urbanization level (URB) has a coefficient of 0.450, passing the 1% significance test. This indicates that the greater degree of urbanization in the cities along the Yangtze River Economic Belt can considerably increase the efficiency of carbon emissions. Currently, China is undergoing large-scale urbanization changes. However, in 2021, the overall urbanization rate of the Yangtze River Economic Belt was still far below that of developed countries. This suggests that the Yangtze River Economic Belt is currently under relatively little environmental strain and that carbon emission efficiency can still be increased. Besides, to balance environmental and economic benefits, the Chinese government proposed "New Urbanization" in 2007, emphasizing that the concept and tenets of ecological civilization may be included in the entire urbanization process. The proposal calls for an intensive, intelligent, low-carbon, and green urbanization path.

It has been shown that the opening-up level (OPE) significantly affects a region's carbon emission efficiency. The empirical evidence shows that the coefficient of OPE is -12.202, passing the 1% significance test. This means that the Yangtze River Economic Belt's increased openness will reduce the capacity to emit carbon emissions. At the initial stage of investment attraction, some domestic and foreign enterprises have gained insight into the economic-oriented preferences of local governments and have taken advantage of the policy concessions offered by local governments to transfer primary industries that were originally energy-consuming and high-emission to the Yangtze River Economic Belt, which has increased the pressure on local carbon emissions. Inland provinces opened up to the outside world relatively late and developed slowly. Therefore, they usually adopt more aggressive foreign

Table 4. Malmquist index and decomposition along the Yangtze River Economic Belt.

Period	Total factor productivity	Technical efficiency change index (EC)	Technological progress change index (TC)	Pure technical efficiency change index (PEC)	Scale efficiency change index (SEC)
2004-2005	1.0654	0.9094	1.2106	0.9701	0.9329
2005-2006	1.1293	0.9738	1.1596	0.9899	0.9844
2006-2007	1.2041	1.0502	1.1490	1.0050	1.0453
2007-2008	1.1549	1.0253	1.1275	1.0020	1.0233
2008-2009	0.9911	0.9624	1.0343	0.9767	0.9856
2009-2010	1.1956	1.0067	1.1873	1.0063	1.0004
2010-2011	1.1734	1.0056	1.1958	0.9628	1.0433
2011-2012	1.0476	0.9933	1.0548	0.9961	0.9977
2012-2013	1.0990	1.0106	1.0889	0.9957	1.0159
2013-2014	1.1111	0.9768	1.1385	0.9875	0.9897
2014-2015	1.0603	0.9404	1.1343	0.9772	0.9635
2015-2016	1.1080	0.9257	1.2097	0.9519	0.9834
2016-2017	1.1161	1.0416	1.0725	0.9958	1.0460
2017-2018	1.0824	0.9960	1.0867	0.9992	0.9971
2018-2019	1.1449	0.9310	1.2477	0.9399	1.0194
2019-2020	1.0207	1.0105	1.0101	0.9976	1.0138
2020-2021	1.1108	0.9604	1.1559	1.0271	0.9756
Average	1.1068	0.9835	1.1331	0.9871	1.0010

Table 5. Regression results.

Variable	Coef.	Std.	p>|z|	Significance
GOV	0.171	0.126	0.176	-
URB	0.450	0.078	0.000	***
OPE	-12.202	3.766	0.001	***
ES	-0.484	0.107	0.000	***
TP	0.041	0.007	0.000	***
IND	0.059	0.059	0.314	-
Constant	0.368	0.099	0.000	***

Note: * p<0.1, ** p<0.05, *** p<0.01;- not significant.

investment introduction strategies to pursue economic growth, which has decreased the efficiency of carbon emissions and caused a great deal of environmental issues.

Energy structure (ES), represented by the ratio of carbon dioxide consumption to total energy consumption, has a considerable impact on carbon emission efficiency, as evidenced by the variable energy structure passing the 1% significance test. The variable's coefficient is -0.484, indicating a reduction in carbon emission efficiency as the amount of carbon dioxide produced from the combustion of fossil fuels increases. At this stage, a third of the world's carbon emissions come from China, which continues to be the country's top producer and consumer of coal, oil, and natural gas. The Yangtze River Economic Belt is a concentrated area of industrial parks in China. Multitudinous industrial enterprises are clustered near the watersheds, promoting rapid economic development while emitting large amounts of carbon dioxide. The Yangtze River

Economic Belt's large fossil energy consumption not only has a detrimental impact on the environment but also reduces the efficiency of carbon emissions, making the reduction of fossil fuel use and adjustment to the energy structure vital.

The coefficient of technological progress (TP) is 0.041, passing the 1% significance test. The empirical findings show that technological progress has led to a significant rise in the carbon emission efficiency of the Yangtze River Economic Belt. Technological progress can bring industrial enterprises cleaner production methods, a rationalized energy use structure, and green product production capacity, contributing to reducing carbon intensity. Comprehensively promoting the low-carbon and eco-friendly growth of the industry is a strategic requirement for implementing the new development idea. However, technological innovation and change are long and continuous processes. Carbon emission technology involves some disciplines, such as energy and the environment, and its technical difficulties are intricate and complex. Local governments should recognize that the use of technological progress to promote carbon emission reduction is a long-term and arduous task that requires sustained efforts and investment.

The coefficient of the variable industrial structure (IND) is 0.059, and $p=0.314$. The results show that there is a positive correlation between the optimization of industrial structure and the improvement of carbon emission efficiency, although it does not reach the level of statistical significance. The degree of rationalization of industrial structure adjustment at different stages of development shows a different impact on carbon emission efficiency. In addition, the influence of other variable factors may lead to the failure of its positive impact on carbon emission efficiency to be fully realized.

Conclusions

(1) This study examines the Yangtze River Economic Belt's carbon emission efficiency from 2004 to 2021, with SBM-Malmquist, from both static and dynamic points of view. It is found that the Yangtze River Economic Belt's total carbon emission efficiency is still quite low, with notable regional variations in efficiency. Furthermore, the overall carbon emission efficiency is continuously improving, as indicated by the calendar year average of the Malmquist mean value being greater than 1.

(2) The Tobit model is used to analyze the pertinent elements influencing carbon emission efficiency values. The empirical results show that urbanization levels and technological progress play a positive role in enhancing the efficiency of carbon emissions. Furthermore, the Yangtze River Economic Belt's capacity to reduce carbon emissions is hampered by two factors: the opening-up level and energy structure.

Recommendations

To improve the carbon emission efficiency level of the Yangtze River Economic Belt, drawing on the empirical findings, the recommendations presented in this study are as follows.

(1) Raising the urbanization level is a complex and systematic process involving policies in many areas. Local governments can promote the transfer of the agricultural population to cities by increasing policy support, improving public services, and raising employment subsidies. At the same time, local governments need to strengthen regional cooperation, form more effective regional coordinated development mechanisms, and accelerate the construction of urban agglomerations. Through the linkage between cities, the agglomeration effect can be enhanced, thereby achieving an overall improvement in carbon emission efficiency.

(2) The open strategy of low standards and thresholds tends to exacerbate the pressure on regional carbon emissions, which in turn triggers a series of negative ecological and environmental effects. On the contrary, the implementation of a high-quality opening-up strategy will not only bring new opportunities for regional economic development but also effectively reduce carbon emission intensity and promote sustainable development. While actively absorbing foreign-funded enterprises, less-developed regions should pay more attention to improving the quality of foreign investment, i.e., by raising the threshold of access to foreign investment and selectively introducing high-technology, low-pollution projects.

(3) Optimizing the energy consumption structure requires strong support from the government. Based on the resource-based view, the government can start from multiple dimensions. The government should play the dual roles of policy guidance and financial support, precisely allocate the flow of resources, and focus on supporting key projects in the field of energy conservation and emission reduction. In addition, the government needs to promote green financing mechanisms, such as green credit, to incentivize enterprises to engage in R&D and boost innovation in energy-saving and emission-reduction technologies.

(4) Technological innovation is a fundamental way to reduce carbon emissions. The "technological dividend" it creates can scale down costs and increase effectiveness, thereby significantly weakening carbon intensity. The government should strengthen its strategic planning and policy support, focus on innovation drivers in the field of energy science and technology, and promote the deepening and popularization of energy-saving and emission-reducing technologies to achieve the goal of green development in the region.

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Conflict of Interest

The authors declare no conflict of interest.

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