

# Comparative analysis of Asian main iron and steel countries' total factor energy efficiency

Chuan Zhang<sup>1</sup>, Weida He<sup>1</sup> and Rong Hao<sup>1,2,\*</sup>

<sup>1</sup>Donlinks School of Economics and Management, University of Science and Technology Beijing, No. 30, Xueyuan Road, Haidian District, Beijing 100083, China

<sup>2</sup>China Nonferrous Metal Industry's Foreign Engineering and Construction Co. Ltd, NFC Building, 10 Anding Road, Beijing 100029, China

**This article evaluates the total factor energy efficiency, energy conservation potential and emission reduction potential of the typical enterprises in the main iron and steel-producing countries such as China, India, Japan and Korea by applying the SBM-desirable DEA model and the SBM-undesirable DEA model. The findings are beneficial for understanding the development status of the main Asian iron and steel-producing countries. The empirical results indicate that the Chinese iron and steel enterprises in the sample made great progress in terms of the total factor energy efficiency. Korea's POSCO and Japan's JFE Group and Nippon Steel enterprise performed the best in terms of energy efficiency, energy conservation and emission reduction. The total factor energy efficiency value of India's Tata Steel is comparatively well. It has completed Jamshedpur Works' brownfield expansion project, which help it add eco-efficient products to its portfolio while using fewer natural resources, less energy and less water per tonne of steel produced.**

**Keywords:** Iron and steel enterprises, total factor energy efficiency, Asian countries, SBM-undesirable DEA model.

CHINA's iron and steel industry has made significant progress in the past several decades. It has become the world's largest steel producer. Its crude steel output increased from 101 million tonnes in 1996 to 820 million tonnes in 2014. In 2015, China adopted a 'de-capacity' policy to promote the transformation and upgrading of the iron and steel industry. As of 2015, China's crude steel production was 804 million tonnes and realized its first decline in 30 years, accounting for 49.54% of the world's production (China Iron and Steel Statistics Annual Report, 1996–2015). Although China is the largest in terms of steel production, it is not a steel power nation. The extensive development of China's iron and steel industry has created many problems and challenges, such as industrial overcapacity, low industrial concentration, malignant market competition, environmental pollution and energy imbalances. China's government has begun to strengthen the transformation and upgradation of the iron and steel industry and promote sustainable and healthy

development. It emphasized the development of circulation in the iron and steel industry during the periods of the '11th five-year plan' and the '12th five-year plan'. In the '13th five-year plan' period (2016–2020), China has promoted the development of a 'green' iron and steel industry. Some studies have begun to explore the energy efficiency and environmental pollution problems of China's iron and steel enterprises.

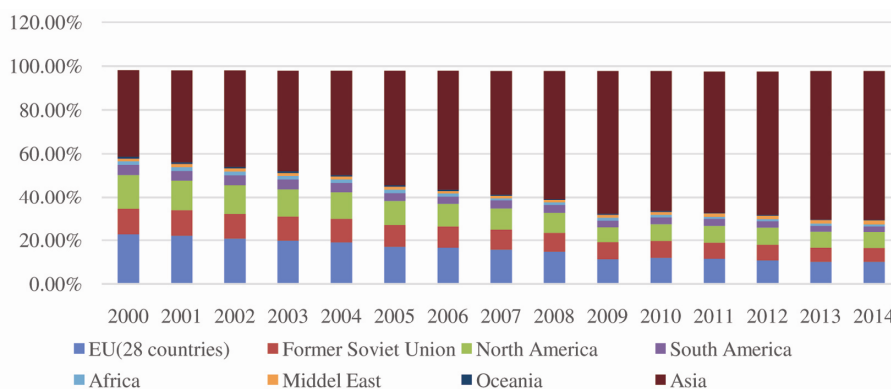
The energy efficiency of China, including regional energy and emissions efficiency and industry energy efficiency, has been studied<sup>1,2</sup>. The early studies on the efficiency of iron and steel enterprises do not consider resource constraints and pollutant emissions and mainly explore technical efficiency and scale efficiency<sup>3–6</sup>. The iron and steel industry consumes large amounts of energy. As the energy consumption of the iron and steel industry rose, the scholars began to study the efficiency of enterprises combined with energy constraints<sup>7,8</sup>. With the advancement of the circular economy, the development of the concept of green environmental protection has stepped into industry. Many studies have begun to pay more attention to the 'dirty' iron and steel industry. Some studies have been conducted on the efficiency and productivity of iron and steel enterprises considering pollutant emissions<sup>9–12</sup>. In terms of research methods for studying energy efficiency of iron and steel enterprises scholars mainly apply stochastic frontier analysis and the DEA method<sup>13–15</sup>.

There is no study on the total factor energy efficiency of representative iron and steel enterprises from Asian countries (China, Japan, Korea and India). In this article, we evaluate Asian iron and steel enterprises taking pollutants into account. The main questions we answer in this analysis are as follows: (1) what is the status of the world iron and steel industry's structure? (2) which iron and steel enterprises have high energy efficiency when taking pollutants into account? and (3) what is the energy conservation and emissions reduction potential of Asian iron and steel enterprises?

## Analysis of the world iron and steel industrial structure

The iron and steel industry is the mainstay and material guarantee in global economic and social development.

\*For correspondence. (e-mail: haorongnfc@hotmail.com)



**Figure 1.** Ratio of the crude steel output of each area to the world in 2000–2014. Data sources: *Steel Statistical Yearbook*.

The world's modern iron and steel industry development began in the early 19th century and fast spread in the 20th century. According to the *Steel Statistical Yearbook*, global crude steel production was only 28.5 million tonnes in 1900. The global crude steel output reached 189 million tonnes in 1950 and 850 million tonnes by 2000. Global crude steel production in the 19th century increased by 30 times. The world iron and steel industry developed most rapidly in the second half the 20th century. The product variety, quality, technology and equipment of the iron and steel industry have undergone revolutionary changes and taken a qualitative leap, which mainly comes from the support of scientific and technological development. Some advanced steel producers have completed the shift from scale expansion to structural optimization strategy. Steel producers from 1990 to 1950 were mainly distributed in the northern Atlantic coast of the US, Western Europe and the former Soviet Union, accounting for 87.5% of the world steel production. The US, partly being far away from the edge of the battlefield, economically and technologically developed rapidly during the two world wars. The crude steel output of US was 95.44 million tonnes in 1951, accounting for 45.3% of the world's crude steel production, demonstrating its dominance. From 1952 to 1974, with the introduction of pulverized coal injection technology, oxygen top blown converters, hot metal pretreatment, external refining, continuous casting, continuous mills, hot and cold strip rolling mills, etc. new technology was widely applied. The continuous development of iron and steel processes and technology contributed to accelerated expansion of global steel production. Global crude steel production reached 644 million tonnes in 1975. During this period, the Japanese iron and steel industry achieved rapid growth, gradually replacing the US and the Soviet Union. From 1975 to the end of the 20th century, the crude steel output of the global iron and steel industry increased from 644 million tonnes to 850 million tonnes. At this stage, the industrialization of Japan, Western Europe and the US was mature. The development pattern of these

countries embarked on the path of intensive quality growth. In contrast, developing countries were in an early stage of industrialization. To promote the industrialization process, developing countries increased their capacity. In the 21st century, iron and steel remain irreplaceable in the global economy and social development. They are also a measure of a country's comprehensive industrial level and national strength. The world iron and steel industry has gradually focused on North America, Western Europe, Eastern Europe and East Asia in the 21st century. With the global economic recovery and accelerating industrialization, developing countries have seen continued growth in crude steel production. Global crude steel production increased from 850 million tonnes in 2000 to 1.665 billion tonnes in 2014, and the average annual growth rate remained at 5%.

The Asian iron and steel industry developed rapidly in the 21st century. New capacity in the iron and steel industry mostly comes from Asia, which is quite rare in other areas. The ratio of the Asian crude steel output to the world increased from 39.41% to 68.29%, and that of the Middle East increased from 1.27% to 1.80%, and those of other areas appeared to decline. The ratio of the European Union (28 countries) decreased from 22.76% to 10.14%, that of the former Soviet Union decreased from 11.64% to 6.35%, and that of North America decreased from 15.29% to 7.25%. As seen from the above, the Asian iron and steel industry has played an important role in the development of the world iron and steel industry in the 21st century.

In 2014, the crude steel output of China, Japan, Korea and India accounted for 95.76% of that Asia, and they are the four largest producers of iron and steel. In 2000, the ratio of the crude steel output of China, Japan, Korea and India to Asia was 38.35%, 31.77%, 12.87% and 8.04% respectively. With the development in 15 years (between 2000 and 2014), the ratios grew to 72.13%, 9.7%, 6.27% and 7.65% respectively (see Figure 1). In addition, the crude steel yields of China, Japan, Korea and India were 822.7 million tonnes, 110.7 million tonnes 86.5 million

tonnes and 71.5 million tonnes respectively, values that are all among the top 5 in the world. Among the world's top 20 iron and steel enterprises, 10 of them from China, 2 from Japan, 2 from Korea and 1 from India. Thus, it can be observed that China, Japan, Korea and India occupy important positions in the world iron and steel industry.

## Methods

The data envelope analysis (DEA) model is a non-parametric mathematical programming method used to evaluate a set of homogeneous decision-making units. The traditional DEA model cannot address undesirable outputs when evaluating the total factor energy efficiency of iron and steel enterprises. In considering capital, labour, production and the benefits of economic indicators, fewer the inputs for the decision-making units and the larger the output, it is better. However, when desirable and undesirable outputs exist at the same time, the traditional DEA method cannot handle such situation. In the background of a circular economy, pollutant discharge blends with output variables, which is to say, desirable outputs and undesirable outputs exist in the model at the same time. For processing methods with pollutants as undesirable outputs, there are the hyperbolic measure method, pollutant input processing method, data transformation function method and distance function method.

### *Hyperbolic measure method*

The hyperbolic measure method is a nonlinear environmental efficiency evaluation method<sup>16</sup>. This method is relative to a radial measure. A radial measure, when evaluating environmental efficiency, cannot effectively distinguish between desirable outputs and undesirable outputs. The hyperbolic measure method makes up for the deficiencies of the radial measure and deals various outputs in an asymmetric manner, allowing the desired outputs to increase while reducing undesirable outputs. Specifically, the hyperbolic measure method uses a radial measure to analyse the expected output efficiency and uses the reciprocal to measure the efficiency of pollutants. This process changes the reference frontier of decision-making units, but can increase the desirable outputs and reduce pollutants at the same time. The hyperbolic measure method is a feasible method for evaluating efficiency when output variables include undesirable outputs. Because the hyperbolic measure method is a type of nonlinear programming efficiency evaluation method, its solving is tedious and accuracy cannot be guaranteed.

### *Pollutant input processing method*

The pollutant input processing method was first put forward by Haynes *et al.*<sup>17</sup>. When researchers evaluate

energy efficiency, they aim to have fewer undesirable outputs. In other words, they aim to reduce the undesirable outputs as much as possible while not affecting the desirable output. This approach is simple and obvious and can be implemented in the classic DEA model. However, pollutants as input can achieve the aim of reducing the undesirable outputs as much as possible, it is contrary to the actual production situation.

### *Data transformation function method*

The data transformation function method transforms undesirable outputs into desirable outputs. When we use the traditional DEA model to analyse the efficiency of each decision making unit, we regard the undesirable outputs as common desirable outputs. From the perspective of the existing research literature, there are three main types of data transformation functions: the negative output method, nonlinear data transformation method and linear data transformation method. These have certain limitations. First, the ratio of inputs and outputs should be a non-negative number. The negative output method regards the pollutants as a negative number, which is not in conformity with the basic requirements of efficiency evaluation. The nonlinear data transformation method destroys the convexity of the model. Finally, the linear data transformation method can maintain DEA validity and classification deformation in the BCC model (named after the first letter of the three authors' last names is a kind of DEA models), but in the CCR model (named after the first letter of the three authors' last names, is a kind of DEA models), it cannot be classified with consistency. Due to the above limitations, the data transformation function method is rarely applied in energy efficiency evaluation.

### *Distance function method*

In this method, the distance between the production point and the production frontier is used to measure the efficiency of decision-making units<sup>18</sup>. Greater the distance, the lower is the efficiency. If the distance is zero, the efficiency of the decision-making unit is located on the production frontier, and the efficiency value is 1. This method changes the efficiency of decision making units according to a certain direction and reduces the input and output according to the predetermined direction, which breaks through the traditional radial measurement method. These are the advantages of the distance function method. Chung *et al.* proposed an environmental efficiency analysis DEA model based on the distance function and a weak treatment of pollutants<sup>19</sup>. The distance function method can set the efficiency, changing the direction according to the willingness of the decision maker. This method combines the subjective preferences

of decision makers and the DEA model has good applicability<sup>20,21</sup>.

Irrespective of the methods, the essence belongs to the radial and output-oriented DEA model. The DEA model can be divided into four types according to its development and measurement (radial and angular, radial and non-angular, non-radial and angular, and non-radial and non-angular). Radial refers to the proportional reduction or amplification of the input or output to achieve effectiveness. Angular refers to the orientation of input or output. The traditional DEA model mostly belongs to the radial and angular measurement. It does not fully consider the slack problem of input and output, which will result in biased and inaccurate efficiency values<sup>22</sup>. Tone put forward an undesirable-SBM model, which is non-radial and non-angular, to solve this problem. We assume that there are  $n$  decision making units (DMUs). Each DMU has three input and output vectors: input vectors, desirable output vectors and undesirable output vectors. The specific model is expressed by eq. (1)

$$\min \rho = \frac{1 - \frac{1}{m} \sum_{i=1}^m s_i^- / x_{ik}}{1 + \frac{1}{q_1 + q_2} \left( \sum_{r=1}^{q_1} s_r^+ / y_{rk} + \sum_{i=1}^{q_2} s_i^{b-} / b_{rk} \right)}$$

$$\text{s.t. } X\lambda + s^- = x_k. \quad Y\lambda - s^+ = y_k.$$

$$B\lambda + s^{b-} = b_k. \quad \lambda, s^-, s^+ \geq 0. \quad (1)$$

$s_i^-, s_r^+$  and  $s_i^{b-}$  represent the input slack variables and output slack variables. The weight  $\lambda$  serves to form a convex combination of observed inputs and outputs. The objective function  $\rho$  strictly decreases around  $s_i^-, s_r^+$  and  $s_i^{b-}$ . For a specific DMU, when  $\rho = 1$  ( $s_i^- = 0, s_r^+ = 0, s_i^{b-} = 0$ ), the DMU is efficient.

Here, we define the total factor energy efficiency of iron and steel enterprises in China according to the total factor energy efficiency research method<sup>23</sup>. The basic idea is that the optimum energy input level of one iron and steel enterprise is used with reference to the other sample enterprises. The optimal energy input of each iron and steel enterprise is compared with its actual energy input levels. Under constant production conditions and factor prices, if an iron and steel enterprise's energy input can no longer be reduced, it means that the total factor energy efficiency value reaches 1 or Pareto efficiency. In contrast, if an iron and steel enterprise's energy input can be further reduced under the same production conditions and factor price levels, which has not reached its optimal energy efficiency level. The distance between the inefficient point of each iron and steel enterprise and the optimal frontier is its efficiency value, demonstrating the degree of efficiency loss. We define the total factor

energy efficiency of China, Japan, South Korea and India's main iron and steel production enterprises. The formula is expressed in eq. (2)

$$EE_{i,t}^{I\&S} = \frac{REI_{i,t}^{I\&S} - LEI_{i,t}^{I\&S}}{REI_{i,t}^{I\&S}} = 1 - \frac{LEI_{i,t}^{I\&S}}{REI_{i,t}^{I\&S}} = \frac{TEI_{i,t}^{I\&S}}{REI_{i,t}^{I\&S}}. \quad (2)$$

Here,  $i$  denotes each sample iron and steel enterprise, and  $t$  denotes the time. The energy efficiency of an iron and steel enterprise is defined as in eq. (2) and is called the total factor energy efficiency ( $EE_{i,t}^{I\&S}$ ) for enterprise  $i$  at time  $t$  because the index is constructed according to the viewpoint of total factor productivity.  $REI_{i,t}^{I\&S}$  represents the actual energy input situation of the enterprise  $i$  at time  $t$ .  $LEI_{i,t}^{I\&S}$  represents the energy loss situation of enterprise  $i$  at time  $t$ .  $TEI_{i,t}^{I\&S}$  shows the target energy input situation (the optimal energy input) of enterprise  $i$  at time  $t$ .

We can calculate the total factor energy efficiency of each sample iron and steel enterprise in a certain period according to eq. (2). On this basis, we construct an energy saving potential model for the sample iron and steel enterprises in China, Japan, Korea and India. The specific model is as in eq. (3).  $ESP_{i,t}^{I\&S}$  is the energy saving potential of enterprise  $i$  at time  $t$

$$ESP_{i,t}^{I\&S} = \frac{LEI_{i,t}^{I\&S}}{REI_{i,t}^{I\&S}}. \quad (3)$$

In addition, we establish an emission's reduction potential model based on eq. (2). In eq. (4),  $ERP_{i,t}^{I\&S}$  represents the emission's reduction potential of enterprise  $i$  at time  $t$ .  $RRP_{i,t}^{I\&S}$  represents the actual amount of pollutant discharge of an enterprise  $i$  at time  $t$ .  $TRP_{i,t}^{I\&S}$  denotes the target amount of pollutant discharge of enterprise  $i$  at time  $t$

$$ERP_{i,t}^{I\&S} = \frac{RRP_{i,t}^{I\&S} - TRP_{i,t}^{I\&S}}{RRP_{i,t}^{I\&S}}. \quad (4)$$

We can calculate the  $TEI_{i,t}^{I\&S}$  and  $TRP_{i,t}^{I\&S}$  of the main iron and steel enterprises in China, Japan, Korea and India based on the SBM-DEA model.

We selected 14 iron and steel enterprises in China, Japan, Korea and India as study objects, which are all of the global top 20 iron and steel enterprises based on crude steel output in 2014, and evaluated each enterprise's total factor energy efficiency status while considering environmental element. Of these 14 enterprises, 10 are from China, 2 from Japan, 2 from Korea and 1 from India. In the process of searching for data for each enterprise, the data for Hyundai Steel Company was not available, hence not included in the analysis.

The fundamental goal of the iron and steel industry is to develop a circular economy which entails coordinating

**Table 1.** Statistical description of the samples

Variable name	Variable symbol	Mean	SD	Minimum	Maximum
Capitalization (million dollars)	K	36277.49	14394.24	13852.17	63983.47
Employees	L	51457.79	18753.13	17877	85269
Energy (tonnes of standard coal)	E	2040.827	824.265	829.69	3794.45
Crude steel output (million tonnes)	Y	32.095	10.645	16.30	49.30
SO <sub>2</sub> (tonne)	WG	29551.76	14324.75	10096.60	58951.47

Data are calculated based on the Financial Annual Report, Environmental Sustainable Report and Corporate Social Responsibility Report.

**Table 2.** Energy efficiency of the samples in 2014

Country	Enterprise	USDEA			SDEA		
		CE	TE	SC	CE	TE	SC
Japan	Nippon Steel	0.601	1	0.601	0.579	1	0.579
China	HBIS	1	1	1	1	1	1
China	BAOSTEEL	1	1	1	0.908	0.916	0.991
Korea	POSCO	1	1	1	1	1	1
China	Shagang Group	1	1	1	0.931	1	0.931
China	ANSTEEL	1	1	1	1	1	1
China	Wuhan Iron & Steel	0.508	0.557	0.911	0.640	0.656	0.975
Japan	JFE Group	1	1	1	0.578	0.598	0.967
China	Shougang Group	0.542	0.629	0.861	0.574	0.629	0.914
India	Tata Steel	0.504	0.677	0.745	0.615	0.671	0.917
China	Shandong Iron & Steel	0.530	1	0.530	0.615	1	0.615
China	MA STEEL	1	1	1	1	1	1
China	BOHAI Steel	1	1	1	0.700	1	0.700
China	BX STEEL	0.401	0.713	0.563	0.481	0.618	0.779

the relationship between economic development and ecological environment, thereby promoting the sustainable development of the economy and environment. Developing a circular economy means, improving the energy efficiency, promoting material circulation utilization and reducing the discharge of pollutants. Iron and steel enterprises consume large amounts of energy in the production process and release massive quantity of pollutants. In this article, we evaluate the total factor energy efficiency of the main iron and steel enterprises in China, Japan, Korea and India. The innovation of evaluation is that we bring together energy consumption and pollutant emissions in the model. Enhancing the energy efficiency of iron and steel enterprises is beneficial to promoting circular economic development.

For the evaluation of DMUs from four countries (China, Japan, Korea and India), data acquisition poses certain difficulties. In the process of selecting indicators, we abide by the principle of being scientific and the availability of data, and we construct an input and output index system. There are two types of input indicators: energy input indicators and non-energy input indicators. These include capitalization and labour. We use the actual number of workers in the iron and steel enterprise as a labour indicator. The desirable output variable in the

analysis is crude steel output. We believe that a quantitative index, compared with a value index (total industrial output value), can more accurately show the energy efficiency levels of iron and steel enterprises; some of the iron and steel enterprises produce iron and steel products and extend to other areas of business. The undesirable output contains sulphur dioxide gas in the iron and steel production process. Data for these sample enterprises are obtained from their Financial Annual Reports, Sustainable Development Reports and Corporate Social Responsibility Reports. All monetary units are converted into US dollars. These enterprises are all leaders in their countries, and their data have significance for comparatively analysing the total factor energy efficiency of the iron and steel industry. Table 1 provides a statistical summary of sample enterprises' input and output variables.

**Results and analysis**

We evaluate and calculate the comprehensive efficiency, technical efficiency and scale efficiency of the sampled iron and steel enterprises in 2014 using the SBM-DEA model with undesirable outputs. The results are provided in Table 2. Here, the results using the SBM-DEA model

**Table 3.** Total factor energy efficiency (TFEE) of the samples in 2014

Enterprise	TFEE	Enterprise	TFEE
Nippon Steel	0.813	JFE Group	1.000
HBIS	1.000	Shougang Group	1.000
BAOSTEEL	1.000	Tata Steel	0.636
POSCO	1.000	Shandong Iron & Steel	0.716
Shagang Group	1.000	MA Steel	1.000
ANSTEEL	1.000	Bohai Steel	1.000
Wuhan Iron & Steel	0.772	BX Steel	0.842

without undesirable outputs are marked as SDEA. The results using the SBM-DEA model with undesirable outputs (SBM-undesirable model) are marked as USDEA.

According to the SBM-DEA (SBM-desirable model and SBM-undesirable model) results (Table 2), we find that the comprehensive efficiency (CE) of HBIS, POSCO, ANSTEEL and MA STEEL is relatively high. The CE of these four enterprises is at the optimal state. The CE of BAOSTEEL (0.908) and SHAGANG (0.931) is relatively high compared to other eight enterprises. The lowest relative CE belongs to BX STEEL, with a value of 0.481. With the SBM-DEA model, which can address undesirable outputs, we find that HBIS, BAOSTEEL, POSCO, SHAGANG, ANSTEEL, JFE Group, MA STEEL and BOHAI Steel are on the production frontier. These eight enterprises are at the optimal state. The CE of the other six sample enterprises is relatively low. The lowest relative CE still belongs to BX Steel, with value of 0.401, with respect to undesirable output of SO<sub>2</sub>.

Table 3 gives the total factor energy efficiency of the sampled iron and steel enterprises, evaluated based on eq. (2). It is clear that the eight sampled enterprises that present optimal CE also achieve high total factor energy efficiencies (Table 4). Korea's POSCO Steel performs noticeably well in environmental protection and energy efficient utilization. In both the SBM-desirable model and SBM-undesirable model, the CE of POSCO Steel reaches relatively optimal levels, and the total factor energy efficiency also achieves the optimal value. POSCO Steel has implemented economic development with ecological environment protection co-ordination. Japan's JFE Group has the optimal total factor energy efficiency (1), whereas that of Nippon Steel is 0.813. Nippon Steel ranks second among the six enterprises that do not reach optimal energy efficiency. As a whole, Japan's JFE Group and Nippon Steel perform better in terms of energy utilization. Seven of the Chinese enterprises exhibit an effective state: HBIS, BAOSTEEL, SHAGANG Group, ANSTEEL, SHOU-GANG Group, MA STEEL and BOHAI STEEL, which exhibit efficiency value of 1. Three of these seven enterprises are on the frontier in the two models. These three enterprises are HBIS, ANSTEEL and MA STEEL. The average total factor energy efficiency of the sampled iron and steel enterprises in China is 0.933. China's large iron

and steel production enterprises have made significant progress in energy efficiency, due in part to the promotion of economic circulation among the iron and steel industries and the government's emphasis on energy conservation and environmental protection in the iron and steel industry in China's 11th and 12th five-year plans. These sample enterprises spent a significant amount of capital and manpower on improving energy efficiency and environmental protection. These enterprises perform well in terms of energy efficiency. The total factor energy efficiency value of India's Tata Steel performs relatively well. The CE efficiency value of India's Tata Steel does not reach the optimal frontier, but has great development space in the future. The total factor energy efficiency of Tata Steel is fairly well according to the local economic development level.

Table 4 reports the energy saving potential and emission reduction potential results for the sample iron and steel enterprises in 2014, which are calculated using eq. (3) and eq. (4). Low average energy efficiency scores reflect a larger potential for reduction in inputs. Coelli argued that inefficient DMUs can adjust their slack to become efficient and reach the production frontier<sup>24</sup>. From the perspective of energy conservation, India's Tata Steel has the largest energy saving potential, followed by Shandong Iron & Steel, Wuhan Iron & Steel, Nippon Steel and BX Steel. From the perspective of emission reductions, HBIS, BAOSTEEL, Shagang Group, ANSTEEL, MA STEEL and BOHAI Steel discharge less SO<sub>2</sub> than the other sample iron and steel enterprises. Of the 14 sample enterprises, China's BX STEEL (0.524) has the greatest emission reduction potential. The emission reduction potential values of Wuhan Iron & Steel, Shougang Group, and Shandong Iron & Steel are 0.521 0.343 and 0.319 respectively. Thus, the SO<sub>2</sub> emission quantity of China's iron and steel enterprises has a significant gap with the world's advanced iron and steel enterprises. Japan's JFE Group is outstanding in terms of both energy conservation and emission reduction. Nippon Steel has space for SO<sub>2</sub> emission reductions. The emission reduction potential of Nippon Steel is 0.217. Obviously, Japan's sample iron and steel enterprises are very competitive in terms of energy conservation and emission reduction. Tata Steel has large scope for SO<sub>2</sub> emission reductions. Korea's

POSCO Group performs well in terms of both energy conservation and SO<sub>2</sub> emission reduction.

### Conclusions and policy implications

We have analysed the present pattern of the global iron and steel industry and determine that new capacities in the industry mostly come from Asia, a trend that is quite different from other areas. Asian crude steel output represented 68.29% of the global output in 2014. In the 21st century, the Asian iron and steel industry has played an important role in the world. China, Japan, Korea and India produce most of Asia's steel, accounting for 95.76% of Asia's crude steel output. Of the world's top 20 iron and steel enterprises, 15 of them come from these 4 countries. We have measured the energy efficiency of 14 large-scale iron and steel enterprises from these 4 Asian countries within a total factor production framework using the SBM-undesirable DEA model.

We selected the most representative iron and steel enterprises of China, Japan, Korea and India as the research objects and analysed the total factor energy efficiency of the 14 enterprises from the perspective of pollutants. The results show that the total factor energy efficiency of China's sample iron and steel enterprises has made great progress. The average total factor energy efficiency of China's sample enterprises is 0.933. The Government of China has promoted the green development of iron and steel circulation during the periods of 11th and 12th five-year plans. In addition, enterprises paid more attention to energy conservation and environmental protection. These helped the increase in the total factor energy efficiency of China's iron and steel enterprises. The total factor energy efficiency of India's Tata Steel is relatively well according to the local economic development level. In terms of energy utilization, Tata Steel has a gap as with Korea's POSCO. As the benchmark of India's iron and steel

industry, Tata Steel has undertaken implementation of Environment Management System at all key sites involved in mining and manufacturing. In 2015, it has completed Jamshedpur Works' brownfield expansion project, which help add eco-efficient products to its portfolio while using fewer natural resources, less energy and less water per tonne of steel produced. Because of data limitation, we have measured the total factor energy efficiency in 2014. Certainly the energy efficiency of Tata Steel will be significantly increased through the implementation of sustainable policies in recent years.

We have also measured the energy conservation potential and SO<sub>2</sub> emission reduction of the sampled enterprises based on total factor energy efficiency. The enterprise with the largest energy conservation potential is India's Tata Steel Group. The energy conservation potential of China's Shandong Iron & Steel and Wuhan Iron & Steel is also relatively large. In terms of SO<sub>2</sub> emission reduction, India's Tata Steel could further reduce. Korea's POSCO and Japan's JFE Group and Nippon Steel perform better in terms of energy conservation and emission reduction. This finding is related to Japan's and Korea's promotion of a circular economy and emphasis on energy conservation and emission reduction.

The governments of Japan and Korea should continue to promote the sustainable development of iron and steel industry, and encourage the enterprises to improve energy efficiency. The samples of Chinese iron and steel enterprises consist of leading companies. Actually, the concentration of China's iron and steel industry is low, and there are many small and medium-sized iron and steel companies. Although the total factor energy efficiencies of China's sampled enterprises have made significant progress, the industry requires more effort to enhance its total factor energy efficiency in the future. First, the Government of China should strengthen environmental regulation, using a reversed transmission mechanism to increase energy efficiency and reducing pollutant emission. Second, according to the Iron and Steel Industry Restructuring Plan, the Government of China should continue to encourage mergers and reorganization of iron and steel enterprises. Finally, the key element for China's iron and steel enterprises is to improve companies' independent innovation abilities and technical level. This improvement is one of the most important means of increasing the total factor energy efficiency of China's iron and steel enterprises. The total factor energy efficiency measured by DEA model is comparative within this analysis. Tata Steel's efficiency ranks top in the global iron and steel industry. For India's iron and steel industry, the enterprises should make full use of the advantage of low cost on labour. Meanwhile, the Indian government should train high quality talent for iron and steel industry. Clearly improving technology innovation ability also plays an important role in India's iron and steel industries. In addition, total factor energy efficiency

**Table 4.** Energy saving potential and emission reduction potential of the samples in 2014

Country	Enterprise	ESP	ERP
Japan	Nippon Steel	0.187	0.217
China	HBIS	0.000	0.000
China	BAOSTEEL	0.000	0.000
Korea	POSCO	0.000	0.000
China	Shagang Group	0.000	0.000
China	ANSTEEL	0.000	0.000
China	Wuhan Iron & Steel	0.228	0.521
Japan	JFE Group	0.000	0.000
China	Shougang Group	0.000	0.343
India	Tata Steel	0.364	0.438
China	Shandong Iron & Steel	0.284	0.319
China	MA Steel	0.000	0.000
China	Bohai Steel	0.000	0.000
China	BX Steel	0.158	0.524

is influenced by some other elements, e.g. the average quality of the staff, the technology and the regulations and policies in different countries. Otherwise, being limited by the data, we selected one kind of pollutant discharge index. This leads to an incomprehensive estimation of results, which is to be studied in the future.

1. Zhang, C., He, W. D. and Hao, R., Analysis of environmental regulation and total factor energy efficiency. *Curr. Sci.*, 2016, **110**, 1958–1968.
2. Zhang, C., He, W. D. and Hao, R., Comprehensive estimation of the financial risk of iron and steel enterprise- based on carbon emission reduction. *J. Sci. Ind. Res.*, 2016, **75**, 143–149.
3. Zhang, X. G. and Zhang, S. Q., Technical efficiency in China's iron and steel industry: evidence from the new census data. *Int. Rev. Appl. Econ.*, 2001, **15**, 199–211.
4. Zhao, G. J. and Hao, Q. M., Data envelopment analysis of steel maker's economical scale in China. *J. Iron Steel*, 2003, **38**, 72–74 (in Chinese).
5. Movshuk, O., Restructuring, productivity and technical efficiency in China's iron and steel industry, 1988–2000. *J. Asian Econ.*, 2004, **15**, 135–161.
6. Han, J., Productivity and production efficiency of China's iron-steel listed companies: a research based on DEA-Tobit. *J. Beijing Norm. Univ. (Soc. Sci.)*, 2008, **1**, 119–126 (in Chinese).
7. Wei, Y. M., Liao, H. and Fan, Y., An empirical analysis of energy efficiency in China's iron and steel sector. *Energy*, 2007, **32**, 2262–2270.
8. Zhang, Q. Z., He, F. and Zhao, X., Analysis of Chinese energy efficiency of iron and steel industry based on super-efficiency DEA. *Soft Sci.*, 2012, **26**, 65–68 (in Chinese).
9. Du, C. L. and Cheng, J. H., Evaluation on circular economy efficiency about iron and steel industry in China: 2003–2006. *Ind. Econ. Res.*, 2009, **5**, 7–14 (in Chinese).
10. Han, Y. J. and Liu, X. L., Analysis of energy efficiency and energy-saving and emission-reduction potential of steel industry in various regions of China based on super-efficiency DEA model. *J. Syst. Sci. Math. Sci.*, 2011, **31**, 287–298 (in Chinese).
11. Zhang, Q. Z., He, F. and Lei, J. S., Study of Chinese iron and steel enterprises energy-saving and emission reduction and scale under the view of technical efficiency. *Soft Sci.*, 2013, **27**, 6–10 (in Chinese).
12. He, F., Zhu, L. Y., Ma, D. D. and Jiang, W., Research on the green technical efficiency of China's iron and steel enterprise. *China Ind. Econ.*, 2015, **7**, 84–98 (in Chinese).
13. Cai, X. C. and Zou, K., The analysis of energy efficiency in the steel industry listed companies based on DEA-Malmquist. *Stat. Inf. Forum.*, 2012, **27**, 90–98 (in Chinese).
14. Lin, B. Q. and Wang, X. L., Exploring energy efficiency in China's iron and steel industry: a stochastic frontier approach. *Energy Policy*, 2014, **72**, 87–96.
15. Zhu, Z. J. and Wang, Q. L., Research on the path of improving China's iron and steel industry energy utilization rate from the perspective of sustainable development. *J. Changchun Univ.*, 2015, **25**, 1–7 (in Chinese).
16. Färe, R., Grosskopf, S., Lovell, C. A. K. and Pasurka, C., Multi-lateral productivity comparisons when some outputs are undesirable. *Rev. Econ. Stat.*, 1989, **71**, 90–98.
17. Haynes, M. A., MacGillivray, H. L. and Mengersen, K. L., Robustness of ranking and selection rules using generalized g-and-k distributions. *J. Stat. Plan. Inter.*, 1997, **65**, 45–66.
18. Shephard, R. W., *Theory of Cost and Production Functions*, University Press, Princeton, NJ, 1970.
19. Chung, Y. R., Färe, R. and Grosskopf, S., Productivity and undesirable outputs: a directional distance function approach. *J. Environ. Manage.*, 1997, **51**, 229–240.
20. Färe, R. and Grosskopf, S., Modeling undesirable factors in efficiency evaluation: comment. *Eur. J. Oper. Res.*, 2004, **157**, 242–245.
21. Zaim, O., Measuring environmental performance of state manufacturing through changes in pollutions intensities: a DEA framework. *Ecol. Econ.*, 2004, **15**, 199–211.
22. Tone, K., A slacks-based measure of efficiency in data envelopment analysis. *Eur. J. Oper. Res.*, 2001, **130**, 498–509.
23. Hu, J. L. and Wang, S. C., Total factor energy efficiency of regions in China. *Energy Policy*, 2006, **34**, 3206–3217.
24. Coelli, T., A multi-stage methodology for the solution of orientated DEA models. *Oper. Res. Lett.*, 1998, **23**, 3–5.

ACKNOWLEDGEMENTS. We thank the anonymous reviewers for their constructive comments and suggestions. We also thank the National Social Science Foundation of China (Grant No. 14ZDA088), the Social Science Foundation of Beijing (Grant No. 14JGA014) and the Ministry of Education Humanities and Social Sciences Research Program (Grant No. 15YJA790020) for financial support.

Received 23 November 2016; accepted 13 February 2017

doi: 10.18520/cs/v112/i11/2226-2233