China’s Provincial Environmental Efficiency Evaluation and Influencing Factors of the Mining Industry Considering Technology Heterogeneity

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ABSTRACT The mining industry has promoted the process of industrialization in China, and the current consumer demand for mineral products is still very large. Since the development of mineral resources has caused serious environmental pollution and waste of resources, the country has raised the development of green mining to a strategic level. Based on China’s provincial data over the 2007-2016 period, this paper measured environmental efficiency (EE) of China’s mining industry (CMI) using Meta-frontier slacks-based measure (SBM) method and reveals the root causes of environmental inefficiency (EI). Then, a panel Tobit regression model was established to discuss the differential impact of relevant factors on the meta-frontier environmental efficiency (MFEE) of CMI in the regional heterogeneity perspective. The results show that: (1) The MFEE of CMI exhibits low score and there is significant regional heterogeneity, with the highest in Eastern China, followed by Central China, and Western China. (2) The technology gap ratio (TGR) in the three regions shows that Eastern China ranks the highest, followed by Central China, and Western China. TGI is the main contributor to the EI of CMI. (3) the overall MFEE of CMI, the MFEE of CMI in Eastern, Central and Western area are negatively related to the environmental regulation intensity, are positively related to the resource utilization rate, respectively. The economic development level, innovative ability, education level, industrial structure and state-owned capital proportion differently effect on China’s overall EE of the mining industry and the EE of the mining industry in different regions of China, respectively.

INDEX TERMS China’s mining industry, environmental efficiency, technological heterogeneity, meta frontier SBM model, Tobit model.

I. INTRODUCTION

The mining industry is an important engine for China’s economic development, and its outstanding contributions are indisputable [1], [2]. By the end of 2017, the value added of China’s mining industry was 2,102.55 billion yuan, accounting for 7.6% of the industrial gross domestic product (GDP). While mining has created high output value for the development of China’s national economy [3], some mining companies have extracted rich ores and discarded poor ores, and they only mine easy-to-mine mines, resulting in a lot of land resources being wasted and polluted [4], [5]. The environmental problems of the mines are becoming more and more serious [6]. Until the end of 2017, the cumulative occupied and damaged land by China’s mining industry had exceeded 2.6 million hectares, while the cumulative restoration area is only 23% [7]. These are contrary to the goal of transforming the exploitation and utilization of mineral resources and promoting the development of green and low-carbon recycling mining industry. Green mining is an industry developed under the condition of coordination between resources conservation, eco-social development and ecological environment protection. In the new period, the Chinese government has put forward higher requirements for the green development of mining industry. “National Mineral Resources Planning (2016-2020)” clearly pointed out that it is necessary to save and intensive use of land resources and strengthen environmental protection during...
the development of mineral resources [8]. “The Ecological Environmental Protection of the 13th Five-Year Plan” also pointed out that it is necessary to strictly evaluate the environmental impact caused by the development of mineral resources and accelerate the construction of green mines [9]. At the same time, the provincial governments have also proposed a series of policies. For example, Hunan Province promulgated the “Three-Year Action Plan for the Construction of Green Mines in Hunan Province (2020-2022)”, which requires that by the end of 2022, all production mines in Hunan Province will meet the green mine standards [10]. Guangxi Province issued the “Opinions on Further Strengthening the Development and Management of Mineral Resources to Promote the Construction of Ecological Civilization”, insisting on green development and innovative governance [11].

This paper studies the environmental efficiency (EE) of China’s mining industry (CMI) and its influencing factors, providing reference for the government and enterprises to better deal with the relationship between resource utilization and ecological environment protection. This study will not only accumulate the research experience of the EE evaluation in CMI, but also contribute to enrich the empirical analysis of green development theory.

The rest of this paper is organized as follows: Section II introduces a related work. Section III introduces the preliminaries, which include the model establishment and variable selection. Section IV conducts a case study. Section VI introduces the research conclusions and recommendations.

II. RELATED WORK

Environmental efficiency is an indicator to measure the impact of economic activities on the environment [12]–[14]. At present, the extensive development of environmental efficiency evaluation has gradually become a powerful theoretical tool to help governments and enterprises to formulate and implement environmental policies to provide reference. There are many methods for evaluating environmental efficiency, among which the data envelopment analysis (DEA) method has been favored by many scholars, and it is applied to the environmental efficiency evaluation of different industries [15]–[17]. Some scholars use DEA method to evaluate the environment of China’s mining industry from the perspective of regions and industries. Ma ding et al. taking CO₂ as an undesirable output, studied the inputs-outputs efficiency of mining industry in different regions of China based on non-radial directional distance function and Malmquist index, and concluded that the inputs-outputs efficiency in China’s mining industry showed a descending trend considering the environment pollutants, and then discussed the influence of relevant factors on it [2]; Zhu Xuehong et al. used the global data envelopment analysis method to analyze the green total factor productivity of China’s mining industry from 1991 to 2014, and found that there were significant differences in sub-industries, and technological progress promoted the growth of green total factor productivity of China’s mining industry [18]; Wu Jie et al. used DEA to measure the energy and environmental efficiency of industrial sectors in China, and concluded that the EE of CMI is not high, and among which mining and washing of coal exhibits the lowest score [19]. However, these studies are based on the original DEA model, which assumes that the input and output indicators change in proportion, which will cause efficiency deviation and cannot deal with slack variables. Subsequently, Tone proposed a slacks-based measure (SBM) model to solve this problem well [20]. More and more scholars use SBM model to study environmental efficiency [21]–[24]. Xiao Chengming et al. used SBM model to calculate that the EE of CMI fluctuates greatly and there is huge space for energy conservation and emission reduction [25]; Zhou Yan used CCR model(DEA model under constant returns to scale) and improved SBM model to measure the EE of CMI, respectively, and found that the efficiency score measured based on improved SBM model was lower compared to that measured based on CCR model [26].

To sum up, the main contributions of the current researches on the environmental efficiency of China’s mining industry are as follows: (1) By evaluating the environmental efficiency of China’s mining industry, scholars have come to the general conclusion that China’s mining industry exhibits low environmental efficiency. (2) Relevant factors affecting the environmental efficiency are analyzed, and corresponding policy suggestions are put forward. Due to the strong differences in the mineral resource structure, mining economic development level, mining technology level, and environmental restoration and governance capabilities of various regions in China [27]–[29], there are obvious regional heterogeneities in the EE of CMI in different regions. However, the above researches directly believe that all decision making units(DMUs) are homogeneous, ignoring the technical heterogeneity of each DMU due to differences in energy structure, economic development, production technology level, and environmental restoration and governance capabilities, which may cause decision making errors. In addition, the differential influence of relevant factors on the EE of CMI in different areas has not been explored. This requires us to use a reasonable method to accurately measure the EE of CMI from three major areas perspective, analyze the causes of environmental inefficiency, and discuss the influencing factors on the EE of CMI. Only in this way can we make practical and differentiated policy recommendations.

In order to bridge the gap of existing studies, this paper introduces the meta frontier theory as the theoretical framework for our research. This theory was first proposed by Battese and Rao (2002) based on stochastic frontier analysis (SFA) [30]. Later, O’Donnell (2008) proposed to use DEA method instead of SFA to construct non-parametric meta frontier theory, mainly because the DEA method does not need to set parameters and it can effectively solve the diversification of input and output indicators [31]. In recent years, meta frontier theory has been widely used in the analysis of environmental efficiency in various
industries [28], [29], [32], [33]. In our research, meta frontier theory is firstly combined with SBM model to measure the EE of CMI by province during 2007-2016, the regional differences, technology gap ratio (TGR) of mining environment is analyzed, and the meta frontier environmental inefficiency (MFEI) of CMI is decomposed into technology gap inefficiency (TGI) and managerial inefficiency (MI). Hence the question that follows is whether relevant environmental factors will cause this difference? How much influence do these factors have on the difference? The second task is to further investigate the factors affecting the EE of CMI. Thus, in this research, a scientific influencing factor system is constructed based on the data from different provinces in China from 2007 to 2016, and a Tobit model is used to empirically analyze the causes of regional differences in EE of CMI, aiming to provide a certain theoretical reference for relevant departments to formulate differentiated mining environmental economic policies.

The contributions of this paper are: (1) This paper initiative uses meta frontier SBM model to examine the EE of CMI, which make up for the inadequacy of the research on it. (2) This paper explores the differential effects of relevant factors on China’s overall EE of the mining industry and the EE of CMI in Eastern, Central and Western area, respectively, by establishing a Tobit econometric model based on the perspective of regional heterogeneity, which will help the design of more effective green production systems in various regions in the future. (3) This paper will enrich the empirical analysis of the environmental efficiency evaluation using meta frontier SBM model, and make a suitable reference for promoting environmental efficiency analysis in other industries.

III. PRELIMINARIES

There are large differences in the structure of mineral resources, resource extraction technology, and environmental governance capabilities of various provinces in China. Obviously, it is unreasonable to put all provinces indiscriminately under a single frontier to map projections to determine whether different provinces are DEA-efficient. In this paper the meta frontier theory is introduced, with the general conception shown as follows: first to divide each DMU into different groups according to certain criteria, subsequently to define the meta frontier of all DMUs and the group frontier of each group of DMUs based on DEA [31], [34], then to measure the environmental efficiency of each DMU under the meta frontier and group frontier separately, and to define the ratio of the two efficiency scores as TGR to measure the technical gap at different technical levels. The SBM model can not only deal with undesirable output, but also take into account the slack variables of input and output and avoid the radial and oriented deviation [20], [35]. Therefore, based on the SBM model, this paper constructs the environmental efficiency measurement model under the meta frontier and group frontiers respectively, to explore the EE of CMI under different frontiers and determine the TGR.

A. PRODUCTION POSSIBILITY SET

Suppose there are \( N \) decision-making units (DMUs) in the production system of this study, all DMUs can be divided into \( H \) groups, and for each DMU \( M \) inputs are used to produce \( R \) desirable outputs and \( J \) undesirable outputs during the \( T \) production period.

Let \( x \in \mathbb{R}^M \), \( y \in \mathbb{R}^R \), and \( b \in \mathbb{R}^R \), representing the input, desirable output, and undesirable output of the production system, respectively, and define the matrices \( X = [x_1, \cdots, x_N] \in \mathbb{R}^{M \times N} \), \( Y = [y_1, \cdots, y_N] \in \mathbb{R}^{R \times N} \) and \( B = [b_1, \cdots, b_N] \in \mathbb{R}^{R \times N} \), respectively. Let \( X > 0 \), \( Y^g > 0 \), \( Y^b > 0 \), and Group \( h \) contains \( N^h \) DMUs. Based on the total factor theory, the production possibility set \( T^h \) under the group frontier of Group \( h \) is:

\[
T^h = \{(x, y, b) : \text{can produce (y, b)}\}
\]

\[
\begin{align*}
\sum_{n=1}^{N} \lambda_n^h x_{mn} &\leq x_m, \quad m = 1, 2, \cdots, M \\
\sum_{n=1}^{N} \lambda_n^h y_{rn} &\geq y_r, \quad r = 1, 2, \cdots, R \\
\sum_{n=1}^{N} \lambda_n^h b_{jn} &\leq b_j, \quad j = 1, 2, \cdots, J \\
\lambda_n^h &\geq 0, \quad n = 1, 2, \cdots, N^h
\end{align*}
\]

(1)

The production possibility set under the meta frontier can be used as the envelope line of the production possibility set under the group frontier \( T^{meta} = \{T^1 \cup T^2 \cup \cdots \cup T^H\} \), expressed as:

\[
T^{meta} = \{(x, y, b) : \text{can produce (y, b)}\}
\]

\[
\begin{align*}
\sum_{h=1}^{H} \sum_{n=1}^{N^h} \lambda_n^h x_{mn} &\leq x_m, \quad m = 1, 2, \cdots, M \\
\sum_{h=1}^{H} \sum_{n=1}^{N^h} \lambda_n^h y_{rn} &\geq y_r, \quad r = 1, 2, \cdots, R \\
\sum_{h=1}^{H} \sum_{n=1}^{N^h} \lambda_n^h b_{jn} &\leq b_j, \quad j = 1, 2, \cdots, J \\
\lambda_n^h &\geq 0, \quad n = 1, 2, \cdots, N^h, \quad h = 1, 2, \cdots, H
\end{align*}
\]

(2)

B. META FRONTIER SBM MODEL

In this paper, the SBM model involving the undesirable outputs is used to construct the efficiency measurement models under the meta frontier and group frontiers respectively. Based on Formulas (1) and (2), the group frontier SBM model of Group \( h \) can be expressed as:

\[
p^h = \min \left( \frac{1 - \frac{1}{M} \sum_{m=1}^{M} \frac{x_{m0}}{x_{m0}}}{1 + \frac{1}{R+J} \left( \sum_{r=1}^{R} \frac{y_{r0}}{y_{r0}} + \sum_{j=1}^{J} \frac{b_{j0}}{b_{j0}} \right)} \right)
\]

\[
s.t. \sum_{n=1}^{N^h} \lambda_n^h x_{mn} + s^x_{m0} = x_{m0}
\]

\[
\sum_{n=1}^{N^h} \lambda_n^h y_{rn} + s^y_{r0} = y_{r0}
\]

\[
\sum_{n=1}^{N^h} \lambda_n^h b_{jn} = b_{j0}
\]

\[
\lambda_n^h \geq 0, \quad n = 1, 2, \cdots, N^h
\]

\[
\sum_{n=1}^{N^h} \lambda_n^h - \sum_{r=1}^{R} s^y_{r0} \leq \sum_{r=1}^{R} y_{r0}
\]

\[
\sum_{n=1}^{N^h} \lambda_n^h - \sum_{j=1}^{J} s^b_{j0} \leq \sum_{j=1}^{J} b_{j0}
\]
The meta frontier SBM model of Group $h$ can be defined as:

$$p_{\text{meta}} = \min \left( 1 - \frac{1}{M} \sum_{m=1}^{M} \frac{s_{m0}}{s_{m0}} \right)$$

$$s.t. \sum_{h=1}^{H} \sum_{n=1}^{N_h} \lambda_{hn} x_{mn} + s_{m0}^x = x_{n0}$$

$$\sum_{h=1}^{H} \sum_{n=1}^{N_h} \lambda_{hn} y_{rn} - s_{m0}^y = y_{r0}$$

$$\sum_{h=1}^{H} \sum_{n=1}^{N_h} \lambda_{hn} b_{jn} + s_{m0}^b = b_{j0}$$

$$\lambda_{hn} \geq 0, s_{m0}^x, s_{m0}^y, s_{m0}^b \geq 0$$

(3)

In Eqs. (3) and (4), $s_{m0}^x$, $s_{m0}^y$, and $s_{m0}^b$ respectively represent the slack variables of input, “good” output, and “bad” output. If $p = 1$ and $s_{m0}^x = s_{m0}^y = s_{m0}^b = 0$, the DMU is SBM-efficient [20], [36].

C. TGR, MFEI AND ITS DECOMPOSITION

TGR is used in this paper to measure the technological gap between the EE of CMI under the meta frontier and that under the group frontier [30,37,38]. The distance between TGR and 1 represents the gap between the group frontier technology level and the national optimal technology level. The closer the TGR is to 1, the smaller the gap between the group frontier technology level and the national potential optimal technology level [39]. Here the MFEI and GFEE are used to represent the meta frontier environmental efficiency of China’s mining industry and the group frontier environmental efficiency of China’s mining industry, respectively, then TGR can be expressed as:

$$0 \leq \text{TGR} = \frac{\text{MFEI}}{\text{GFEE}} \leq 1$$

(5)

In order to further explore the causes of the environmental inefficiency of CMI in various regions, this paper decomposes the meta frontier environmental inefficiency (MFEI) of the mining industry in the eastern, central and western areas from the technical and management levels into technology gap inefficiency (TGI) and managerial inefficiency (MI) according to relevant literatures [28], [40], then the following equations are obtained:

$$\text{MFEI} = 1 - \text{MFEE} = \text{TGI} + \text{MI}$$

(6)

$$\text{TGI} = \text{GFEE} \times (1 - \text{TGR})$$

(7)

$$\text{MI} = 1 - \text{GFEE}$$

(8)

D. VARIABLE SELECTION AND DATA SOURCES

1) INPUT VARIABLES

According to the relevant literatures and the availability of data, the input variables in this paper include labor input, capital input and land use input [12], [41]–[43]. The average annual number of employees in CMI is taken as the labor input, with the approved registered area by the mining license being land input and the capital stock being the capital investment variables. The capital stock is usually estimated using the perpetual inventory method [44]. Since the data of the initial capital stock and capital depreciation rate of CMI are difficult to obtain, in this paper, by referring to the research of Gao Wei (2018), the net fixed asset value of the mining industry in 2006 (constant price of the year) is taken as the initial capital stock $K_{t0}$, and the net added value of fixed assets in the next two years as new fixed assets, then the value is converted into 2007 constant prices according to the price index of investment in fixed assets [45].

$$K_{t+1} = K_{t0} + \sum_{t=t+1}^{t+b} \Delta K_{t+1}$$

(9)

2) OUTPUT VARIABLES

The industrial sales output value of the mining industry was introduced as desirable output and was converted into 2007 constant prices using the producer price index of industrial products by sector. Cumulative area of land occupied or destroyed by mining was taken as undesirable output to reflect the damage to the land environment during the process of resource exploitation and utilization [45]. Table 1 provides the statistical information for each of the indicators.

3) DATA COLLECTION

Considering that city-level data and enterprise-level micro-data are incomplete and the statistical criteria of them are often different, 31 provinces (including autonomous regions and municipalities) in China were selected as the research objects of this paper. According to the meta frontier theory, we divided all DMUs (in this paper, provinces) into different groups with heterogeneous technical characteristics firstly. This article refers to relevant researches [46]–[48] and takes into account the characteristics of the resource endowment in various regions of CMI [8], 31 DMUs were divided into three groups according to the geographical location (Eastern China includes Beijing, Tianjin, Hebei, Liaoning, Shanghai, Jiangsu, Zhejiang, Shandong, Guangdong, Hainan and Fujian. Central China includes Shanxi, Jilin, Heilongjiang, Anhui, Jiangxi, Henan, Hubei and Hunan. Western China includes Inner Mongolia, Guangxi, Chongqing, Sichuan, Guizhou, Yunnan, Tibet, Shaanxi, Gansu, Qinghai, Ningxia and Xinjiang). Since the Ministry of Land and Resources of the People’s Republic of China implemented a new mineral resource planning database from 2007 and the data on the number of employees in mining industry by province were only updated to 2016, the study period was set as 2007-2016. All data were obtained from the China Industrial Statistical Yearbook.
IV. CASE STUDY

A. EE EVALUATION OF CMI AND ITS REGIONAL DIFFERENCE

The EE of CMI by province is calculated under the meta frontier and group frontiers during 2007-2016 using input-oriented SBM model under variable returns to scale, respectively, which are respectively expressed by MFEE and GFEE. The results are shown in Table 2.

It is estimated that the average MFEE score of CMI in 31 provinces is 0.643 during 2007-2016, which means that the resource input needs to be reduced by 35.7% to achieve DEA-efficient. The average GFEE score of CMI in 31 provinces can reach 0.848. The reason for the large gap between the meta frontier and group frontiers is the reference standards of them are different. The former takes the potential optimal technology of China as the reference standard, while the latter takes the potential optimal technology of the group to which it belongs. It can be seen from Table 2 that the EE of CMI in most provinces differ greatly under the meta frontier and group frontiers. Taking Jilin Province as an example,
the GFE of the mining industry located at the production frontier with the average score of 1, which means that on the premise of taking the optimal production technology of the central group as the benchmark, the DEA-efficient of mining industry has been realized in Jilin Province. While the MFEE of the mining industry in Jilin Province is low with the average score of 0.332 during 2007-2016, which means that based on the China’s optimal production technology, there is a 66.8% input reduction potential in Jilin Province. In addition to Jilin Province, Heilongjiang, Anhui, Tibet, Gansu, Ningxia, Xinjiang and the other provinces share some similarities with great difference under the meta frontier and the group frontiers. Most of these provinces are located in Central and Western China. Various areas in China have strong heterogeneity mineral resource structure, mining economic development level, mining technology level, and environmental restoration and governance capabilities. The frontier of environmental technology in the central and western regions has a huge catch-up space compared to the eastern region. In addition, the study also found that, whether based on China’s optimal technology or the group best technology, the EEs in Eastern China of the mining industry are basically the same (Figure 1). The main reason for this situation is that Eastern China makes full use of its inherent advantages, publicizes the importance of resource extraction and environmental protection, and seizes the opportunity of mining transformation and upgrading, and further integrates the ecological production technology and capital by increasing finance and investment in green mining. Therefore, Eastern China exhibits the highest EE of the mining industry. This also reflects that the EE of the mining industry in Eastern China can be used as the representative of the China’s optimal level.

Because the reference standard of GFE of CMI in each province is the environmental technology level of different groups and the reference standard of different group provinces is different, the GFE of the MI in different group provinces is incomparable. Therefore, we use the meta frontier as a unified reference standard to compare and analyze the differences between EE of CMI in 31 provinces and three major regions. It can be seen from Figure 1 and Table 2 that the EE of CMI in different provinces and three major regions has obvious heterogeneity. Among them, Tianjin, Shanghai and Shandong provinces exhibit the highest average EE score of 1 during this period, representing the China’s best mining and environmental governance technology. Secondly, the average MFEE score of the mining industry in Guangdong (0.947), Sichuan (0.944), Inner Mongolia (0.921), Fujian (0.911) and the other provinces are close to the production frontier, and there is a high level of coordination between mining economic growth and mining environmental protection. In contrast, the provinces with the lowest average MFEE score of the MI are Tibet (0.226), Ningxia (0.293), Gansu (0.295), and Hainan (0.296). Most of these provinces belong to the less developed western region. Weak economic strength, backward production technology and environmental protection technology are the common characteristics of these provinces. Hainan is the province with the lowest average EE score of the MI in the eastern group, which may be because the mining industry plays a small role in the national economic development of Hainan Province, and the resource input and environmental protection in mineral development have not attracted the attention of relevant government departments.

From three regions perspective, the average MFEE score of CMI in eastern, central and western area is 0.775, 0.633 and 0.528 respectively, with the pattern presented as Eastern China > Central China > Western China, and the average MFEE scores of the MI in Midwestern China are lower than the national average level(0.643). Eastern China shows the highest average MFEE score of the mining industry and a good balance between resource exploitation and environmental protection, which is mainly due to its superior location, strong economic strength and advanced resource exploitation technology. Central China has a large amount of mineral resources and a high concentration of resources and it is an important energy base in China. However, the resource mining mode in this region is relatively extensive and the long-term resource-based economic development mode is difficult to achieve rapid mode transformation, and the pressure on mine environmental protection is enormous. Western China is sparsely populated and the distribution of mineral resources is relatively scattered. In recent years, the strategy of western development has stimulated the acceleration of industrial development in Western China, the development of mineral resources has been strengthened, and the development methods have been more extensive, resulting in the continuous deterioration of the environmental quality of mines. Western China is the most vulnerable region in China’s ecological environment. In the process of promoting mineral exploration and development in the western region, the effective use of various resource elements should be implemented, environmental protection should always be the first priority, and regions with low environmental carrying capacity should be carefully protected in the development.

**FIGURE 1.** The average MFEE score and the average GFE score by province during 2007-2016.
B. TGR OF CHINA’s MINING ENVIRONMENT

In order to investigate the gap between the efficiency values of group technology frontiers and national technology frontier in different regions, expose the environmental technology gap rate of mining industry in China’s provinces are calculated according to Formula (5) in this section. Figure 2 shows the evolution trends of the mining environment TGR in the three major groups of eastern, central and western regions in China over the period 2007-2016. It can be seen from the calculation that the average TGR scores of the mining environment in Eastern, Central and Western China are 0.990, 0.648 and 0.626, respectively. The mining environmental technology of Eastern China is closer to the national potentially optimal level. It can be seen from Figure 2 that Eastern China has the highest TGR during the period of 2007-2016, which is consistent with the fact that the Eastern China has been playing the leading character in terms of economy, technology and environmental governance. The average TGR scores of Central and Western China are relatively close to each other, and there is a 35.2% and 37.4% optimization potential away from the best technology frontier, respectively. Judging from the evolutionary trend, the TGR of Central China dropped down dramatically during 2007-2016, while the TGR of Western China leaped upward during this period, that is, the technological level of the mining environment in Central China is declining, and that in Western China is improving, and since 2014, it has surpassed Central China for three years in a row.

Subtract the TGRs between Eastern China and Central China, Eastern China and Western China, Central China and Western China, respectively, the results obtained are shown in Figure 3.

From Figure 3, it can be found that TGR between Eastern China and Central China, Eastern China and Western China fluctuates and has been ranging from 0.1 to 0.6, and the mining environmental technology gap is relatively large. Midwestern China are rich in energy resources, characterized with a heavy industry ratio, excessively simple and extensive production methods, lack of funds for environmental governance; and emphasizing hardware over software prevails everywhere in Midwestern China. All these factors make it difficult for Midwestern China to get rid of the sluggish development mode of “high investment and low efficiency”. In addition, the openness of Midwestern China is not high, and the introduction of advanced production management technology in Eastern China is insufficient, resulting in a large gap in the TGR of China’s mining environment between Midwestern China and Eastern China. The TGR between Central China and Western China has gradually decreased, from 0.117 in 2007 to −0.069 in 2016. Thus it can be seen that Western China has seized and effectively made the best of the development opportunities of the western development, actively eliminated backward production capacity in the process of mineral resources development, improved the resource integration mechanism, and gained achievements in environmental protection. It can also be seen that Central China faces the greatest pressure in the process of realizing green mining development. Compared with Eastern and Western China, Central China has a rich variety and high concentration of mineral resources, but some poor mines are discarded, resulting in pollution and waste of a large amount of land resources, and the mine geological environment governance and recovery are more difficult. Therefore, relevant departments should take effective measures as soon as possible to improve this situation and narrow the technological gap in the mining environment between areas in China.

C. MFEI ANALYSIS OF CMI

The above analysis reveals the regional differences of the environmental efficiency of China’s provincial mining industry and the gap of regional environmental technology level, but it is still impossible to judge the root cause of the EI of CMI. This section will locate at the root cause of the EI, thus finding out the weak links of the environmental efficiency in each province and increasing the pertinence of policy making. According to Formulas (6) to (8), in this paper the MFEI of CMI is decomposed into TGI and MI, and the ratio of TGI to MFEI and the ratio of MI to MFEI are calculated to explore the root causes of the EI of the mining industry in different regions of China, respectively. The proportion of TGI and MI in MFEI by province is shown in Figure 4.
According to calculations, China’s provincial average MFEI score of the mining industry is 0.358 during 2007-2016 with the TGI being 0.206 and the MI 0.152. It can be seen that TGI and MI are all contributors to the MFEI of CMI, and TGI has a greater contribution, accounting for 57.5%. On a province basis, TGI and MI of Tianjin, Shanghai and Shandong are all zero, indicating that these three provinces represent China’s optimal level in terms of green mining technology and resource allocation level. During the 2007-2016 period, the GMI is the root source of the MFEI of CMI in Beijing, Jiangsu, Zhejiang, Guangdong and Hainan, and these provinces are all in the eastern region, which shows that the eastern region has a high level of resource extraction technology but ignores the environmental management level. In the future, the eastern region should further strengthen resource allocation and improve the management level of the mining environment. The TGI is the root cause of the MFEI in Jilin, Jiangxi, Henan, Hubei and the other provinces, which shows that the environmental technology level of these provinces is low, and there is a large gap with the developed provinces in the east. It has been found that TGI and MI together contribute to the MFEI of the MI in these provinces such as Hebei, Shanxi, Chongqing, Guizhou and Gansu. These provinces not only need to improve technological progress but also need to strengthen resource allocation and environmental management capabilities.

The evolution trend of the MFEI of CMI and its decomposition at the national level are shown in Figure 5. During 2007-2013, the MFEI of CMI shows a general downward trend, from 0.361 in 2007 to 0.333 in 2013; after rising to 0.498 in 2014, it falls again. Over the period 2007-2013, the TGI fluctuates slightly, and after a rise to 0.270 in 2014, it drops sharply. From 2007 to 2013, the MI shows a downward trend, but it has increased year by year since 2014.

This shows that during 2007-2013, efficient resource allocation and environmental management measures are the main reasons for the improvement of the EE of CMI. However, in recent years, the TGI has shown a downward trend, while the MI has shown an upward trend, that is, the level of mining environmental management is declining, which means that the obstacles that hinder the improvement of the EE of CMI in the future are likely to be the imbalance of resource allocation and the decline in environmental governance capabilities. In the future, sufficient attention should be paid to the restoration and governance of the mining environment.

In these three major areas perspective (Table 3), the average value of the TGI and the MI in Eastern China are 0.010 and 0.285, respectively, indicating that invalid environmental management is the main cause of the MFEI of the MI in Eastern China. Eastern China has strong economic strength, superior location advantages and excellent technical conditions. To achieve EE improvement of CMI, it is necessary to continue to maintain technical advantages...
TABLE 3. The TGI and MI of the mining industry in China’s three major regions during 2007-2016.

| Year | TGI in Eastern China | MI in Eastern China | TGI in Central China | MI in Central China | TGI in Western China | MI in Western China |
|------|----------------------|---------------------|----------------------|---------------------|---------------------|---------------------|
| 2007 | 0.000                | 1.000               | 0.298                | 0.000               | 0.338               | 0.113               |
| 2008 | 0.000                | 0.185               | 0.226                | 0.062               | 0.331               | 0.110               |
| 2009 | 0.006                | 0.190               | 0.405                | 0.000               | 0.301               | 0.168               |
| 2010 | 0.000                | 0.188               | 0.360                | 0.000               | 0.356               | 0.155               |
| 2011 | 0.000                | 0.220               | 0.323                | 0.000               | 0.319               | 0.178               |
| 2012 | 0.000                | 0.126               | 0.337                | 0.019               | 0.314               | 0.150               |
| 2013 | 0.000                | 0.171               | 0.347                | 0.000               | 0.316               | 0.156               |
| 2014 | 0.030                | 0.270               | 0.452                | 0.150               | 0.367               | 0.242               |
| 2015 | 0.040                | 0.254               | 0.311                | 0.061               | 0.222               | 0.219               |
| 2016 | 0.019                | 0.243               | 0.250                | 0.069               | 0.156               | 0.211               |
| Mean | 0.010                | 0.285               | 0.331                | 0.036               | 0.302               | 0.170               |

and increase efforts to improve environmental management. In contrast, in the sample period, TGI and MI in Central China are 0.331 and 0.036, respectively, and TGI and MI in Western China are 0.302 and 0.170, respectively. It can be seen that the TGI in Central and Western China has reached 90.1% and 64.0% respectively, which is the main contributor for the MFEI of the mining industry in Central and Western China. Therefore, provinces in Central and Western China should increase technology investment, implement the use of funds, focus on narrowing the production technology gap between regions, and at the same time, introduce superior management modes to Eastern China and take advanced resource allocation methods to create better conditions for the mining industry to achieve efficient and clean mining.

D. RESULTS ANALYSIS OF TOBIT REGRESSION

1) INDEX SELECTION OF TOBIT MODEL

We have discussed the EE of CMI, analyzed regional differences, TGR, and decomposed MFEI, but what are the reasons of such differences and how do they affect the EE of CMI needs to be further discussed by establishing an econometric mode. Thus, in this paper, the MFEE of CMI during 2007-2016 are taken as the dependent variables, and influencing factors are used as the independent variables of regression model to calculate the effects on China’s overall MFEE of the mining industry, the MFEE of CMI in Eastern, Central and Western area.

a: ECONOMIC DEVELOPMENT LEVEL

It is generally believed that the development of regional mining industry is affected by the regional economic development level. The higher the regional economic development level, the higher the environmental governance level, the greater the corresponding environmental efficiency [17], [51], [52]. This paper selects the per capita gross domestic product (GDP) expressed at constant 2007 prices to represent the economic development level of each province in China, and uses lnGDP to eliminate the non-stationarity of the sample data.

b: INNOVATIVE ABILITY

The proportion of research and development (R&D) personnel to the total number of employees is used to measure the region’s technological innovation potential in each province [53], [54]. R&D personnel have played a non-negligible role in the development of the mining economy, the improvement of resource exploitation technology and environmental governance technology. For this reason, this article regards it as one of the influencing factors of the environmental efficiency in the mining industry.

c: ENVIRONMENTAL REGULATION INTENSITY

In recent years, the research between environmental regulation and environmental efficiency has attracted extensive attention from scholars [17], [55], [56]. The mining industry is a high consumption, high pollution, high emission (‘‘three highs’’) industry and China has issued a number of policies aiming at improving the resource utilization efficiency of mining industry and reducing pollutant emissions. As one of the influencing factors of environmental efficiency, the environmental regulation intensity is expressed by the investment in anti-pollution projects as percentage of GDP in each province.

d: EDUCATION LEVEL

Generally speaking, the higher the education level, the higher the level of environmental protection willingness, the higher the work skills and management level, and the easier the improvement of the EE of CMI [53], [57]. In this paper, the proportion of students in ordinary colleges and universities in the permanent population at the end of the year is used to measure the education level of each province.

e: INDUSTRIAL STRUCTURE

Differences in industrial structure will affect the demand for mineral products, which will have a certain impact on the development of the mining industry [56], [58]. This paper uses the proportion of the tertiary industrial added value to the secondary industrial added value to measure the heightening of the industrial structure, and explores the impact of the
industrial structure of each province on the environmental efficiency of the mining industry.

f: RESOURCE UTILIZATION RATE
The approved mining land resources by the mining license are a prerequisite for the development of the mining industry [59]. The Ministry of Land and Resources P.R.C. issued a document requesting the full utilization of the mine land, aiming at increasing the utilization rate of land resources. Therefore, this paper uses the per unit output value of mining area to measure the resource utilization rate of the mining industry. It is expressed as the proportion of the approved registered area by the mining license to the industrial sales output value of the mining industry and we convert it into 2007 constant prices using the producer price index of industrial products by sector.

g: STATE-OWNED CAPITAL PROPORTION
We use the proportion of state-owned capital to paid-up capital to represent the state-owned capital proportion. Mining is an important industry in the national economy and has always been playing an important part of the state-owned economy [41]. The higher the state-owned capital proportion in the mining industry, the easier it is to obtain special support from government departments, but it may also cause problems such as low efficiency and insufficient innovation in the mining industry [60].

2) REGRESSION RESULTS OF TOBIT MODEL
This paper used Tobit model to estimate the influencing factors of the EE of CMI. The MFEE, a restricted dependent variable, has its value between 0 and 1 Using ordinary least squares (OLS) will cause biased estimates and regression coefficient inconsistency [56], [61], [62]. Thus, we used Tobit panel econometric model for regression analysis so that we could get a consistent estimate of the parameters. The data of influencing factors were collected from China Statistical Yearbook [50], China Science and Technology Statistical Yearbook [63], China Environmental Statistical Yearbook [64], China Industrial Statistical Yearbook [49] and China Land and Resources Statistical Yearbook [7]. The Tobit econometric model is established as Eq. (10):

\[ y_{it}^* = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_3 \\
+ \beta_4 X_4 + \beta_5 X_5 + \beta_6 X_6 + \beta_7 X_7 + \epsilon_{it} \]  

(10)

In Formula (10): \( i \) indicates the \( ith \) province, and \( t \) indicates the year between 2007 and 2016. \( y^* \) indicates the MFEE of CMI by province, \( X_1 \) indicates economic development level, \( X_2 \) indicates innovative ability, \( X_3 \) indicates environmental regulation intensity, \( X_4 \) indicates education level, \( X_5 \) indicates industrial structure, \( X_6 \) indicates resource utilization rate, \( X_7 \) indicates state-owned capital proportion, \( \beta_i \) (\( i = 0, 1, \cdots, 7 \)) is an unknown coefficient, and \( \epsilon \) is a random error term, and obey normal distribution.

Tobit regression was conducted with STATA12.0 software. The regression results are shown in Table 4.

It can be seen from the regression results that there are obvious differences in the role of the seven influencing factors in overall China, Eastern China, Central China and Western China:

1. Nationally, economic development level can significantly improve China’s overall MFEE of the mining industry, and that has significantly positive effect on the MFEE of CMI in Eastern area. The high economic development level in Eastern China has brought many opportunities to the development of mining, such as high-tech R&D talents, management talents, and advanced production methods, which is conducive to the improvement of the MFEE of the mining industry in Eastern China. Similarly, economic development level has a positive effect on the MFEE of the mining industry in Western China, but the regression coefficient failed to pass the significance test, indicating that the effect is not obvious. On the contrary, economic development level has hindered the improvement of the environmental efficiency. This conclusion supports the “Environmental Kuznets Curve Hypothesis”. On the one hand, if the central region wants to achieve substantial economic growth, it needs to increase investment, thereby increasing the mineral resources such as coal, which leads to more pollution emissions, so it has a negative impact on the MFEE of the mining industry.

2. Innovative ability has a negative effect on the MFEE of CMI. This conclusion does not support the “Porter Hypothesis”, mainly because the central and western regions have lowered China’s ability to transform scientific and technological innovation. On the one hand, the possible explanation is that use the ratio of R&D personnel to the total number of employees to measure the regional technological innovation potential is not a suitable indicator. On the other hand, in the short term, mining companies in Midwestern China employ a large proportion of labor in the society for scientific and technological research and development, and squeeze the production resources directly used for production and operation. In addition, there is a lag in technological innovation, so it has not brought a positive effect on the MFEE of the mining industry. The scientific and technological innovation achievements in Eastern China have been effectively transformed, which has promoted the improvement of the environmental efficiency, and is significant at a 10% level.

3. At a 1% level, there is a significant negative correlation between the environmental regulation intensity and the MFEE of the mining industry, indicating that environmental regulation measures have had a “offset effect” on the mining industry and brought a negative impact on the environment. Enterprises invest a lot of manpower and material resources in environmental governance, and improve the environment while causing cost losses.

4. Nationally, increasing education level is conducive to the progress of the MFEE of CMI and that it passes the significance test at 5% level. Education level has significantly positive impacts on the environmental efficiency in
TABLE 4. Tobit regression results of factors affecting MFEE of CMI.

| Variable | Overall China | Eastern China | Variable | Central China | Western China |
|----------|---------------|---------------|----------|---------------|---------------|
|          | Coefficient   | Std.Error     | Coefficient | Std.Error    | Coefficient   |
| X1       | 0.2260***     | 0.0629        | 0.5720*** | 0.1712        |               |
| X2       | -0.0365       | 0.1669        | 0.5679*  | 0.3200        |               |
| X3       | -0.1101***    | 0.0409        | -0.1370   | 0.1183        |               |
| X4       | 0.0016**      | 0.0007        | -0.0044* | 0.0015        |               |
| X5       | 0.3228***     | 0.0914        | 0.7745***| 0.2218        |               |
| X6       | 0.0948***     | 0.0327        | 0.1477** | 0.0550        |               |
| X7       | -0.0018       | 0.0023        | -0.0075  | 0.0058        |               |
| constant | -1.9539**     | 0.6769        | -5.7854**| 1.8512        |               |
| R2       | 0.2380        | 0.2430        |          |               |               |
| OBS      | 310           | 110           |          | MEI           | 120           |

Note: ***,** and * are respectively at the 1%, 5% and 10% significance levels.

Midwestern China at a 1% level. Generally speaking, the higher the education level, the higher the people’s environmental protection awareness, working skills and management level, the higher the MFEE of the mining industry, which have been supported by our research. It is worthy of noting that the educational level of the eastern region is negatively correlated with the MFEE of the mining industry, indicating that the efficiency of the mining industry in Eastern China to absorb regional excellent human resources is low.

5. The industrial structure has significantly promoted the MFEE of CMI in Eastern area, indicating that the higher the added value of the tertiary industry, the more conducive to improving the MFEE of the mining industry in Eastern China. The tertiary industry is mainly the circulation service industry including transport, storage and post industry, management of water conservancy, environment industry. It not only has low environmental pollution, but also provides transportation, management, technology and other conveniences for mining development. On the contrary, the industrial structure has had a significant negative effect on the MFEE of the mining industry. In recent years, with the rise of the central region and the implementation of the western development strategy, China has increased infrastructure construction in the Midwestern region. Excessive investment has led to unreasonable input and output of the tertiary industry in the Midwestern region, and waste of resources, which is not conducive to implement green management in the mining industry.

6. The resource utilization rate has significant positive effects on the progress of the MFEE of CMI. The regression coefficients of the eastern, central and western regions are 0.1477, 0.1275 and 0.3451, respectively, which shows that improving the resource utilization rate of the mining industry has a very important impact on the improvement of the environmental efficiency.

7. Nationally, the relationship between the state-owned capital proportion and the MFEE of CMI is negative. In these three areas, the regression results of the eastern and western regions are consistent with the whole country. Government investment can help the mining industry to share the pressure, but if the government is involved too much in the investment, it may cause some enterprises to lose their initiative, which is not conducive to environmental improvement. The central region effectively uses the government’s financial support to improve environmental efficiency.

V. CONCLUSIONS AND RECOMMENDATIONS

A. CONCLUSIONS

Based on China’s provincial data during 2007-2016, this paper uses meta frontier theory to measure the EE of CMI by province, analyzes regional differences and the TGR. The MFEI of CMI is decomposed into “TGI” and “MI”. Subsequently, a Tobit econometric model is established based on the perspective of regional heterogeneity, to explore the differential impact of relevant factors on the overall MFEE of CMI, the MFEE of CMI in Eastern, Central and Western area, respectively. This paper further analyzes the economic and environmental effects of the mining industry, and provides policy reference for the sustainable development of the mining industry. The study shows:

1. During 2007-2016, the average MFEE score of CMI is 0.643, and there is still 35.7% room for improvement from the production frontier. The average MFEE score of CMI in eastern, central and western area are 0.775, 0.633 and 0.528, respectively, indicating that the MFEE of the mining industry in Eastern China represents nation’s optimal level.

2. The TGR of the mining environment in Eastern, Central, and Western China are 0.990, 0.648, and 0.626, respectively. Eastern China has a superior mining economic development environment. The TGR between Eastern China and Midwestern China is relatively large and has been hovering between 0.1 and 0.6. The TGR between the central and western regions is getting smaller and smaller, dropping from 0.117 in 2007 to -0.069 in 2016.

3. The average MFEI score of CMI is 0.358, with the TGI and the MI accounting for 57.5% and 42.5%, respectively. The MI is the main contributor of the MFEI of the mining industry in Eastern China, and the TGI is the main contributor of the MFEI of CMI in Midwestern area.
(4) The regression results of the influencing factors show that the economic development level improves the EE of the mining industry in Eastern and Western China and hinders that in Central China. The innovative ability has a negative effect on the EE of the mining industry in Midwestern China, and exhibit the opposite effect in Eastern China. At a significant level of 1%, there is a significantly negative correlation between the environmental regulation intensity and the EE of the mining industry. The education level has significantly positive impacts on the EE of CMI in Midwestern area, while the education level has a negative correlation with the EE of CMI in Eastern area. The industrial structure significantly promotes the environmental efficiency in Eastern China, while for Midwestern China; the industrial structure has a significantly negative effect on the improvement of the environmental efficiency. The resource utilization rate has significantly promoted the progress of the EE of CMI and the regression coefficients of the three major regions of east, central and west are 0.1477, 0.1275 and 0.3451, respectively. Nationally, the relationship between the state-owned capital proportion and the EE of CMI is negative. From a region perspective, the results of the regression in Eastern and Western China are consistent with that in the national level, while in Central China the results are contrary to that in the national level.

B. RECOMMENDATIONS

Based on the above conclusions, we make the following recommendations:

(1) The fundamental way out to improve the EE of CMI is that all provinces should economize and intensively use land resources, publicize green mine environmental protection policies from time to time, expand the environmental protection intensity of mineral resources exploitation, and strictly evaluate the environmental impact of mineral resources exploitation. All provinces should actively implement the principles of “The process of mining should be accompanied with managing and recovering; the one who mines should manage to govern and restore”, and timely control and restore the mine geological environment.

(2) The mining environments in the three major regions of east, central and west are very different. The government should fully consider the regional imbalances and formulate targeted economic policies of the mining industry. On the one hand, the eastern region should play an exemplary role, make full use of superior location conditions, advanced technology and other resources to promote the construction of green mines in China, on the other hand, it must support the improvement of mining technology research and environmental management in Midwestern China.

(3) The TGR between the eastern and central and western of the mining industry is relatively large. In order to narrow the TGR between regions, regional technical exchanges and cooperation should be strengthened to promote the transfer of advanced production and environmental protection technologies from Eastern China to Midwestern China. Eastern China should focus on improving the quality and benefits of environmental management of the mining industry, strengthen the rational allocation of resources, and make full use of advanced technical conditions to solve the problems left over by the history of mine geological environment restoration and comprehensive treatment. Midwestern region strive to increase investment in technology, learn advanced production and environmental protection technologies in the eastern region, and introduce superior management modes and resource allocation methods to achieve scale economy in mining industry.

(4) Mine environmental protection needs to coordinate the forces of all parties and make an overall consideration of each one. On the one hand, the government urges enterprises to implement the requirements of green mining through the introduction of environmental regulation policies and the establishment of environmental regulatory agencies; on the other hand, mining enterprises should promote the idea of sharing and building together in the mine area, strengthen cooperation with local residents, and establish a win-win mode of resource and environment management in the mining area.

(5) Based on the heterogeneous impact of various external factors on the MFEE of CMI, the following recommendations are made: The eastern region should strengthen the human resources construction, improve the efficiency of the mining industry in absorbing the excellent human resources, establish a national fund use regulatory agency, and implement every use of the funds. While raising the economic development level in the central region, it is also important to provide talent and financial support for the prevention and control of mining pollution, and achieve economic growth under the conditions of low investment and low pollution. In addition, the central region should increase the support of R&D funds in the mining industry, equip mining companies with full-time technology managers, formulate special rewards and management systems for them, seize the opportunities for the development of emerging digital technologies, and reasonably allocate resources to promote infrastructure construction in the process of the rise of Central China. The western region should improve the talent introduction system, attract outstanding scientific and technical personnel and management personnel to participate in the green activities of the mining industry, use the innate resource advantages to vigorously develop the tertiary industry, and use state capital for technological innovation in the field of mining production and environmental governance, actively declare green mines.

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