Frontiers in Environmental Science

TYPE Brief Research Report
PUBLISHED 08 August 2022
DOI 10.3389/fenvs.2022.972473

OPEN ACCESS

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SPECIALTY SECTION
This article was submitted to
Environmental Economics and
Management,
a section of the journal
Frontiers in Environmental Science

RECEIVED 18 June 2022
ACCEPTED 11 July 2022
PUBLISHED 08 August 2022

CITATION
Lu Q (2022), Energy consumption and pollution control from the perspective of industrial economic activity: An empirical study of China's coastal provinces.
Front. Environ. Sci. 10:972473.
doi: 10.3389/fenvs.2022.972473

Energy consumption and pollution control from the perspective of industrial economic activity: An empirical study of China's coastal provinces

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From the perspective of production performance, energy supply are the basic material conditions. However, greenhouse gas, air pollution and waste water are also produced in the process of production. If the undesired characteristics are ignored in the process of performance evaluation, the production efficiency will be misestimated. Based on this, this study uses Data Envelopment Analysis (DEA) to evaluate the undesired output, and discusses the production efficiency with thermal consumption in Chinese port cities, especially with severe shipping emissions, during 2015–2019. The empirical results show that the efficiency declines first (2015–2017) and then increases (2018–2019) when considering the undesired output of wastewater and SO_2 generated by thermal consumption.

KEYWORDS

pollution, undesired output, energy supply, economic, efficiency

Introduction

Since China's power supply is mainly fossil fuel power generation, since 2014, China has vigorously promoted the implementation of *Ultra-Low Emissions and Energy Conversation Projects* in its coastal power plants in order to effectively reduce environmental pollution (Wang and Li, 2019; Zhang et al., 2021a; Lei Zhang et al., 2022). Stricter standards for energy efficiency and environmental protection have been introduced, and the emission concentration of air pollutants from newly built generating units should basically meet the emission limits for gas turbine units, with the focus on developing clean combustion technologies (Han et al., 2018; Zhang et al., 2021b; Yansong Zhang et al., 2022). For example, the application of pressurized fluidized bed combined cycle (PFBC) power generation technology, integrated coal gasification combined cycle (IGCC) power generation technology and high efficiency ultra-supercritical (USC) coal-fired power generation technology and coupling power generation technology based on coal generators, etc. (Qian et al., 2021; Wei et al., 2021). And other different types of fuel oil units in service will implement ultra-low emission transformation, such as adding desulfurization, denitration and dust removal devices and other technical means on the original unit to reduce the discharge of industrial pollutants such as wastewater and sulfur dioxide. But some scholars mentioned that thermal production caused by the undesirable output (e.g., shipping emission) in the port city is still prominent (Rezaei et al., 2019; Gregoris et al., 2021; Chen et al., 2022).

Sulfur dioxide and nitrogen oxide emissions from ship fuel burning have been major air pollutants in port cities. The most commonly used marine fuels include light diesel oil, heavy diesel oil, fuel oil and residual fuel oil. Specific include: 0# diesel, −10# diesel, 20# heavy wood, 4# fuel oil, 120# fuel oil, 180# fuel oil, 380# fuel oil (Kondrasheva et al., 2018; Fang et al., 2021; Jing Chen et al., 2021). Depending on the tonnage of the ship (the size and type of engine used), different ships need different marine fuels. In Shanghai, for example, sulfur dioxide and nitrogen oxide emissions from ships accounted for 12.4% and 11.6% of the local total emissions in 2012, while the figures rose to 25.7% and 29.4% in 2015, respectively, according to the Shanghai Environmental Monitoring Center. Data from Hong Kong's Environmental Protection Department showed that in 2016, ships accounted for 49% of sulfur dioxide, 37% of nitrogen oxide, 38% of PM10 and 44% of PM2.5 emissions (Chen et al., 2019; Ma et al., 2022; Yang et al., 2022). Therefore, it is necessary to evaluate the undesirable output of energy consumption in coastal area.

In this study, the power supply is analyzed from the perspective of electricity and heating supply, and an economic model is used to discuss. Different from the previous traditional efficiency model, energy consumption activities in coastal areas are economic behaviors that have both positive impacts on economic production and negative impacts on environmental conservation. If the output value of pollution generated by energy consumption activities is not taken into account in the analysis process, there will be an error in the estimation. Based on the above discussion, this paper therefore studies the situation of energy consumption and environmental pollution in coastal cities. From the perspective of undesired output, this paper discusses the production efficiency of cities in Fujian, Zhejiang and Jiangsu provinces of China. On the basis of estimating output efficiency, Malmquist Productivity Index is further applied to discuss the correlation between output and productivity.

Literature review

Models such as Tobit model, spatial Durbin model, GMM panel estimation and multiple regression analysis are often used to evaluate the impact mechanism of industrial environmental efficiency (Emrouznejad and Yang, 2016; Yang and Li, 2017; Young and Lipták, 2018; Zhang et al., 2020; Sunari Magar et al., 2021). For example, Wang et al. (2019), Hanafiah et al. (2017), Qiu et al. (2022a) used Tobit model to conduct regression analysis and explore the relationship between economic growth, energy consumption and industrial environmental sustainability. Qiu et al. (2022b), Quan et al. (2022), Miao et al. (2020) studies the impact of energy consumption and environmental pollution on technological innovation efficiency of industrial enterprises by using GMM model based on panel data of industrial enterprises in 30 provinces of China. Scholars such as Zhang et al. (2021c), Khan et al. (2019) and Zia et al. (2021) used spatial Durbin model and multiple regression analysis method to study the influence mechanism of industrial transfer and environmental regulation factors on industrial energy and ecological efficiency of provinces in China. Wang and Luo (2022), Cheng et al. (2019) used the prefecture-level data of urban agglomerations in Yangtze River Delta from 2003 to 2016 and the spatial Tobit model to consider the spatial spillover effect. Further regression analysis showed that industrial structure, environmental regulation and innovation level were positively correlated with industrial technology costs. However, foreign direct investment is not conducive to the growth of industrial technology costs (Teng et al., 2021; Wang et al., 2022; Wu et al., 2021). The popularity of these studies leads to more studies on the measurement of industrial environmental efficiency. The research mainly involves the construction of index system and the selection of measure model (Yin et al., 2021; Lirong Yin et al., 2022). Some studies take capital investment and consumption of various resources as input indexes and gross economic output value as output indexes to construct the index system of industrial resource and environmental efficiency (Alvarado et al., 2018). For example, Shahbaz et al. (2021) selects total energy investment and energy resource utilization as input indicators. Scholars such as Zakari et al. (2021) and choose energy consumption, capital and labor input as the input index of industrial sectors, and total industrial output value as the output index of industrial sectors, so as to study the energy efficiency of China's industrial sectors. Importantly, most studies add industrial pollutant emissions as undesired output, making its efficiency measurement more scientific and reasonable. For example, Emrouznejad et al. (2019) analyzed China's manufacturing industry by using carbon emission reduction as an unintended output, so as to maintain the productivity index and reduce carbon emissions at the same time. Han et al. (2021) not only adds industrial waste water and SO_2, but also adds industrial soot and industrial waste emissions as undesired output, so as to calculate the value of China's regional industrial ecological efficiency. However, these current studies generally focus on the overall national situation and rarely make classification judgment for regions, and seldom study the situation of cities with ports as the leading industry. Because in theory, the situation in coastal port cities could be more important because of the presence of high-polluting industries such as shipping.

As for the estimation of industrial resource and environmental efficiency, many scholars currently use ecological footprint method, Stochastic Frontier Analysis (SFA), life cycle method and decoupling model. For example, Cao et al. (2022), Bibi et al. (2022), Chishti et al. (2021), Dagar et al. (2022), Chandel et al. (2022) used the SFA model to explore the energy efficiency of industrial sectors in India north. However, the method of Data Envelopment Analysis (DEA) has increasingly been adopted to measure the efficiency of industrial resources and environment. The early experts and scholars mostly measure the efficiency based on CCR and BCC models. In 1978, Charnes, Cooper and Rhode put forward the first DEA model—CCR model. Then Banker, Charnes and Cooper put forward another basic form of DEA model—BCC model. DEA model does not need any subjective enactment of significant and small cost, nor does it need to set production function in advance, and it can simultaneously measure the efficiency of multiple decision-making units of the same type. Scholars such as Godil et al. (2022), Islam et al. (2021), Zeng et al. (2019), Yang and Zhu (2022) used the traditional CCR-BCC model to calculate the energy efficiency of five Central Asian countries and the Yangtze River Economic Belt respectively. Currently, the improved DEA-SBM model or super-efficiency DEA model and other methods are often used to measure. Muhammad and Khan (2022), Oryani et al. (2021), Oryani et al. (2022), Qin et al. (2021), Rehman et al. (2022), Yufeng Chen et al. (2021) calculates the industrial energy efficiency and industrial environmental efficiency values of 30 provinces and regions in China in different years by constructing the SBM model. Ni Ni Yin et al. (2022) evaluated the industrial energy efficiency of areas along the "Belt and Road" in China by using the SBM model containing unintended outputs. For example, Yang et al. (2020) took undesired outputs in shipping industry into consideration and conducted an empirical analysis of 25 provinces using simple linear programming. In this study, when the linear programming method is used to measure efficiency, the purpose of considering the undesirable output is to get closer to the real efficiency. Moreover, Cecchini et al. (2018), Zakari et al. (2021), Zhang et al. (2021d), Zia et al. (2021), Weimin et al. (2022) used data envelopment analysis (DEA) model to discuss the efficiency including undesired outputs. After the inclusion of undesired outputs, the efficiency value obtained will be lower than the efficiency value estimated in the traditional way, indicating that if the phenomenon of undesired outputs is ignored in the empirical estimation, the efficiency evaluation will be misestimated. Then it affects the judgment of input and production behavior strategy of the object. Gao et al. (2021) measured the green total factor energy efficiency and the effects of urban agglomerations in the Yangtze River Delta. The empirical results show that, under environmental regulation, excessive pollutant emissions led to a decrease in the growth rate of energy and technical efficiency. They believe that the ignorance of the sustainable technology improvement led to the decrease of the growth rate of energy technology progress. And the cumulative growth rate of technical efficiency, GDP, exhaust emissions per unit GDP, and energy consumption have different degrees of influences on energy efficiency. Zhao et al. (2020) used the DEA method and spatial spillover methods to show the infrastructure level and industrial efficiency cities in Pearl River Delta region of China. The results show that regional infrastructure has significant promotion effect and spatial spillover effect on industrial efficiency. However, there are significant differences in the effects of different infrastructures among the three regions. Overall, there are many literatures on environmental efficiency at present but the research on environmental efficiency in coastal areas is relatively rare. In this paper, DEA method is used to reveal the efficiency difference between coastal areas in combination with the practical situation of China's coastal areas, providing reference for improving the environmental efficiency of China.

Materials and Methods

Data Envelopment Analysis (DEA) mainly constructs a nonparametric broken line surface and boundary from observed data in the way of linear programming. The relative efficiency of each required estimation sample compared with this boundary is calculated accordingly. Traditionally, the observed data are constructed into a nonparametric broken line surface and boundary by linear programming method, and the relative efficiency between samples is compared. In the production activity category, there are I producers, and each producer has n inputs to carry out the production activity and produce the final output M. For the *i*th producer, these output and input data can be represented by vector qi and xi respectively. Where N×I and M×I represent input matrix X and output matrix Q respectively. DEA makes mathematical planning for the comparison of all outputs and inputs of each producer by using the productivity ratio pattern. Therefore, the estimation model is the vector form expressed in the following Eq. 1:

$$\begin{gathered}\max_{\theta,\lambda} u'q_i / v'q_i \\ \text{s.t.} \\ u'q_j / v'q_j \leq 1 \\ u, v \geq 0 \\ j = 1, 2, \ldots\ldots\ldots, I\end{gathered} \tag{1}$$

Through linear programming of Eq. 1, all producers are solved to find the most favorable weight for each producer's input distribution. By introducing Eq. 1 into the dual pattern, the output guiding pattern of Eq. 2 can be obtained:

$$\begin{gathered}\mathrm{Max}_{\theta,\lambda} \theta \\ \text{s.t.} \\ \theta q_j \leq Q\lambda \\ \theta x_i \geq X\lambda \\ \lambda \in R^+\end{gathered} \tag{2}$$

Eq. 2 is the most commonly used type of datagram analysis, where θ is a scalar. λ is a constant vector with dimension $I \times 1$. The θ value obtained is the production efficiency of the i-th producer, and the θ value is between 0 and 1. If it is 1, it represents the point on the boundary. The producer is defined as an efficient operator. According to Eq. 2, the number of samples to be studied (for example, there are I samples) is determined to solve the production efficiency values respectively.

Considering the existence of undesirable outputs in reality, if the estimation equation is still estimated in accordance with Eq. 2, it is possible to misestimate the efficiency result of undesirable outputs. Therefore, we need to distinguish output Q from desired output Q and from undesired output B. In order to distinguish it from λ of Eq. 2, we assume that the constant vector ϑ, the desired output vector O_Q, and the undesired output value O_B are taken into account. Where, $O_Q + O_B = Y$ indicates that the total output is the sum vector of desired output value and undesired output value. Therefore, Eq. 2 is extended to Eq. 3 as follows:

$$\begin{gathered} \mathit{Max\,Scores} \\ \mathrm{s.t}\ \mathrm{X}\vartheta + \mathit{Scores}g_x \leq x_k \\ \mathrm{Q}\vartheta - \mathit{Scores}O_Q \geq y_k, \\ \mathrm{B}\vartheta - \mathit{Scores}O_B \geq b_k, \vartheta \geq 0 \end{gathered} \tag{3}$$

Where, the production may be set as:

$$\mathrm{S} = \{(x, y) | x \geq \mathrm{X}\vartheta, \mathrm{y} \leq \mathrm{Q}\vartheta, \mathrm{b} \geq \mathrm{B}\vartheta\} \tag{4}$$

Eq. 4 represents that in the case of given desired and undesired output value, the production behavior must weigh the proportion of the two to find the optimal efficiency result. Finally, it can be concluded through linear programming:

$$\begin{gathered} \mathrm{Max}\,\theta \\ \mathrm{s.t.} \\ \theta\mathrm{Q} \leq \mathrm{Q}\vartheta \\ \theta\mathrm{B} = \mathrm{B}\vartheta \\ \mathrm{x_j} \geq \mathrm{X}\vartheta \\ \vartheta \in \mathrm{R}^+ \end{gathered} \tag{5}$$

Eq. 5 is the relative ratio of efficiency values in each period. When the value is less than 1, it means that productivity increases relative to the previous period; when the value is greater than 1, it means that productivity decreases relative to the previous period. The empirical data in this paper are extracted from the Statistical Yearbook of Chinese Cities regularly published by the Department of Urban Social and Economic Survey of the National Bureau of Statistics from 2015 to 2020, which includes the statistical data of urban construction and other aspects of 656 cities (including prefecture-level and above cities and county-level cities) in China. In the present research, we used the data of 33 coastal cities in Fujian, Zhejiang and Jiangsu provinces revealed by the yearbook from 2015 to 2019. In the selection of variables, the economic activity variables were taken as the output variables of urban GDP (Unit: million RMB), PM2.5 (annual average concentration of fine suspended particulates in 2.5 microns) and sulfur dioxide (Unit: ton), among which PM2.5 and sulfur dioxide were the undesired output. Secondly, employees (Unit: 10,000 people), industrial electricity consumption (Unit: 10,000 KWH) and fixed asset investment (Unit: million RMB, excluding agricultural products) are input variables. In addition, in order to analyze the impact of environmental governance and economic conditions on production efficiency, we also consider urban per capita income and environmental fiscal expenditure. The descriptions of relevant variables are summarized in Table 1.

Results

According to the estimated results of Eqs 2, 3, we can obtain the production efficiency of each city from 2015 to 2019 considering environmental pollution. Table 2 lists the production efficiency values of each province over the years by year and province. Firstly, it can be found that by province, taking into account the undesirable output of PM2.5 and sulfur dioxide generated in industrial heating activities, Jiangsu Province has the highest production efficiency, followed by Fujian Province, and Zhejiang Province has the lowest. For example, from the perspective of annual changes, the production efficiency of all samples showed a trend of decreasing first (2015–2017) and then increasing (2018 and 2019). The empirical results show that with the evolution of time, the production efficiency of China's coastal cities over the years has improved as a whole.

Table 3 collates productivity changes over the years according to Eq. 4. As can be seen from the figure, productivity pointer less than 1 means productivity declines relative to the previous period, while productivity pointer greater than 1 means productivity increases relative to the previous period. It can be found that the productivity indicator showed a downward trend from 2015 to 2017 and an upward trend from 2018 to 2019. The results in Table 3 are consistent with those in Table 2. Such estimation results show that the production performance of industrial economic activities in cities decreases first and then rises, taking into account the output value generated by electric heating supply and pollution problems.

Figure 1 further depicts the changes of each region in Table 3. It can be found that, although Jiangsu province has the best performance in production efficiency on the whole, from the perspective of productivity change, Fujian Province has the best productivity change on the whole, showing an increase since 2017. One possible reason for the downward trend and then upward trend is that China has been vigorously promoting the implementation of ultra-low emission and energy saving renovation projects in domestic power generation since 2014. In our opinion, this reflects that the adjustment of the thermal policy made local industries first face the pain period and the stage of transformation of production mode, and the efficiency declined during 2015–2017. After the completion of the transformation stage, the overall efficiency and productivity gradually improved. This proves that the promotion of policy

TABLE 1 Definition of variables and the descriptive statistics.

Variable	Mean	Std. dev.	Unit
Gross value of production (Desired output value)	27701	2214	10 million RMB
Sulfur dioxide (undesired output value)	126	164	Kiloton
PM2.5	58.453	23.312	CBM cubic meter
Employee	71.694	56.047	10,000
Electric and heating consumption	1096436	11048	Million KWH
Fixed investment	15111	1115	10 million RMB
Per capita	4.101	1438	10,000
Environmental protection expenditure	422.4	2721	10 million RMB

TABLE 2 Production efficiency estimation results.

Category	Mean	Std. dev.
Region		
Zhejiang	0.701	0.782
Jiangsu	0.783	0.689
Fujian	0.725	0.336
Year		
2015	0.737	0.335
2016	0.710	0.314
2017	0.689	0.784
2018	0.705	0.668
2019	0.768	0.441
Total	0.724	0.586

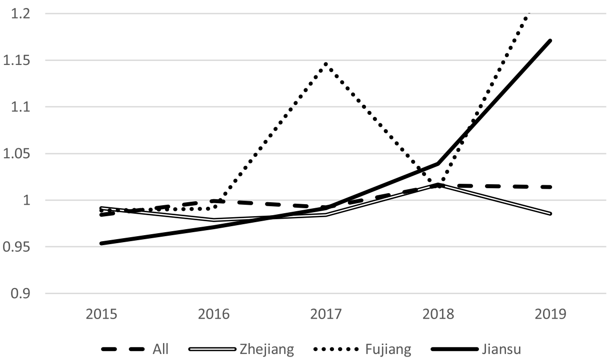

FIGURE 1
Productivity changes over years.

TABLE 3 Productivity changes.

Year	All	Zhejiang	Fujiang	Jiansu
2015	0.9843	0.9914	0.9889	0.9536
2016	0.9992	0.9787	0.9909	0.9711
2017	0.9924	0.9843	1.146	0.9914
2018	1.0157	1.0167	1.0111	1.0388
2019	1.0141	0.9857	1.246	1.171

has improved the efficiency value of production input, and this change has achieved the result of curbing environmental pollution while pursuing production capacity.

Conclusion

Through considering undesired output, this paper explores the production efficiency of 33 Chinese coastal cities dominated by coastal industry and shipbuilding industry from 2014 to 2019 considering the undesired output. Considering the undesired output of air pollution generated in industrial energy consumption activities, Fujian Province has the highest production efficiency, followed by Jiangsu Province, and Zhejiang Province has the lowest. From the perspective of annual change, the production efficiency of coastal cities showed a changing trend of decreasing first (2015–2017) and then increasing (2018–2019), reflecting the thermal production regulation and the input level has reached a certain balance, thus driving the increase of efficiency.

According to the policies of the National Energy Administration of China, the state has formulated a number of supporting policies, such as electricity price, power generation and sewage charge, in order to mobilize the enthusiasm for the renovation of shipping industry and coastal industry. At present, China pays 0.5 cent for electricity and 1 cent for heat for new and active units that achieve ultra-low emission levels. Where the pollutant discharge concentration is more than 50% below the limits set by the State or local authorities, the policy of halving the pollutant discharge fee shall be earnestly implemented. The empirical results show that the efficiency decreases first and then increases, which should be related to the adjustment of China’s electric and heating power policy in recent years.

It can be seen that energy-intensive industries are easy to manage and produce quick results, and they can be channeled through policies such as electricity and heating prices. This paper suggests that in the future, the industries such as shipping should continue to take the lead in carrying out ultra-low emission transformation and greatly reduce the emission of air pollutants, which can not only contribute to the control of air pollution, but also explore ways for other energy-intensive industries to implement ultra-low emission transformation in the future, and help promote the cleaner thermal combustion in China. The empirical results of this paper confirm that the policy promotion has improved the efficiency value of economic production input level on the one hand, and on the other hand, the promotion of environmental protection policy has brought positive effects on economic activities and sustainable environmental development under the attempt to improve the air pollution problem. However, it is needed to point out the limitations of this paper. Since this paper focuses on the situation before COVID-19, future follow-up studies may further include comparative studies before and after the epidemic (Emrouznejad and Yang, 2016; Sunari Magar et al., 2021; Yang and Li, 2017; Young and Lipták, 2018; Zhang et al., 2020).

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding author.

Author contributions

QL contributed to the study conception and design. Material preparation, data collection, and analysis were performed by QL, and QL commented on previous versions of the manuscript. QL read and approved the final manuscript.

Acknowledgments

This research thanks for the comments from reviewers.

Conflict of interest

The author declares that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher’s note

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