Research on Evaluation of Technology Innovation Efficiency in China's Pollution-Intensive Industries

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Abstract. Based on 20 pollution-intensive industries’ data in China during 2007-2016, this paper employs two-stage SBM model to evaluate the technology innovation efficiency of Chinese pollution-intensive industries. The results show that: the industry with the efficiency value between 0.6 and 1 in the R&D stage and the commercialization stage only accounts for 30% and 50%. Also, the R&D ability limits the improvement of technology innovation efficiency in pollution-intensive industries.

1. Introduction
Under the pressure of resources and environmental restrictions, for pollution-intensive industries, technological innovation is an important way to break through resource constraints and promote environmental sustainability. The technological innovation policy has pushed various industries to continuously increase investment in Research and Development (R&D). Taking the coal industry as an example, according to the Statistical Bulletin of National Science and Technology Funds Input in 2017, the coal industry's R&D investment in 2017 was 14.89 billion yuan, and the R&D intensity (the ratio of the investment to the main business income) was 0.59% [1]. The total profit of the coal industry in 2017 was 295.269 billion yuan [2]. Whether the strong R&D investment has achieved the desired economic and environmental returns has not been thoroughly studied. Therefore, in order to promote the innovation transformation of China's pollution-intensive industries, it is particularly important to evaluate the technology innovation efficiency of pollution-intensive industries and analyse its development trends.

2. Literature Review
Domestic and foreign scholars mainly study the measurement of technology innovation efficiency from four levels: nation, region, industry and enterprise. The mainstream methods to calculate innovation efficiency in academia are stochastic frontier analysis (SFA) and data envelopment analysis (DEA), both of which have their own advantages and disadvantages. The DEA method doesn’t consider the dimensional unification and index weight. Li, Hu, and Wang (2016) analysed the innovation efficiency of 27 cities in the middle reaches of the Yangtze River based on DEA [3]. Liu, Wu, and Chu (2018) proposed DEA’s Hicks-Moorsteen index model to accurately measures technological change and environmental efficiency [4]. In addition, Bi, Huang, and Wang used DEA model to analyse low-carbon technological innovation of China's manufacturing industry [5]. Ni (2016) believed that non-radial
super-efficiency DEA with lag better reflected the lagging effect of input and output of university scientific research system [6]. However, in the above studies using DEA method, relaxation improvement is generally ignored and only economic benefits are considered in the output. Therefore, using the non-radial SBM (Slack Based Measure) model to measure innovation efficiency can obtain more objective and deeper result information.

For the research on technological innovation in pollution-intensive industries, scholars mostly analyze the influencing factors such as Chintrakarn (2008) [7], Jiang and Teng (2014) [8], Wu (2018) [9], etc. However, the research on measuring the technology innovation efficiency of pollution-intensive industries is relatively scarce, and only some literatures are related to it. Li, Yao and Tong (2014) measured the technological innovation abilities of 11 heavy polluting industries from the perspective of input and output [10]. Wu, Yang, Tang, Wu and Fu (2018) evaluated the green innovation efficiency of 16 heavily polluting industries in China based on the dual attributes of green innovation [11].

From the above analysis, it can be seen that the academic research on industrial technological innovation is mostly from the perspective of manufacturing industry or strategic emerging industry. And there is a little research on pollution-intensive industries. As the pollution-intensive industries are closely related to energy conservation and emission reduction, the research on the technological innovation of pollution-intensive industries should be paid more attention. Therefore, based on the data of 20 pollution-intensive industries from 2007 to 2016, this paper evaluates the efficiency of technological innovation from a static point of view by using the SBM method.

3. Methodology

3.1. Two-stage innovation process

Schumpeter (1934) first proposed that innovation was a recombination of production factors [12]. Subsequently, the scientific community further defined that innovation was a phenomenon under the complex interaction of innovation subjects and elements. The single-stage innovation process does not conform to the actual production activities of the enterprise. Guan and Chen (2010) simplified the whole technological innovation process from the perspective of economics, and divided it into 2 stages: R&D stage and commercialization stage [13]. Specifically, the R&D stage uses innovation inputs to obtain scientific and technological output, while the commercialization stage uses R&D output to obtain economic benefits. The two-stage innovation process pays more attention to the internal structure of technological innovation, which contributes to a comprehensive evaluation of the technological innovation process. Therefore, this study uses a two-stage innovation process to evaluate the innovation efficiency of pollution-intensive industries.

3.2. Two-stage SBM model

Based on the above research on two-stage innovation process, this paper builds a two-stage SBM model under the assumption of variable returns to scale (VRS). Assume that there are n decision making units (DMUs), denoted by DMU_k (k = 1, 2, ..., n). For each DMU_k, the innovation process is divided into two stages, there are M R&D input X_{mk} (m = 1, 2, ..., M), W intermediate output Z_{wk} (w = 1, 2, ..., W), R expected output Y_{rk} (r = 1, 2, ..., R) and U undesired output P_{uk} (u = 1, 2, ..., U).

In the second stage, Guan & Chen (2010) proposed that it was the intertwined efforts of the R&D and non-R&D technological innovation inputs that eventually result in the final technological innovation outcomes [13]. Therefore, this paper adds intermediate input in the commercialization stage: the intermediate input is denoted as V_{tk} (t = 1, 2, ..., T).

For the calculation of R&D stage, R&D input should be reduced as much as possible to improve R&D efficiency. Therefore, this paper adopts the input-oriented SBM model, and the formula is as follows:

\[
\text{Min} E_R = 1 - \frac{1}{M} \sum_{m=1}^{M} \frac{s_m^{m}}{x_{mk}}
\]

s.t. \[\sum_{j=1}^{n} \varphi_j x_{mj} + s_m^- = x_{mk}\]
\[\sum_{j=1}^{n} \varphi_j z_{wj} \geq z_{wk}\]
\[\sum_{j=1}^{n} \varphi_j = 1\]
3.3. Data and sample
In order to match the industry classification in the statistical yearbook, this paper refers to the classification methods of Zhao (2003) [14] and Jiang (2010) [8], selects 20 pollution-intensive industries as samples, divides the 20 pollution-intensive industries into light, medium and heavy polluting industries, and numbers them by 1-20, as shown in table 1.

| Pollution Level | Num | Industry | Pollution Level | Num | Industry |
|-----------------|-----|----------|-----------------|-----|----------|
| Heavy pollution | 1   | Coal mining and processing industry | Moderate pollution | 11 | Agro-food processing industry |
|                 | 2   | Oil and gas exploitation industry  |                 | 12 | Medicine industry |
|                 | 3   | Ferrous metal mining and dressing industry |                 | 13 | Chemical fiber manufacturing industry |
|                 | 4   | Nonferrous metal mining and dressing industry |                 | 14 | Non-ferrous metallurgical smelting and rolling processing industry |
|                 | 5   | Non-metallic mining and dressing industry |                 | 15 | Metal products industry |
|                 | 6   | Papermaking and paper product industry | Light pollution | 16 | Textile industry |
|                 | 7   | Chemical raw material and products manufacturing industry |                 | 17 | Leather, coat products industry |
|                 | 8   | Non-metal mineral product processing industry |                 | 18 | Printing and recording media reproduction industry |
|                 | 9   | Ferrous metallurgical smelting and rolling processing industry |                 | 19 | Petroleum refining and coking industry |
|                 | 10  | Electricity, thermal production and supply industry |                 | 20 | Rubber and plastic industry |

R&D is the first stage of innovation and its main inputs include Time Equivalent of R&D Personnel as the labor input [15], and Internal Expenditure of R&D funds as the financial input [15].
Griliches (1990) argued that patents as a measure of R&D output have certain limitations, not all inventions are patented, and the quality of patented inventions varies greatly [16]. However, patents are closely related to innovation activities, and they represent new technologies [17]. Therefore, this paper uses Number of Patent Applications as the intermediate output [18].

In the second stage, this paper chooses Expenditure on New Product Development to measure additional investment. The final output of pollution-intensive industries is divided into expected output and non-expected output. According to the usual practice, this paper chooses the Sales Revenue of New Products as the expected output. In addition, technological innovation activities may involve the improvement of existing products or processes. And the sales revenue of new products can’t fully reflect the economic output. Therefore, it is necessary to add the output index of Main Business Income.

For the unexpected output of the pollution-intensive industries, it must be the pollutants produced in the production process. Therefore, industrial water waste, gas waste and solid waste are selected as the pollutants of the pollution-intensive industries in this paper. However, different pollutants have different units. In order to eliminate the influence of dimension units, this paper refers to Wu [9] and chooses industrial pollutant index of different industries as the unexpected output. The formulas are as follows:

First, dimensionless processing is carried out on the original data:

\[ r'_{i,n,t} = \frac{r_{i,n,t} - r_{n,\min}}{r_{n,\max} - r_{n,\min}} \quad i = 1,2 \ldots 20; \quad n = 1,2,3; \quad t = 1,2 \ldots 10 \tag{4} \]

In (4), \( r'_{i,n,t} \) represents the pollution-intensive industry, and \( n \) is the type of pollutant.

Secondly, according to the proportion of pollutants, the non-expected output index can be obtained by weighted sum of pollutants (the weight of waste water, waste gas and solid waste is 0.40, 0.37 and 0.23 respectively).

\[ \varphi_{lt} = \sum_{n=1}^{3} r_{n} r'_{i,n,t} \tag{5} \]

This paper takes 20 pollution-intensive industries in China from 2007 to 2016 as samples. All the data are from the corresponding years of Statistical Yearbook. In the static evaluation, due to the time lag of the transformation of innovation input into final output, this paper refers to Xiao [15] to take the lag period of 2 years: input in the R&D stage, intermediate output and additional input, the final output year is 2007-2014, 2008-2015, 2009-2016 in turn.

4. Empirical Analysis

4.1. Inter-industry efficiency comparison

The comprehensive efficiency of technological innovation in eight industries, such as ferrous metal mining and dressing industry, has reached a relatively optimal state. The overall efficiency of 15 industries is higher than 0.6, indicating that the comprehensive efficiency of technological innovation in most industries is at the medium or high level. For R&D efficiency, efficiency between 0.6 and 1 industries accounts for only 30%. Although innovative resources are continuously invested, the industry has poor absorptive capacity of innovative resources and the output of R&D is not satisfactory. In the second stage, the industry with efficiency of 0.6-1 accounts for 50%. The overall mean value is 0.75, indicating that the transformation of innovation achievements in all industries still needs to be improved, but the overall trend is in a good state. Among them, both the comprehensive efficiency and the staged efficiency of the ferrous metal mining and dressing industry are in a relatively optimal state, which indicates that the effectiveness of technological innovation has been continuously improved in the 12th Five-Year Plan period.

| Number | Mean | Mean | Mean |
|--------|------|------|------|
|        | \( E \) | \( E_R \) | \( E_M \) | \( E \) | \( E_R \) | \( E_M \) | \( E \) | \( E_R \) | \( E_M \) |
| 1      | 0.18 | 0.09 | 0.96 | 8      | 0.45 | 0.49 | 0.83 | 15     | 0.73 | 0.80 | 0.52 |
| 2      | 0.04 | 0.18 | 0.86 | 9      | 0.88 | 0.17 | 0.99 | 16     | 0.97 | 0.59 | 0.85 |
| 3      | 1.00 | 1.00 | 1.00 | 10     | 1.00 | 0.85 | 1.00 | 17     | 1.00 | 0.75 | 0.58 |
4.2. Efficiency analysis of heavy, medium and light polluting industries

In order to further explore the industrial differences of technological innovation efficiency, this study evaluates the innovation efficiency of industries with different pollution levels. The overall efficiency of China's pollution industry is stable. The efficiency of light pollution industry is the highest, while that of heavy pollution industry is the lowest. The main reason is that the unexpected output is taken into account in the calculation of comprehensive efficiency. Moreover, heavy pollution industry is dominated by traditional heavy industry with unreasonable industrial structure. In addition, R&D efficiency in medium-polluted industries is the lowest. From Table 3, it can be seen that the R&D investment in medium-polluted industries ranks first, while the efficiency of R&D is the lowest. These industries may have serious waste of investment resources, or the number of patent unauthorized is the majority. In the second stage, relative to the medium and light pollution industries, the heavy pollution industries are better at transforming scientific and technological achievements into economic benefits. However, the commercialization and R&D efficiency in the medium pollution industries are also at a low level. For the medium pollution industries, they need to reduce the waste of R&D resources while improving the output of economic benefits.

Table 3. Two-stage technological innovation efficiency values of industries with different pollution levels

| Pollution Level | Mean Value | R&D Personnel | Internal Expenditure of R&D funds / million |
|-----------------|------------|---------------|------------------------------------------|
| Heavy           | 0.66       | 0.53          | 0.88                                     |
|                 |            |               | 37596                                    |
|                 |            |               | 16239.27                                 |
| Moderate        | 0.84       | 0.42          | 0.59                                     |
|                 |            |               | 45762                                    |
|                 |            |               | 17565.44                                 |
| Light           | 0.88       | 0.53          | 0.64                                     |
|                 |            |               | 25088                                    |
|                 |            |               | 8746.53                                  |

5. Conclusions

In this paper, data of 20 pollution-intensive industries in China from 2007 to 2016 are selected as research samples, and two-stage SBM model is employed for static evaluation of their technological innovation efficiency. Specific conclusions and policy suggestions are as follows: In view of different pollution levels, due to unexpected output and unreasonable industrial structure, the comprehensive efficiency of heavy-polluted industries is not satisfactory. Therefore, for heavy-polluted industries, they should not pursue the maximization of economic benefits while neglecting the protection of environmental resources. They should pay more attention to upgrading industrial structure and developing green economy. Whether in the stage of R&D or in the commercialization stage, the efficiency values of medium polluting industries are lower than heavy and light polluting industries, so medium polluting industries should make rational use of resources and strengthen the ability of transforming the R&D output into economic benefits. For light polluting industries, because of its lowest pollution level, light polluting industries should pay more attention to improving the efficiency of commercialization stage than heavy polluting industries and medium polluting industries. They should pay more attention to marketization and deepen cooperation between industries university and research institutes.

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