RESEARCH ARTICLE

Efficiency assessment of coal energy and non-coal energy under bound dynamic DDF DEA

Ying Li[1] · Tai-Yu Lin[2] · Yung-ho Chiu[3] · Hongyi Cen[1] · Yi-Nuo Lin[3]

Abstract
The demand for energy has continued to increase because of global economic development, which has led to rising fuel prices and continued pollution problems. China is currently the largest coal consumer and is also the largest emitter of coal-fired CO_2 emissions. However, past efficiency studies have been mostly limited to static analyses and have not considered undesirable outputs. Therefore, this study developed a bound dynamic directional distance function (DDF) data envelopment analysis (DEA) model to explore the energy and environmental efficiencies in 30 Chinese provinces from 2011 to 2015, from which it was found that (1) the overall efficiency was the best in the eastern region, but relatively low in the western region; (2) Beijing, Guangdong, Jiangsu, Shandong, Shanghai, Tianjin, Jiangxi, Jilin, and some other regions had efficiencies of 1; (3) the revenue and non-coal indicator efficiencies were reasonably good, but the expenditure and emissions efficiencies were generally poor; and (4) the key direction for primary improvements was found to be the emissions index.

Keywords Coal and non-coal consumption · Energy efficiency · Directional distance function (DDF) · Dynamic data envelopment analysis (DEA)

✉ Tai-Yu Lin
  eickyla@gmail.com

  Ying Li
  liyinggs@scu.edu.cn

  Yung-ho Chiu
  echiu@scu.edu.tw

  Hongyi Cen
  2016141084121@stu.scu.edu.cn

  Yi-Nuo Lin
  lyn9402@qq.com

[1] Business School, Sichuan University, Wangjiang Road No. 29, Chengdu 610064, Republic of China

[2] Department of Business Administration, National Cheng Kung University, No. 1, University Road, Tainan City 701, Taiwan, Republic of China

[3] Department of Economics, Soochow University, 56, Kueiyang St., Sec. 1, Taipei 100, Taiwan, Republic of China

Introduction

The BP (2019) "World energy statistics review" reported that in 2018, mainland China's total energy use was 3273.5 million tonnes of oil equivalent, 58.2% of which was from coal generation and 22.2% of which was from natural gas and other clean energies; that is, 1906.7 million tonnes of oil equivalent of coal was used in China, which was more than half the annual global coal use of 3772.1 million tonnes of oil equivalent (BP 2019). This massive coal use resulted in significant CO_2 emissions. The International Energy Agency (IEA) (2018) reported that China's CO_2 emissions in 2016 were 9102 megatonnes (Mt), ranking China first in the world and far ahead of the second placed USA (4833 megatonnes).

While coal energy efficiency has been widely examined in the past decade, many studies have failed to include undesirable outputs or carryover activities. For example, Du and Mao (2015) analyzed China's coal-fired power plant environmental efficiencies in 2004 and 2008, and Song et al. (2014) used a slacks-based measurement (SBM) model to analyze China's coal enterprise performances, neither of which included carryover factors. As most past models have also tended to use static analyses, the changes over time or consequent improvements have not been fully investigated; therefore, to fill this

research gap, this paper proposes a bound dynamic directional distance function (DDF) data envelopment analysis (DEA) model to examine the environmental and energy efficiencies in 30 Chinese provinces/municipalities/autonomous regions (hereafter referred to as provinces) from 2011 to 2015, with labor, coal, non-coal, and government expenditure being the inputs; revenue and CO_2 being the outputs; and fixed assets being the carryover (all input and output variables are described in Fig. 1).

Previous studies on energy consumption have generally failed to distinguish coal and non-coal efficiencies. Therefore, this study used the dynamic DDF data envelopment analysis model to average the industrial and environmental efficiencies of both coal and non-coal production to determine the main undesirable output sources, thereby allowing for more precise policy recommendations to be given to improve the operating and environmental energy production efficiencies.

This research makes four contributions. First, the paper develops a bound dynamic DDF DEA model to improve the efficiency of the traditional DEA to assess coal energy efficiencies in Chinese provinces over multiple periods. Second, based on the original model, a bounded variable model is adopted to limit the coal input item. Third, to better reflect the current energy use situation in China, the energy inputs are divided into coal and non-coal to more intuitively assess coal use. Fourth, undesirable output was added to the outputs to elucidate the connections between coal energy and the environment.

The remainder of this paper is organized as follows: "Literature review" section gives the literature review, "Methodology" section describes the research method, "Statistical analysis" section gives the empirical results and discussion, and "Conclusions and policy recommendations" section gives the conclusions and policy recommendations.

Literature review

Data envelopment analysis is a statistical method based on relative efficiency that can process multiple inputs and outputs without the need for preset estimation parameters; therefore, it does not underestimate the subjective factors, is easier to calculate, and has less errors (Qiao 1994). Consequently, DEA has been widely used in energy and carbon emissions efficiency research.

Because of coal's primary role in power generation, most energy studies have only included coal as the input and ignored the non-coal contributions. For example, Cui et al. (2015) used a three-stage DEA model to examine coal–carbon resource utilization efficiencies in 29 Chinese provinces in 2012, in which coal consumption, labor, and capital were the inputs and GDP was the output, and then used a bootstrap DEA model to adjust the error values, from which significant differences were found across the regions, with the eastern region having the highest utilization efficiency, followed by the central and the western regions. Long et al. (2016) employed both static and dynamic analyses using DEA and the Malmquist index to examine coal consumption efficiencies in 30 Chinese regions from 2000 to 2012, in which investment, labor, and coal consumption were the inputs and GDP and industrial solid waste emissions were the outputs. The static analyses found the coal consumption technical efficiency (TE) to be 0.710, the pure technical efficiency (PTE) to be 0.803, and the scale efficiency (SE) to be 0.889, and the dynamic analyses found China's comprehensive coal consumption efficiency change index to be 0.899; the annual efficiency change (EC) and technology change (TC) growth rates to be − 4.7% and − 5.7%, respectively; and the average annual growth rate to be − 10.1%.

Fig. 1 Dynamic DDF model
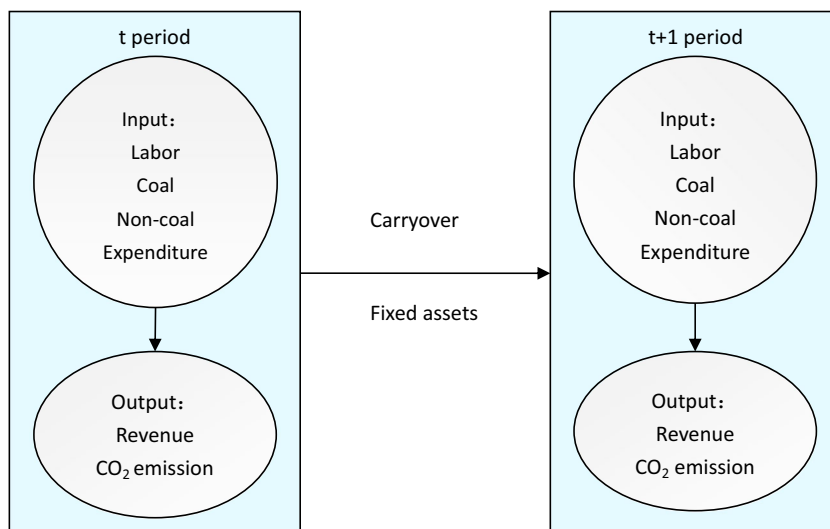
Guo et al. (2017a) used an SBM-DEA model to explore the coal consumption efficiencies in 30 Chinese provinces from 2003 to 2014 under a meta-frontier framework, in which capital stock, labor force, and coal consumption were the inputs and GDP, CO^2, SO^2, soot, and dust were the outputs, a finding that the eastern provinces, such as Beijing, Shanghai, and Guangdong, had the best coal consumption efficiencies, followed by the central and western regions. Guo et al. (2017b) then evaluated the eco-efficiencies in 44 coal-fired cogeneration plants in 31 ecological industrial parks in China (160 units), for which coal consumption, fresh water consumption, capital depreciation, and operating costs were the inputs and electricity, heat, and greenhouse gas emissions were the outputs, a finding that the more energy-intensive industries there were in an industrial park, the lower the ecological efficiency. Guo et al. (2018) used a BBC-DEA model to explore the environmental total factor productivity (TFP) index in six energy-intensive industries in China in 2015, in which coal, capital resources, and labor were the inputs, and the value of industry sales, industrial sulfur dioxide emissions, industrial nitrogen oxide emissions, and industrial smoke, dust, and soot emissions were the output, a finding that the coal economic efficiency was generally higher than the coal environmental efficiency, the economic benefits reduced the negative environmental impact, and the low coal environmental efficiency was mainly because of the combined effect of the pure technical efficiency and the scale efficiency.

Previous studies have rarely restricted the energy inputs when examining the relationship between energy consumption and carbon emissions. For example, Song et al. (2014) used an input-oriented CCR-DEA model to examine 34 Chinese coal-fired generating units in coal-fired power plants, in which coal consumption and auxiliary electricity consumption were the output and generated electricity and capacity utilization rate were the desirable outputs. Du and Mao (2015) used a non-parametric DEA model to estimate the environmental efficiencies, emissions reduction potential, and marginal carbon dioxide emissions abatement costs in Chinese coal-fired power plants in 2004 and 2008, in which labor, capital, and energy were the inputs and CO_2 emissions were the output, and found that significant emissions reduction could be achieved and government subsidies could alleviate the low coal–fired power plant environmental efficiency problems. Meng et al. (2016) used six DEA models to analyze the energy and carbon emissions efficiencies in 30 Chinese provinces from 1995 to 2012, in which labor force, capital stock, and total energy consumption were the inputs and GDP and CO^2 emissions were the outputs, a finding that the efficiencies were stable from 1996 to 2000, declined from 2000 to 2005, and increased from

2006 to 2010, with the efficiencies in eastern China being the highest and those in the central region being the lowest. Liu et al. (2016) compared the efficiencies in Shanxi and Inner Mongolia from 2005 to 2012 and evaluated sustainable development coal industry policy effectiveness using operational, environmental, and uniform efficiency indicators, and found that while China's integrated reform had had a negative impact on coal productivity, it had significantly improved the coal industry's environmental performances. Guo et al. (2017c) used a dynamic DEA model to evaluate the energy efficiencies in China and 26 OECD countries from 2000 to 2010, in which land area, own energy use, and population were the inputs and CO^2 emissions and GDP were the outputs, a finding that the overall efficiency in all countries was 0.78, and the energy use and CO^2 emissions efficiencies in Canada and China were lower than those in the other countries. Wu et al. (2018) analyzed the ecological efficiencies in 58 Chinese coal-fired power plants using an improved two-stage analytical model, in which installed capacity, labor, coal consumption, auxiliary power consumption, oil consumption, and water consumption were the inputs, and found that over 60% of the coal-fired power plants had acceptable production conditions, others were facing unfair investment problems, environmental factors such as policy preferences and the economic situation had a significant impact on the performance of local factories, resource allocations had little impact, the rise in coal prices assisted in increasing eco-efficiency, and high-power unit age and feed-in tariffs had the potential to damage production performances. Ren et al. (2020a) used a two-stage dynamic DEA model to evaluate the carbon emissions and crop damage efficiencies in 30 Chinese provinces from 2013 to 2017, a finding that all efficiency indicators in the eastern region were higher than those in the other regions. Lin et al. (2020) used an SBM-DEA model to analyze the CO_2 emissions efficiencies in some countries and regions in the world, in which oil, natural gas, and coal were the inputs and CO^2 emissions and GDP were the outputs, and found that the overall efficiencies in the developed countries were higher than those in the developing countries, the average efficiencies in Europe and Oceania were relatively high, and the average efficiencies in Asia in the previous 2 years had been the lowest of all five continents examined.

Due to a lack of data or other factors, static DEA has been commonly used to evaluate energy and carbon emissions efficiencies. For example, based on a review of 648 coal-fired power plants in 2008, Du et al. (2016) used 1-year cross-sectional data to propose a new meta-frontier estimation method, concluding that if all coal plants were fully efficient, the total emissions could be reduced by 44%. Liu et al. (2017) studied the eco-efficiencies in 23

Chinese coal-fired power plants and found that most were performing poorly, with only five achieving efficiencies greater than 0.9. Chen and Dong (2018) used a DDF-DEA model to analyze the efficiencies in 20 coal-fired power plants in Shanghai from 2007 to 2010, a finding that the efficiencies were stable, and although the average power plant forecast prices were increasing every year, they were far below the predicted energy consumption prices in the industry and slightly lower than the ETS market transaction prices. Cheng et al. (2019) used energy consumption, labor, and capital stock as the inputs and GDP and CO_2 emissions as the outputs in an environmentally extended input–output (EEIO) analysis and employed DEA to measure the energy efficiencies in 30 Chinese provinces in 2012, which were divided under a consumption-based principle into emissions-importing regions and emissions-exporting regions, a finding that the emissions-importing regions had higher efficiencies and higher abatement costs than the emissions-exporting regions. Wang et al. (2019) used SBM-DEA and the Malmquist Productivity Index to evaluate energy efficiencies and energy improvements in 25 countries, in which gross capital formation, labor force, and energy consumption were the inputs and GDP and CO_2 emissions were the outputs, a finding that the energy consumption and CO_2 emissions in India and China had continued to grow. Zhang et al. (2019) used DEA to evaluate the energy-saving and emissions reduction efficiencies in 30 provinces in China in 2015, in which fixed assets, water consumption, electricity consumption, and gas consumption were the inputs and GDP, wastewater, and soot emission were the outputs, a finding that China's overall environmental efficiency was very low, and the emissions reduction efficiency in the central region was better than that in the eastern and western regions. Ren et al. (2020b) used a DEA model to study the energy and carbon emissions efficiencies in China's transportation system, a finding that the performances in eastern China were better than those in central China, which, in turn, were better than those in western China.

However, most of this previous coal efficiency research has been based on static analyses, have not included comparisons over time, and have not considered that it is difficult for input variables to improve significantly over the short term. Because there have been no restrictions placed on the energy input items and because coal use reductions cannot be assessed using mathematical models, it has been difficult to achieve accurate simulation results. Further, as most coal research has only added coal to the input items, the full picture of the energy use in each Decision-Making Unit (DMU) is not reflected, which reduces the results credibility. Therefore, to improve the value of the input variables, this study proposes a bound

dynamic DDF DEA model to analyze the coal energy and environmental efficiencies, with the bounded variable mode being used to limit and dynamically analyze the coal inputs. The inputs were divided into coal and non-coal and put into the DEA model at the same time to ensure that the research targeted the coal and better simulated the energy use in the selected Chinese provinces. As this study also included an undesirable CO_2 output, it provides a more comprehensive coal efficiency analysis than most previous studies.

Methodology

DEA has been extensively used in the past two decades for energy, environmental, and ecological efficiency and productivity analyses. While some studies have included environmental pollutant emissions as inputs, few have included undesirable outputs, which do not fully reflect real production processes. Some studies have even considered undesirable outputs to be *ideal output*, basically ignoring the need to increase the good output and reduce bad output.

Referencing Luenberger (1992), Chung et al. (1997) extended the output distance function proposed by Shephard (1970) to a directional output distance function (or radial DEA) to allow for both desirable and undesirable outputs to be recognized. However, these radial efficiency methods directly ignored any variable differences, which inevitably resulted in estimation biases. To overcome this shortcoming, Färe and Grosskopf (2010) proposed a non-radial DDF model, which, compared with other methods, was found to result in better evaluation performances and more accurate estimation results. However, Färe and Grosskopf (2010) failed to consider the intertemporally sustained effects or the need for limits on some variables. For example, there is only a certain range within which coal efficiency improvements can be achieved. To resolve these issues, this paper proposes a bound dynamic non-radial DDF DEA model that divides the energy input into coal and non-coal, considers dynamic analysis, and uses a bounded variable mode based on the original model to limit the input item (coal), which is the main innovation of this model, the details for which are described in the following.

Assume that N cities use four inputs—labor (L), coal (C), non-coal (NC), and government expenditure (G)—to produce two outputs: a desirable revenue (R) output and an undesirable CO_2 emission (Co) output, with the carryover being the fixed asset (Z).

The production technology for group R_h at time t is defined as $T^C = \{ (L^t, C^t, NC^t, G^t, R^t, Co^t) : (L^t, C^t, NC^t,$

G^t) can produce (R^t, Co^t)}, with Z^t being the carryover, where $t = 1, \ldots, T$. Following Färe and Grosskopf (2010), Zhou et al. (2012), Zhang et al. (2013), and Tone (2012), the dynamic non-radial directional distance function is as shown in the following:

$$
\begin{aligned}
&\max \sum_{t=1}^{T} \beta_{tL} + \beta_{tC} + \beta_{tNC} + \beta_{tG} + \beta_{tR} + \beta_{tCo} && n = 1 \cdots N \quad t = 1, 2, \ldots, T \\
&\text{s.t.} \sum_{t=1}^{T} \sum_{n=1}^{N} \lambda_{nt} L_{nt} \leq (1 - \beta_L) L_{0t}, && n = 1 \cdots N \quad t = 1, 2, \ldots, T \\
&\quad \sum_{t=1}^{T} \sum_{n=1}^{N} \lambda_{nt} C_{nt} \leq (1 - \beta_C) C_{0t}, && n = 1 \cdots N \quad t = 1, 2, \ldots, T \\
&\quad \sum_{t=1}^{T} \sum_{n=1}^{N} \lambda_{nt} NC_{nt} \leq (1 - \beta_{NC}) NC_{0t}, && n = 1 \cdots N \quad t = 1, 2, \ldots, T \\
&\quad \sum_{t=1}^{T} \sum_{n=1}^{N} \lambda_{nt} G_{nt} \leq (1 - \beta_G) G_{0t}, && n = 1 \cdots N \quad t = 1, 2, \ldots, T \quad (1) \\
&\quad \sum_{t=1}^{T} \sum_{n=1}^{N} \lambda_{nt} R_{nt} \leq (1 + \beta_R) R_{0t}, && n = 1 \cdots N \quad t = 1, 2, \ldots, T \\
&\quad \sum_{t=1}^{T} \sum_{n=1}^{N} \lambda_{nt} Co_{nt} \leq (1 - \beta_{Co}) Co_{0t}, && n = 1 \cdots N \quad t = 1, 2, \ldots, T \\
&\quad \sum_{t=1}^{T} \sum_{n=1}^{N} \lambda_{nt-1} Z_{nt} = \sum_{t=1}^{T} \sum_{j=1}^{N} \lambda_{nt} Z_{nt}; && n = 1 \cdots N \quad t = 1, 2, \ldots, T \\
&\quad \sum_{n=1}^{N} \lambda_{nt} = 1; && n = 1 \cdots N \quad t = 1, 2, \ldots, T
\end{aligned}
$$

$1 > \beta_L \geq 0;$ $0 \leq \beta_C \leq 10\%; 1 > \beta_{NC} \geq 0; 1 \geq \beta_G \geq 0; 1 \geq \beta_R \geq 0; 1 \geq \beta_{C0} \geq 0;$
$\lambda_n \geq 0; n = 1, 2, \ldots N, \quad t = 1, 2, \ldots, T$

Statistical analysis

Data and variables

Thirty mainland Chinese provinces were selected as the research sample, which, based on China's regional planning administration, were divided into three regions. The eastern region, which, for analysis convenience, included the three northeastern provinces, encompassed Hebei, Liaoning, Beijing, Tianjin, Shandong, Jiangsu, Shanghai, Zhejiang, Fujian, Guangdong, and Hainan. The central region encompassed Shanxi, Henan, Anhui, Hubei, Jiangxi, Hunan, Jilin, and Heilongjiang. The western regions encompassed Shaanxi, Sichuan, Yunnan, Guizhou, Guangxi, Gansu, Qinghai, Ningxia, Xinjiang, Chongqing, and Inner Mongolia.

These 30 Chinese provinces were selected as the DMUs to evaluate the industry energy efficiencies (mining, manufacturing, and power industries) over the 12th 5-year planning period (2011–2015). The data for annual average employees, total assets, and principal business revenue were extracted from the *China Industry Statistical Yearbooks* from 2012 to 2016, with fixed assets being used as the carryover between two periods and the energy consumption input being divided into coal and non-coal. The consumption data for the different energy types in the provincial industrial sectors were extracted from the *China Energy Statistical Yearbooks* and converted into the standard coal energy unit tonnes of standard coal equivalent (tce), after which the consumption of the raw coal, cleaned coal, coke, and other coal products were summed to determine the overall coal consumption (abbreviated as coal in this study), with the consumption data for petroleum products (crude oil, gasoline, diesel oil, etc.) and natural gas. Finally, the data on industrial waste gas emissions (shortened to emissions) were extracted from the *China Statistical Yearbooks on the Environment*.

Overall efficiency

Table 1 shows the overall efficiencies from 2011 to 2015, and Fig. 2 shows the national average and the annual average efficiency trends in the eastern, central, and western Chinese regions.

Table 1 Overall efficiencies from 2011 to 2015

	DMU	Score	Rank	2011	2012	2013	2014	2015
East	Beijing	1	1	1	1	1	1	1
	Fujian	0.9439	14	0.9653	0.8886	0.9001	0.9822	0.9880
	Guangdong	1	1	1	1	1	1	1
	Hainan	0.9625	11	0.8920	0.9890	0.9719	0.9862	0.9770
	Hebei	0.8574	26	0.9483	0.8627	0.8460	0.7976	0.8390
	Jiangsu	1	1	1	1	1	1	1
	Liaoning	0.9147	18	0.9936	0.9877	0.9494	1.0000	0.6842
	Shandong	1	1	1	1	1	1	1
	Shanghai	1	1	1	1	1	1	1
	Tianjin	1	1	1	1	1	1	1
	Zhejiang	0.7737	28	0.8618	0.8165	0.7583	0.7282	0.7123
Eastern average		0.9502	9.3636	0.9692	0.9586	0.9478	0.9540	0.9273
Central	Anhui	0.9415	15	1	0.9963	0.9493	0.8612	0.9081
	Heilongjiang	0.9364	16	0.9425	0.9277	0.9408	0.9515	0.9197
	Henan	0.9527	12	1	0.9514	0.9910	0.9209	0.9041
	Hubei	0.8728	22	0.9431	0.9571	0.8468	0.7863	0.8418
	Hunan	0.9818	10	0.9996	0.9732	1	0.9387	0.9991
	Jiangxi	1	1	1	1	1	1	1
	Jilin	1	1	1	1	1	1	1
	Shanxi	0.7356	30	0.6232	0.5994	0.8027	0.8058	0.8830
Central average		0.9276	13.3750	0.9385	0.9256	0.9413	0.9081	0.9320
West	Chongqing	0.8976	20	0.8585	0.8754	0.8012	0.9667	1
	Gansu	0.8592	24	0.8247	0.8469	0.8916	0.8689	0.8650
	Guangxi	0.7863	27	0.6916	0.7150	0.8191	0.8423	0.8787
	Guizhou	0.8582	25	0.8638	0.8870	0.7857	0.8802	0.8783
	Inner Mongolia	0.9928	9	1	0.9985	0.9923	0.9877	0.9856
	Ningxia	0.8946	21	0.8884	0.8119	0.9205	0.9279	0.9299
	Qinghai	0.9207	17	0.9548	0.9146	0.9190	0.9042	0.9114
	Shaanxi	0.7255	31	0.7037	0.6990	0.7028	0.6929	0.8374
	Sichuan	0.7640	29	0.6653	0.6356	0.8537	0.7465	0.9589
	Xinjiang	0.9469	13	0.9649	0.9595	0.9516	0.9050	0.9546
	Yunnan	0.8636	23	0.7959	0.8212	0.9077	0.8870	0.9121
Western average		0.8645	21.7273	0.8374	0.8331	0.8677	0.8736	0.9193
National average		0.9127	14.9667	0.9127	0.9038	0.9167	0.9123	0.9256

Fig. 2 Average total efficiency by region
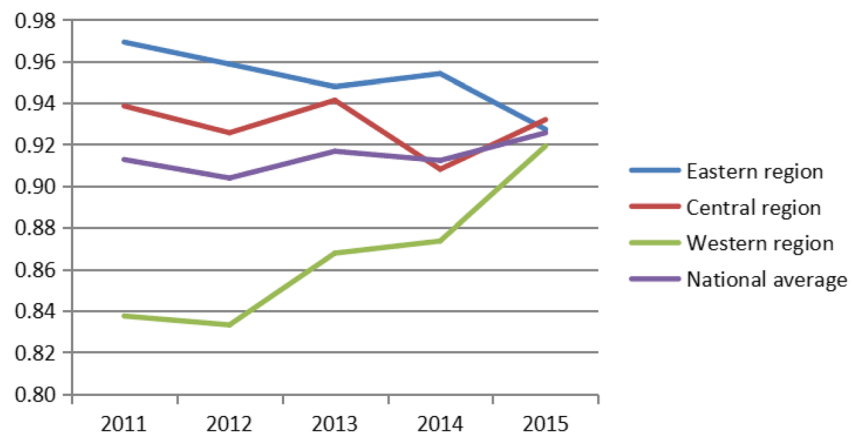
Regional analysis

Table 1 indicates that Beijing, Guangdong, Jiangsu, Jiangxi, Jilin, Shandong, Shanghai, and Tianjin had overall efficiencies of 1 and had no need for further improvements. However, Shanxi with an overall efficiency of 0.74 and Shaanxi with an overall efficiency of 0.73 had the poorest efficiency performances.

Guangxi's efficiency was rising, Zhejiang's and Inner Mongolia's efficiencies were falling, Gansu's efficiency first rose and then fell, and the efficiencies in Anhui, Fujian, Hebei, Ningxia, Shanxi, and Xinjiang first fell and then rose. Sichuan, Chongqing, Guizhou, Hainan, Heilongjiang, Henan, Hubei, Hunan, Liaoning, Qinghai, Shaanxi, and Yunnan all had fluctuating efficiencies, with Liaoning, Shanxi, and Sichuan having larger changes; in 2014, the efficiency in Liaoning decreased significantly, Shanxi's efficiency in 2012 increased, and Sichuan's efficiency in 2012 and 2014 increased significantly.

Eastern, central, and western regions

Figure 2 shows that the average overall efficiency in the eastern region was 0.95, the average overall efficiency in the central region was 0.93, and the average overall efficiency in the western region was 0.86. However, the efficiency in the eastern region had a general downward trend, with a slight increase only in 2014; the efficiency in the central region was volatile, and the overall efficiency in the western region was rising.

Six of the 11 eastern provinces accounted for 75% of all provinces that had efficiencies of 1. Most eastern provinces had good overall efficiencies except for Hebei (0.86) and Zhejiang (0.77), both of which were lower than the average. The central provinces' efficiencies were uneven, with Jiangxi and Jilin having efficiencies of 1 and Hunan having an efficiency of 0.98, which were higher than the average; however, Shanxi and Hubei at 0.74 and 0.87 were significantly lower than the average. The western provincial efficiencies were somewhat lower, except for Inner Mongolia at 0.99, which was much higher than the average.

National analysis

The average efficiency for all 30 provinces was 0.91 and was relatively stable over the period, indicating that there was only a small need for improvements.

Input and output efficiency

Coal efficiency

Table 2 shows the annual provincial coal index efficiencies, and Fig. 3 shows the annual average coal index efficiencies in the eastern, central, and western regions and nationally from 2012 to 2015.

Regional analysis The average coal index annual efficiencies were 1 in Beijing, Guangdong, Jiangsu, Jiangxi, Jilin, Shandong, Shanghai, and Tianjin, and 0.9 in Anhui, Chongqing, Gansu, Guizhou, Ningxia, Shanxi, Sichuan, Xinjiang, and Yunnan.

In Guangxi (2012, 0.93), Hubei (2014, 0.98), Qinghai (2011, 0.91), Shaanxi (2011, 0.96), Hebei (2012, 1), Hunan (2013, 1), and Inner Mongolia (2011, 1), the coal index annual efficiencies were lower than 0.9 in some years, and those in Liaoning (2015, 0.9) and Zhejiang (2011, 0.9; 2015, 0.9) were lower than 1 in some years. Fujian's coal index annual efficiencies fluctuated after falling from 1 in 2013, Heilongjiang's continued to decline from 1 in 2013, Hainan's continued to decline, and Henan's fell and then rose.

Eastern, central, and western regional analyses The average eastern coal index efficiency was 0.98, the average central coal index efficiency was 0.94, and the average western coal index efficiency was 0.91.

From 2011 to 2015, the eastern region coal index efficiency had a slow downward trend with a slight increase in 2012, the central coal index efficiency fluctuated, and the western region coal index efficiency was relatively stable at 0.9.

In the eastern region, six of the 11 provinces had efficiencies of 1; therefore, the eastern region had the highest number of provinces with high efficiencies. However, there were uneven performances in the eight central provinces, with Jilin's efficiency being 1 and Anhui's and Shanxi's efficiencies being 0.9. The western region had the greatest number of provinces with lower efficiencies.

National analysis The average coal index annual efficiency across the 30 provinces was stable at 0.94, indicating that the overall national efficiency was good and the improvement space was small.

Non-coal efficiency

Table 3 shows the annual provincial non-coal index annual efficiencies in the 30 provinces from 2011 to 2015, and Fig. 4 shows the non-coal index annual efficiencies for the eastern, central, and western regions and nationally from 2011 to 2015.

Regional analysis The average non-coal index annual efficiencies in Anhui, Beijing, Guangdong, Guizhou, Jiangsu, Jiangxi, Jilin, Shandong, Shanghai, Tianjin, and Zhejiang were 1, and those in Fujian, Gansu, Hainan, Heilongjiang, Qinghai, and Xinjiang were 0.9.

Table 2 Coal efficiency

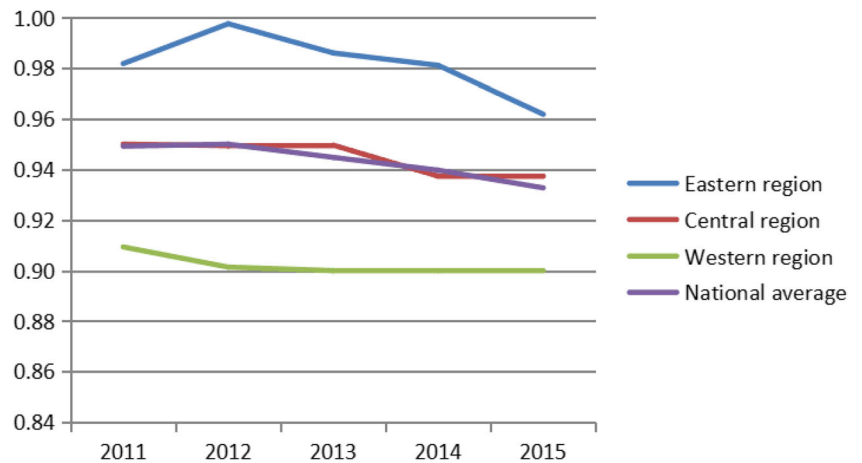|	DMU	Rank	Average	2011	2012	2013	2014	2015
East	Beijing	1	1	1	1	1	1	1
	Fujian	9	0.9885	1	1	0.9760	0.9874	0.9791
	Guangdong	1	1	1	1	1	1	1
	Hainan	14	0.9502	1	0.9740	0.9705	0.9051	0.9014
	Hebei	15	0.9200	0.9	1	0.9	0.9	0.9
	Jiangsu	1	1	1	1	1	1	1
	Liaoning	10	0.9800	1	1	1	1	0.9
	Shandong	1	1	1	1	1	1	1
	Shanghai	1	1	1	1	1	1	1
	Tianjin	1	1	1	1	1	1	1
	Zhejiang	12	0.9600	0.9	1	1	1	0.9
Eastern average		6	0.9817	0.9818	0.9976	0.9860	0.9811	0.9619
Central	Anhui	22	0.9	0.9	0.9	0.9	0.9	0.9
	Heilongjiang	13	0.9541	1	1	0.9478	0.9229	0.9
	Henan	11	0.9689	1	0.9953	0.9491	0.9	1
	Hubei	18	0.9151	0.9	0.9	0.9	0.9756	0.9
	Hunan	15	0.9200	0.9	0.9	1	0.9	0.9
	Jiangxi	1	1	1	1	1	1	1
	Jilin	1	1	1	1	1	1	1
	Shanxi	22	0.9	0.9	0.9	0.9	0.9	0.9
Central average		12.8750	0.9448	0.9500	0.9494	0.9496	0.9373	0.9375
West	Chongqing	22	0.9	0.9	0.9	0.9	0.9	0.9
	Gansu	22	0.9	0.9	0.9	0.9	0.9	0.9
	Guangxi	20	0.9061	0.9	0.9307	0.9	0.9	0.9
	Guizhou	22	0.9	0.9	0.9	0.9	0.9	0.9
	Inner Mongolia	15	0.92	1	0.9	0.9	0.9	0.9
	Ningxia	22	0.9	0.9	0.9	0.9	0.9	0.9
	Qinghai	21	0.9030	0.9148	0.9	0.9	0.9	0.9
	Shaanxi	19	0.9123	0.9613	0.9	0.9	0.9	0.9
	Sichuan	22	0.9	0.9	0.9	0.9	0.9	0.9
	Xinjiang	22	0.9	0.9	0.9	0.9	0.9	0.9
	Yunnan	22	0.9	0.9	0.9	0.9	0.9	0.9
Western average		10.8610	0.9099	0.9094	0.9014	0.9	0.9	0.9
National average		13.2667	0.9433	0.9492	0.9500	0.9448	0.9397	0.9327

Fig. 3 Average coal efficiency by region

Table 3 Non-coal index efficiencies from 2011 to 2015

	DMU	Rank	Average	2011	2012	2013	2014	2015
East	Beijing	1	1	1	1	1	1	1
	Fujian	28	0.9	0.9	0.9	0.9	0.9	0.9
	Guangdong	1	1	1	1	1	1	1
	Hainan	30	0.9	0.9	0.9	0.9	0.9	0.9
	Hebei	16	0.9715	0.9	0.9576	1	1	1
	Jiangsu	1	1	1	1	1	1	1
	Liaoning	22	0.9200	0.9	0.9	0.9	1	0.9
	Shandong	1	1	1	1	1	1	1
	Shanghai	1	1	1	1	1	1	1
	Tianjin	1	1	1	1	1	1	1
	Zhejiang	1	1	1	1	1	1	1
Eastern average		9.3636	0.9720	0.9636	0.9689	0.9727	0.9818	0.9727
Central	Anhui	1	1	1	1	1	1	1
	Heilongjiang	26	0.9	0.9	0.9	0.9	0.9	0.9
	Henan	20	0.9298	1	0.9	0.9490	0.9	0.9
	Hubei	15	0.9782	1	1	1	0.9404	0.9504
	Hunan	14	0.9845	0.9803	0.9600	1	1	0.9822
	Jiangxi	1	1	1	1	1	1	1
	Jilin	1	1	1	1	1	1	1
	Shanxi	13	0.9907	1	1	1	1	0.9533
Central average		11.375	0.9729	0.9850	0.9700	0.9811	0.9676	0.9607
West	Chongqing	21	0.9201	0.9	0.9	0.9347	0.9268	0.9392
	Gansu	27	0.9	0.9	0.9	0.9	0.9	0.9
	Guangxi	19	0.9408	0.9482	0.9778	0.9639	0.9142	0.9
	Guizhou	1	1	1	1	1	1	1
	Inner Mongolia	17	0.9471	1	0.9357	0.9332	0.9303	0.9363
	Ningxia	24	0.9106	0.9	0.9094	0.9	0.9270	0.9168
	Qinghai	29	0.9	0.9	0.9	0.9	0.9	0.9
	Shaanxi	18	0.9411	0.9	1	0.9222	0.9	0.9835
	Sichuan	23	0.9126	0.9	0.9011	0.9	0.9620	0.9
	Xinjiang	25	0.9001	0.9	0.9005	0.9	0.9	0.9
	Yunnan	12	0.9925	1	1	1	1	0.9624
Western average		10.2848	0.9324	0.9351	0.9354	0.9325	0.9317	0.9307
National average		13.6667	0.9580	0.9576	0.9581	0.9601	0.9600	0.9541

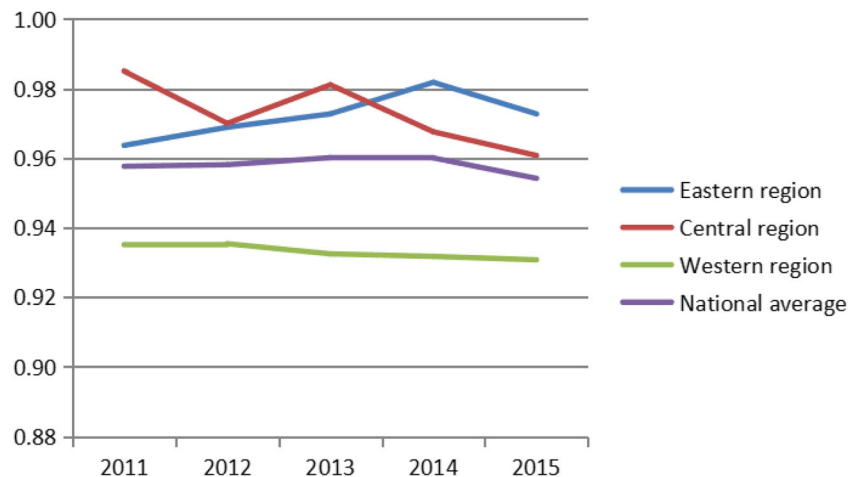**Fig. 4** Average non-coal efficiency by region

Table 4 Government expenditure efficiencies in the 30 provinces from 2011 to 2015

	DMU	Rank	Average	2011	2012	2013	2014	2015
East	Beijing	1	1	1	1	1	1	1
	Fujian	10	0.9712	0.9823	0.9410	0.9474	0.9910	0.9939
	Guangdong	1	1	1	1	1	1	1
	Hainan	15	0.9373	0.9429	0.9615	0.9857	0.9071	0.8890
	Hebei	30	0.3503	0.3174	0.2937	0.3671	0.3525	0.4210
	Jiangsu	1	1	1	1	1	1	1
	Liaoning	14	0.9496	0.9968	0.9646	0.9740	1	0.8125
	Shandong	1	1	1	1	1	1	1
	Shanghai	1	1	1	1	1	1	1
	Tianjin	1	1	1	1	1	1	1
	Zhejiang	27	0.7570	0.7912	0.8014	0.6935	0.7546	0.7442
Eastern average		9.2727	0.9059	0.9119	0.9057	0.9062	0.9096	0.8964
Central	Anhui	22	0.8764	0.9487	0.9982	0.9254	0.7241	0.7859
	Heilongjiang	11	0.9671	0.9704	0.9625	0.9695	0.9751	0.9582
	Henan	9	0.9758	1	0.9751	0.9955	0.9588	0.9496
	Hubei	18	0.9265	0.9512	0.9699	0.9170	0.8804	0.9141
	Hunan	12	0.9634	0.9998	0.9864	1	0.9684	0.8626
	Jiangxi	1	1	1	1	1	1	1
	Jilin	1	1	1	1	1	1	1
	Shanxi	29	0.6083	0.2946	0.4464	0.7209	0.6998	0.8799
Central average		12.8750	0.9147	0.8956	0.9173	0.9410	0.9008	0.9188
West	Chongqing	20	0.9134	0.8113	0.8902	0.8826	0.9831	1
	Gansu	19	0.92239	0.90394	0.91711	0.94271	0.92056	0.92763
	Guangxi	28	0.6801	0.5701	0.5013	0.7638	0.7853	0.7801
	Guizhou	23	0.8571	0.8498	0.9144	0.8055	0.8443	0.8717
	Inner Mongolia	17	0.9284	1	0.9070	0.9108	0.9112	0.9129
	Ningxia	26	0.7781	0.7260	0.4497	0.8877	0.9164	0.9104
	Qinghai	16	0.9346	0.9590	0.9252	0.8854	0.9497	0.9536
	Shaanxi	25	0.8284	0.8261	0.7606	0.8255	0.8186	0.9115
	Sichuan	24	0.8489	0.7990	0.7115	0.9002	0.8549	0.9790
	Xinjiang	13	0.9576	0.9821	0.9793	0.9431	0.9067	0.9768
	Yunnan	21	0.8821	0.8864	0.7732	0.8803	0.9165	0.9540
Western average		10.9787	0.8566	0.8202	0.8344	0.8834	0.9084	0.9252
National average		14.5667	0.8938	0.8836	0.8677	0.9041	0.9006	0.9130

Fig. 5 Average expenditure efficiency by region
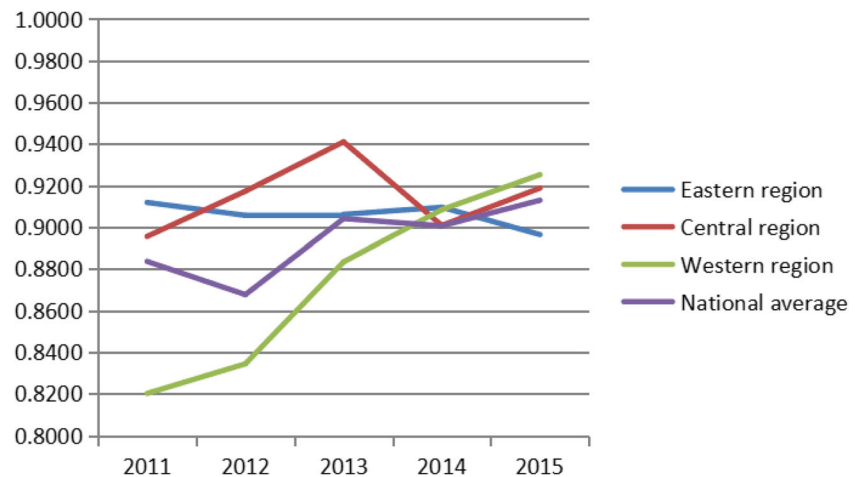
The non-coal index annual efficiencies in Hubei (from 1 to 0.94) and Inner Mongolia (from 1 to 0.93) both fell from an efficiency of 1 but were stable in the other years. The non-coal index annual efficiencies in Liaoning (2014, 1) and Sichuan (2014, 0.96) also fell to 0.9, those in Shanxi (2015, 0.95) and Yunnan (2015, 0.96) were 1 in all years except one, those in Guangxi first rose and then fell, those in Hebei continued to rise, and those in Chongqing, Henan, Hunan, Ningxia, and Shaanxi (which rose sharply in 2011 and 2015) had large fluctuations.

Eastern, central, and western regional analyses The average non-coal index annual efficiency was 0.97 in the eastern region, 0.97 in the central region, and 0.93 in the western region. The non-coal index annual efficiency in the eastern region had a slow upward trend and then fell after a slight increase in 2014, there were small fluctuations in the central region, and the western region was very stable at around 0.93. Most provinces (7 out of 11) with high non-coal index annual efficiencies were in the east, and four out of eight provinces had efficiencies close to 1 in the central region; however, only three of the 11 provinces in the west had non-coal index annual efficiencies of 0.9.

National analysis The average national non-coal index annual efficiency was stable at 0.96; therefore, there was only a small need for further improvements.

Government expenditure efficiency

Table 4 shows the government expenditure efficiencies from 2011 to 2015 in the 30 provinces, and Fig. 5 shows the eastern, central, and western regional and national government expenditure efficiencies.

Regional analysis Beijing, Guangdong, Jiangsu, Jiangxi, Jilin, Shandong, Shanghai, and Tianjin had average government expenditure efficiencies of 1; however, Shanxi's (0.61) and Hebei's (0.35) were significantly lower. Fujian, Qinghai, Xinjiang, Yunnan, and Hainan had fluctuating government expenditure efficiencies, and there were also fluctuations in Hebei, Liaoning, Zhejiang, Anhui, Heilongjiang, Henan, Hubei, Hunan, Shanxi, Chongqing, Gansu, Guangxi, Guizhou, Ningxia, Shaanxi, and Sichuan. Therefore, in most provinces, the annual government expenditure efficiencies were unstable.

Eastern, central, and western regional analyses The average government expenditure efficiency was 0.95 in the eastern region, 0.93 in the central region, and 0.86 in the western region, indicating that greater improvements were needed in the west.

The government expenditure efficiency in the eastern region had a slow downward trend with only a slight increase in 2014, was volatile in the central region, and had a large upward trend with a slight decline in 2012 in the western region; however, in 2015, the average government expenditure efficiencies were similar in all three regions. More provinces in the eastern region (6 out of 11) had government expenditure efficiencies of 1; however, Hebei's (0.86) and Zhejiang's (0.77) were significantly lower than the average. The government expenditure efficiencies in the eight central provinces were much higher than the average, especially Jiangxi and Jilin at 1 and Hunan at 0.98; however, the government expenditure efficiencies in Shanxi (0.74) and Hubei (0.87) were much lower than the average. Most provinces with lower government expenditure efficiencies were in the western region; however, the government expenditure efficiency in Inner Mongolia at 0.99 was much higher than the average.

National analysis The average government expenditure efficiency in the 30 provinces fluctuated around 0.91, indicating that only small improvements were needed.

Labor efficiency

Table 5 shows the labor efficiencies in the 30 provinces from 2011 to 2015, and Fig. 6 shows the labor efficiencies in the eastern, central, and western regions and the national average from 2011 to 2015.

Regional analysis In Beijing, Guangdong, Jiangsu, Jiangxi, Jilin, Shandong, Shanghai, and Tianjin, the average labor efficiency was 1, the lowest was in Shaanxi at 0.84 and in Shanxi at 0.85, and seven provinces had falling and then rising labor efficiencies: Fujian, Anhui, Heilongjiang, Shanxi, Chongqing, Ningxia, Xinjiang, and Gansu. The labor efficiencies in Zhejiang and Inner Mongolia both slowly declined but remained close to 1, and there were significant labor efficiency fluctuations in 11 provinces: Hainan, Hebei, Liaoning, Henan, Hubei, Hunan, Guizhou, Qinghai, Shaanxi, Sichuan, and Yunnan. Overall, therefore, the labor efficiencies in most provinces were somewhat unstable.

Eastern, central, and western regional analyses The average annual labor efficiency was 0.96 in the eastern region, 0.95 in the central region, and 0.92 in the western region, with the labor efficiencies fluctuating in the eastern and central regions and rising in the western regions. In 2015, the labor efficiencies in all three regions were similar.

The average annual labor efficiency was 1 in six of the 11 eastern provinces, was 0.87 in Zhejiang, was 0.86 in Fujian, and was much higher than the average in the central provinces of Jiangxi and Jilin; however, most of the western provinces had lower labor efficiencies.

Table 5 Labor efficiency

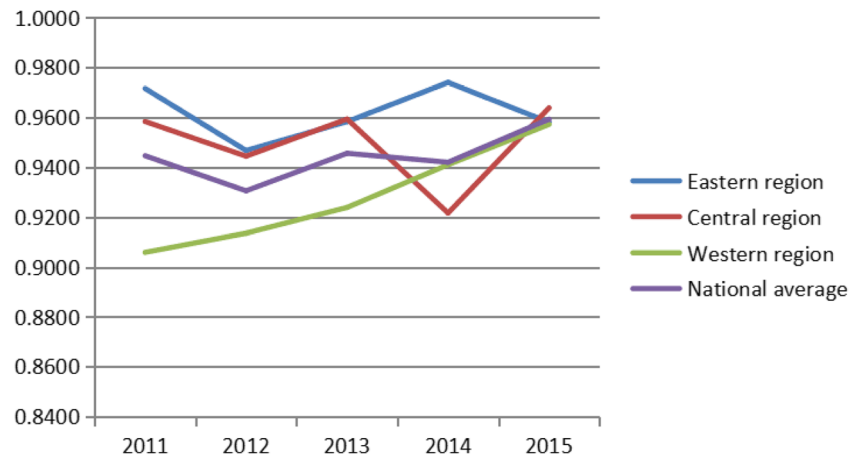|	DMU	Rank	Average	2011	2012	2013	2014	2015
East	Beijing	1	1	1	1	1	1	1
	Fujian	27	0.8605	0.9133	0.6004	0.8037	0.9910	0.9939
	Guangdong	1	1	1	1	1	1	1
	Hainan	11	0.9680	0.8783	0.9945	0.9857	0.9931	0.9884
	Hebei	24	0.9232	0.9734	0.9263	0.9166	0.8874	0.9125
	Jiangsu	1	1	1	1	1	1	1
	Liaoning	15	0.9552	0.9968	0.9938	0.9731	1	0.8125
	Shandong	1	1	1	1	1	1	1
	Shanghai	1	1	1	1	1	1	1
	Tianjin	1	1	1	1	1	1	1
	Zhejiang	26	0.8724	0.9258	0.8990	0.8625	0.8427	0.8320
Eastern average		9.9091	0.9618	0.9716	0.9467	0.9583	0.9740	0.9581
Central	Anhui	12	0.9679	0.9958	0.9922	0.9740	0.9255	0.9519
	Heilongjiang	14	0.9571	0.9704	0.9532	0.9524	0.9514	0.9582
	Henan	16	0.9542	1	0.9215	0.9409	0.9588	0.9496
	Hubei	20	0.9321	0.9707	0.9781	0.9170	0.8804	0.9141
	Hunan	18	0.9375	0.9623	0.9611	1	0.7645	0.9996
	Jiangxi	1	1	1	1	1	1	1
	Jilin	1	1	1	1	1	1	1
	Shanxi	29	0.8477	0.7679	0.7495	0.8906	0.8925	0.9378
Central average		13.8750	0.9495	0.9584	0.9444	0.9594	0.9216	0.9639
West	Chongqing	19	0.9375	0.9239	0.9236	0.8896	0.9502	1
	Gansu	22	0.9243	0.9039	0.9171	0.9427	0.9299	0.9276
	Guangxi	25	0.8804	0.8177	0.8338	0.9005	0.9144	0.9355
	Guizhou	23	0.9237	0.9269	0.9401	0.8800	0.9363	0.9352
	Inner Mongolia	9	0.9964	1	0.9992	0.9961	0.9938	0.9927
	Ningxia	17	0.9444	0.9409	0.8962	0.9586	0.9626	0.9637
	Qinghai	13	0.9587	0.9769	0.9554	0.9578	0.9497	0.9536
	Shaanxi	30	0.8409	0.8261	0.8228	0.8255	0.8186	0.9115
	Sichuan	28	0.8514	0.7990	0.7772	0.8743	0.8272	0.9790
	Xinjiang	10	0.9727	0.9821	0.9794	0.9752	0.9501	0.9768
	Yunnan	21	0.9268	0.8864	0.9018	0.9516	0.9401	0.9540
Western average		10.3253	0.9155	0.9059	0.9136	0.9239	0.9410	0.9572
National average		14.5667	0.9444	0.9446	0.9305	0.9456	0.9420	0.9593

Fig. 6 Average labor efficiency by region

Table 6 Revenue efficiency

	DMU	Rank	Average	2011	2012	2013	2014	2015
East	Beijing	1	1	1	1	1	1	1
	Fujian	14	0.9736	0.9829	0.9473	0.9524	0.9912	0.9940
	Guangdong	1	1	1	1	1	1	1
	Hainan	11	0.9822	0.9488	0.9946	0.9861	0.9932	0.9886
	Hebei	23	0.9345	0.9748	0.9358	0.9285	0.9081	0.9255
	Jiangsu	1	1	1	1	1	1	1
	Liaoning	17	0.9659	0.9968	0.9939	0.9753	1	0.8636
	Shandong	1	1	1	1	1	1	1
	Shanghai	1	1	1	1	1	1	1
	Tianjin	1	1	1	1	1	1	1
	Zhejiang	28	0.8996	0.9354	0.9160	0.8922	0.8804	0.8742
Eastern average		9	0.9778	0.9853	0.9807	0.9759	0.9793	0.9678
Central	Anhui	15	0.9729	1	0.9982	0.9753	0.9351	0.9561
	Heilongjiang	16	0.9692	0.9720	0.9651	0.9712	0.9763	0.9614
	Henan	12	0.9776	1	0.9763	0.9955	0.9619	0.9542
	Hubei	21	0.9421	0.9723	0.9790	0.9288	0.9035	0.9267
	Hunan	10	0.9913	0.9998	0.9868	1	0.9703	0.9996
	Jiangxi	1	1	1	1	1	1	1
	Jilin	1	1	1	1	1	1	1
	Shanxi	29	0.8882	0.8415	0.8331	0.9102	0.9115	0.9447
Central average		13.1250	0.9677	0.9732	0.9673	0.9726	0.9573	0.9678
West	Chongqing	19	0.9537	0.9339	0.9414	0.9096	0.9836	1
	Gansu	24	0.9344	0.9194	0.9289	0.9486	0.9385	0.9368
	Guangxi	26	0.9057	0.8664	0.8753	0.9170	0.9269	0.9428
	Guizhou	25	0.9344	0.9362	0.9465	0.9032	0.9435	0.9426
	Inner Mongolia	9	0.9964	1	0.9992	0.9961	0.9939	0.9928
	Ningxia	20	0.9458	0.9471	0.9140	0.9367	0.9652	0.9661
	Qinghai	18	0.9620	0.9779	0.9591	0.9611	0.9543	0.9576
	Shaanxi	30	0.8805	0.8710	0.8692	0.8706	0.8669	0.9248
	Sichuan	27	0.9003	0.8566	0.8459	0.9318	0.8875	0.9799
	Xinjiang	13	0.9743	0.9828	0.9802	0.9764	0.9546	0.9778
	Yunnan	22	0.9371	0.9074	0.9179	0.9559	0.9465	0.9579
Western average		11.0602	0.9329	0.9262	0.9311	0.9395	0.9518	0.9617
National average		14.5667	0.9607	0.9608	0.9568	0.9608	0.9598	0.9656

Fig. 7 Average revenue efficiency by region
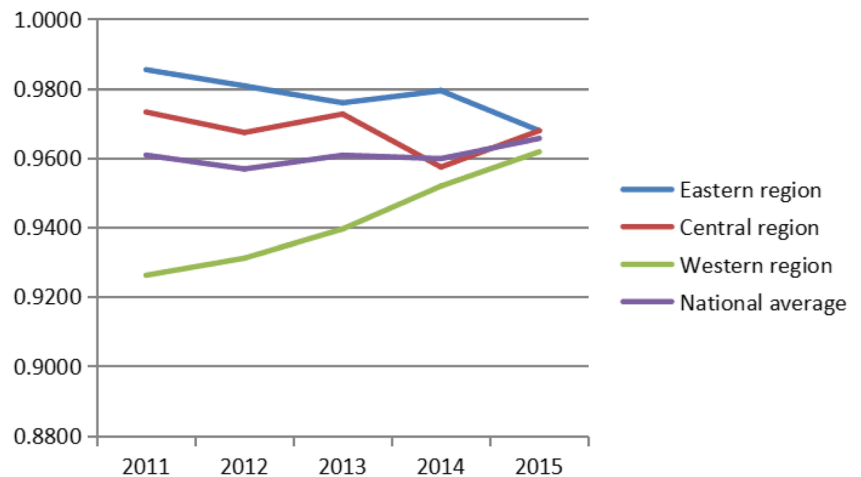
National analysis The average national efficiency was 0.94 and fluctuating; therefore, overall, there were only small improvements needed.

Revenue efficiency

Table 6 shows the revenue efficiencies in the 30 provinces from 2011 to 2015, and Fig. 7 shows the average annual revenue efficiencies in the eastern, central, and western regions, and nationally from 2011 to 2015.

Provincial analysis Beijing, Guangdong, Jiangsu, Jiangxi, Jilin, Shandong, Shanghai, and Tianjin all had revenue efficiencies of 1, with the lowest being in Shaanxi at 0.89 and in

Shanxi at 0.88. The revenue efficiencies in Fujian, Hebei, Anhui, Shanxi, Ningxia, and Xinjiang first fell and then rose, those in Gansu first rose and then fell, those in Guangxi continued to rise, and those in Zhejiang and Inner Mongolia had slow small declines to around 0.99. There were revenue efficiency fluctuations in 12 provinces: Hainan, Liaoning, Heilongjiang, Henan, Hubei, Hunan, Chongqing, Guizhou, Qinghai, Shaanxi, Sichuan, and Yunnan.

Eastern, central, and western regional analyses The average revenue efficiency was 0.98 in the eastern region, 0.97 in the central region, and 0.93 in the western region. While the revenue efficiencies in the eastern and central regions fluctuated over the period, there was a significant revenue efficiency rise

Table 7 Emissions efficiency

	DMU	Rank	Average	2011	2012	2013	2014	2015
East	Beijing	1	1	1	1	1	1	1
	Fujian	11	0.9304	0.9610	0.8527	0.9474	0.9362	0.9544
	Guangdong	1	1	1	1	1	1	1
	Hainan	12	0.9289	0.9429	0.9945	0.9035	0.9012	0.9023
	Hebei	30	0.3326	0.3140	0.3352	0.3085	0.3237	0.3815
	Jiangsu	1	1	1	1	1	1	1
	Liaoning	19	0.8815	0.9211	0.9169	0.8622	1	0.7073
	Shandong	1	1	1	1	1	1	1
	Shanghai	1	1	1	1	1	1	1
	Tianjin	1	1	1	1	1	1	1
	Zhejiang	20	0.8724	0.9258	0.8990	0.8625	0.8427	0.8320
Eastern average		8.9091	0.9042	0.9150	0.9089	0.8986	0.9094	0.8889
Central	Anhui	24	0.8432	0.9108	0.8986	0.8748	0.7652	0.7666
	Heilongjiang	14	0.9203	0.9418	0.9311	0.9178	0.9016	0.9091
	Henan	22	0.8654	1	0.8564	0.9190	0.6651	0.8862
	Hubei	16	0.9140	0.9707	0.9504	0.9170	0.8179	0.9141
	Hunan	9	0.9813	0.9998	0.9390	1	0.9684	0.9996
	Jiangxi	1	1	1	1	1	1	1
	Jilin	1	1	1	1	1	1	1
	Shanxi	28	0.6626	0.3853	0.4289	0.6687	0.8925	0.9378
Central average		14.3750	0.8984	0.9010	0.8755	0.9122	0.8763	0.9267
West	Chongqing	10	0.9398	0.9239	0.9336	0.8896	0.9698	0.9823
	Gansu	26	0.7970	0.7062	0.6317	0.9044	0.9299	0.8127
	Guangxi	29	0.5211	0.2839	0.3052	0.6389	0.6673	0.7100
	Guizhou	25	0.8410	0.9269	0.9401	0.6991	0.8212	0.8177
	Inner Mongolia	13	0.9215	1	0.8985	0.9026	0.9007	0.9056
	Ningxia	21	0.8678	0.7968	0.6972	0.9372	0.9442	0.9637
	Qinghai	17	0.9089	0.8988	0.8516	0.9578	0.8826	0.9536
	Shaanxi	27	0.7510	0.5948	0.7936	0.7943	0.7455	0.8268
	Sichuan	23	0.8511	0.7990	0.7772	0.9211	0.7791	0.9790
	Xinjiang	15	0.9182	0.9253	0.9254	0.9752	0.8741	0.8911
	Yunnan	18	0.8949	0.8523	0.9018	0.9253	0.9152	0.8800
Western average		10.6006	0.8146	0.7893	0.8273	0.8625	0.8706	0.8839
National average		14.5667	0.8782	0.8660	0.8553	0.8909	0.8815	0.8971

Fig. 8 Average emissions efficiency by region
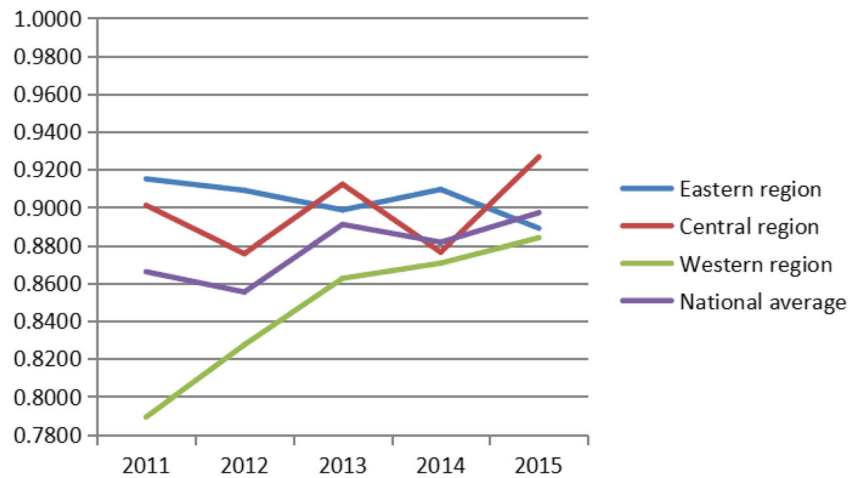
in the western region; however, in 2015, the revenue efficiencies in the three regions were similar.

Six of the 11 eastern provinces had revenue efficiencies of 1, with Hebei at 0.93 and with Zhejiang at 0.90 being significantly lower than the average. The central region's revenue efficiencies were uneven, and the western provinces had lower overall revenue efficiencies.

National analysis The average national revenue efficiency was 0.96 and stable; therefore, only small improvements were needed.

Emissions efficiency

Table 7 shows the emissions efficiencies in the 30 provinces from 2011 to 2015, and Fig. 8 shows the average eastern, central, western, and national emissions efficiencies from 2011 to 2015.

Provincial analysis Beijing, Guangdong, Jiangsu, Jiangxi, Jilin, Shandong, Shanghai, and Tianjin all had emissions efficiencies of 1, with Hebei (0.33) and Guangxi (0.52) having the lowest. The emissions efficiencies in Anhui, Heilongjiang, Hubei, and Ningxia first dropped and then rose, those in Shanxi and Guangxi were continually rising, those in Zhejiang were declining, and those in fifteen provinces (Fujian, Hainan, Hebei, Liaoning, Henan, Hunan, Chongqing, Gansu, Guizhou, Inner Mongolia, Qinghai, Shaanxi, Sichuan, Xinjiang, Yunnan) were fluctuating. Therefore, the annual emissions efficiencies in many provinces were relatively unstable.

Eastern, central, and western regional analyses The average emissions efficiency was 0.9 in the eastern region, 0.9 in the central region, and 0.81 in the western region. While overall, the emissions efficiency in the east was stable and the emissions efficiency in the western region fluctuated; in 2015, the

average emissions efficiencies in the three regions were similar.

The emissions efficiencies in six of the 11 eastern provinces were 1; however, in Hebei (0.33) and Zhejiang (0.87), they were significantly lower than the average. The central provinces' emissions efficiencies were uneven, and the lowest provincial emissions efficiencies were in the western region.

National analysis The average national annual emissions efficiency was 0.96 and fluctuating; however, overall, there were only small improvements needed.

Regional improvements

The coal, non-coal, and emissions efficiencies in the 30 provinces from 2011 to 2015 were then compared to assess the needed efficiency improvements.

Regional analysis

Beijing, Guangdong, Jiangsu, Shandong, Shanghai, Tianjin, Jiangxi, and Jilin all had efficiencies of 1 for all three indicators; therefore, these provinces required no further improvements. There were four provinces in which coal index efficiency improvements were needed. Anhui had an annual coal efficiency of 0.9 and an annual non-coal index efficiency of 1; however, its emissions index declined from 0.91 in 2011 to 0.77 in 2015, which indicated that both coal and emissions efficiency improvements were needed with the primary improvement direction being coal efficiency.

Hunan had a coal efficiency of 1 in all years except 2013, a non-coal index efficiency fluctuating between 0.96 and 1, and an emissions efficiency that fluctuated from 0.94 in 2012 to 1 in 2013; therefore, only small improvements were needed in all three indicators. Chongqing had an annual coal index efficiency of 0.9, a non-coal index efficiency that fluctuated between 0.9 and 0.94, and an emissions efficiency that

fluctuated from 0.89 in 2013 to 0.98 in 2015; therefore, small improvements were needed in all three indicators. Yunnan had an annual coal index efficiency of 0.9, a non-coal index efficiency of 0.96 except for 2015 when it was 1, and an emissions index efficiency that fluctuated between 0.88 and 0.93; therefore, small improvements were needed in all three indicators.

The primary improvement direction was in the non-coal indicators in three provinces. Fujian had a coal index efficiency between 0.98 and 1, a non-coal index efficiency of 0.9, and an emissions efficiency that fluctuated from 0.96 in 2011 to 0.85 in 2012; therefore, while small improvements were needed in these two indicators, a greater focus needed to be placed on non-coal efficiency. Hainan had a declining coal efficiency from 1 in 2011 to 0.9 in 2015, a non-coal annual efficiency of 0.9, and a fluctuating emissions efficiency, with the highest being 0.99 in 2012; therefore, small improvements were needed in all three indicators. Heilongjiang had a declining coal efficiency from 1 in 2011 and 2012 to 0.9 in 2015, a steady annual non-coal index efficiency of 0.9, and an emissions index efficiency from 0.90 to 0.94; therefore, small improvements were needed in all three indicators.

The primary improvement directions were in the coal and non-coal indicators in two regions. Qinghai had a coal index efficiency of around 0.91, a non-coal index efficiency of 0.9, and a fluctuating emissions index efficiency, with the lowest being 0.85 in 2012 and the highest being 0.96 in 2013; therefore, small improvements were needed in all three indicators. Xinjiang had coal and non-coal efficiencies of 0.9 and a fluctuating emissions index efficiency, with the highest being 0.98 in 2013 and the lowest being 0.87 in 2014; therefore, small improvements were needed in all three indicators.

The primary improvement direction was the emissions indicator in 13 provinces. Hebei had a coal index efficiency of 1 in 2012 and 0.9 in all other years; a non-coal index efficiency that rose from 0.9 in 2011 to 1 in 2013, where it remained; and an emissions index efficiency from 0.30 to 0.38; therefore, while small improvements were needed in two indicators, significant improvements were needed in emissions performances. Liaoning had a coal index efficiency of 1 in all years except 2015 when it fell to 0.9, a non-coal index efficiency of 0.9 except for 2014, and a fluctuating emissions index efficiency from 1 in 2014 to 0.71 in 2015; therefore, while small improvements were needed in two indicators, more emissions performance improvements were needed. Zhejiang had an annual coal index efficiency of 1 and 0.9, a non-coal index efficiency of 1, and an emissions efficiency between 0.80 and 0.90 except for 2011; therefore, while small improvements were needed in coal index efficiency, a greater focus needed to be placed on emissions. Henan's coal index efficiency fluctuated, with the lowest being 0.9 in 2014 and the highest being 1 in 2011 and 2015, a fluctuating non-coal index efficiency with the lowest being 0.9 in 2014 and the highest

being 1 in 2011, and a widely fluctuating emissions efficiency from 1 in 2011 to 0.67 in 2014; therefore, while small improvements were needed in two indicators, a greater focus needed to be placed on emissions. Hubei had a coal index efficiency around 0.9 except for 2014 at 0.98, a fluctuating non-coal index efficiency from 0.94 in 2014 to 1 in 3 years, and a fluctuating emissions index efficiency from 0.97 in 2011 to 0.82 in 2014; therefore, while small improvements were needed in two indicators, a greater focus needed to be placed on emissions. Shanxi had a coal index efficiency of 0.9, a non-coal index efficiency of 1 except for 2015, and a rising emissions index efficiency from 0.39 in 2011 to 0.94 in 2015; therefore, both the coal indicator and the emissions indicator required improvements. Gansu had a coal index efficiency of 0.9, a non-coal index efficiency of 0.9, and a fluctuating emissions efficiency from 0.63 in 2012 to 0.93 in 2014; therefore, while small improvements were needed in all three indicators, a greater focus needed to be placed on emissions. Guangxi had a coal efficiency around 0.9, a fluctuating non-coal indicator efficiency from 0.98 in 2012 to 0.90 in 2015, and an improving emissions index efficiency from 0.28 in 2011 to 0.71 in 2015; therefore, while small improvements were needed in two indicators, a greater focus needed to be placed on emissions. Guizhou had a coal index efficiency of 0.9, a non-coal index efficiency of 1, and a fluctuating emissions efficiency from 0.93 in 2011 to 0.70 in 2013; therefore, both the coal and emissions efficiencies needed improvements. Inner Mongolia had a coal index efficiency of 0.9 except for the 2011 when it was 1, a non-coal index efficiency of around 0.93 to 0.94 except for 2011 when it was 1, and an emissions efficiency of around 0.90 except for 2011 when it was 1; therefore, small improvements were needed in all indicators. Ningxia had a coal index efficiency of 0.9, a fluctuating non-coal index efficiency between 0.9 and 0.93, and a fluctuating emissions efficiency from 0.70 in 2012 to 0.96 in 2015; therefore, all three indicators needed small improvements. Shaanxi had a coal index efficiency of 0.9 except for 2011 (0.96), a fluctuating non-coal index efficiency from 0.9 in 2011 and 2014 and 1 in 2012, and a rising emissions index efficiency from 0.60 in 2011 to 0.83 in 2015; therefore, while small improvements were needed in two indicators, a greater focus needed to be placed on emissions. Sichuan had a coal index efficiency of 0.9, a non-coal index efficiency of 0.96, and a fluctuating emissions index efficiency from 0.78 in 2012 to 0.98 in 2015; therefore, small improvements were needed in all three indicators.

Eastern, central, and western regional analyses

Six provinces in the eastern region required no improvements, non-coal index efficiency primary improvements were needed in two provinces, and primary emissions improvements were needed in three provinces. The provinces in the eastern region

had the best overall performances; however, the coal index efficiencies were better than the non-coal and emissions index efficiencies.

Two provinces in the central region required no improvements, coal index efficiency improvements were needed in two provinces, one province required non-coal index efficiency improvements, and emissions efficiency was the primary improvement direction in three provinces.

Coal index efficiencies were the primary improvement directions for two western provinces, two provinces required coal and the non-coal index efficiency improvements, and emissions index efficiency improvements were the primary direction for seven western provinces. Therefore, in the western region, most provinces needed to improve their emissions efficiencies.

National analysis

There were no improvements necessary in eight provinces, coal index efficiency was the primary improvement direction in four provinces, non-coal index efficiency was the primary improvement direction in three provinces, both coal and non-coal index efficiencies were the primary improvement directions in two provinces, and emissions efficiencies were the primary improvement direction in 13 provinces.

Conclusions and policy recommendations

This paper used a DDF DEA model, in which labor, coal, non-coal, and government expenditure were the inputs, fixed assets was the carryover, and revenue and emissions were the outputs, to analyze overall provincial, regional, and national efficiencies and the efficiencies of each index, from which the following conclusions were made:

(1) The total efficiencies and the efficiencies for the various indicators in the eastern region were higher than those in the central region, which, in turn, were higher than those in the western region. Beijing, Guangdong, Jiangsu, Jiangxi, Jilin, Shandong, Shanghai, and Tianjin had efficiencies of 1 for each indicator and were the benchmarks, Shanxi and Shaanxi had the lowest efficiencies for all indicators and had very poor revenue and labor efficiencies, and Hebei had extremely poor expenditure and emissions efficiencies.

(2) The coal and non-coal index efficiencies fluctuated significantly in the various regions. While the basic total, revenue, and labor efficiencies in the three regions were generally similar, the overall revenue and labor efficiencies were declining in Zhejiang and rising in Guangxi.

(3) The comparison of the coal, non-coal, and emissions index efficiencies revealed that the greatest

improvements needed were in emissions efficiencies in many provinces such as Shanxi, Shaanxi, Sichuan, Zhejiang, and Guangxi.

(4) The coal index efficiency in the eastern region was better than the non-coal and emissions index efficiencies, but the primary improvement direction in the western region was emissions efficiency. Some provinces in the central region did not need improvements, but there were others that required coal, non-coal, and emissions efficiency improvements. Emissions efficiency improvements were needed in most western region provinces.

(5) The national expenditure and emissions efficiencies were lower than 0.9 at only 0.89 and 0.88, and the revenue and non-coal index efficiencies were 0.96.

Based on these conclusions, the following policy recommendations were made:

(1) First, the government needs to develop policy incentives to encourage the eastern region to share its advanced technologies and experience with the western region to improve the region's environmental energy production efficiencies. As each region has its own unique resource endowments, the energy industry structures need to be adjusted according to local conditions and clean and new energies rationally planned.

(2) Second, external environmental monitoring and internal information systems need to be built to facilitate responses to the internal and external environmental changes, and predictive models need to be developed to assess environmental changes, maintain stable efficiencies, and monitor resource utilization.

(3) Third, environmental pollution control investment needs to be strengthened. The national, regional, and local governments need to focus on their pollutant emissions, strengthen financial support, and based on local meteorological and geological conditions, adopt new technologies to improve emissions reduction efficiencies to meet international and domestic environmental protection requirements.

(4) Fourth, private funds should be encouraged to participate in energy industry environmental governance. Because government-led environmental pollution control has diverse management requirements, the limited resources in many regions make it difficult to get government support; therefore, it is suggested that private funds be encouraged to invest in industry environmental pollutant control, especially in high emissions enterprises. Encouraging private capital to invest in shares and strengthening government systems and management support could greatly improve the environmental pollutant emissions control efficiencies.

(5) Fifth, establish a carbon emissions trading market. Due to regional differences in China's energy industry, some companies have greater energy industry and environmental protection development advantages and varied economic and social needs; therefore, a carbon emissions trading market could effectively guide emissions reduction.

Authors' contributions Y.L. conceived and designed the topic; Y.N.L. and Y.L. performed the model; H.C., Y.-h.C., and T.-Y.L. analyzed the data; Y.-h.C. contributed the reagents/materials/analysis tools; Y.L. and T.-Y.L. wrote the paper.

Data availability The datasets generated and/or analyzed during the current study are available in the China National Bureau of Statistics (www. stats.gov.cn).

Compliance with ethical standards

Competing interests The authors declare that they have no competing interests.

Ethical approval and consent to participate Not applicable

Consent for publication Not applicable

References

BP (2019) Statistical review of world energy. LNG Global, 1730 E. Holly Avenue El Segundo, CA, USA.

Chen J, Dong X (2018) Carbon efficiency and carbon abatement costs of coal-fired power enterprises: a case of Shanghai, China. Journal of Cleaner Production 206:452–459

Cheng Y, Lv K, Wang J, Xu H (2019) Energy efficiency, carbon dioxide emission efficiency, and related abatement costs in regional China: a synthesis of input–output analysis and DEA. Energy Efficiency 12: 863–877

Chung Y, Färe R, Grosskopf S (1997) Productivity and undesirable outputs: a directional distance function approach. Journal of Environmental Management 51:229–240

Cui Y, Huang G, Yin Z (2015) Estimating regional coal resource efficiency in China using three-stage DEA and bootstrap DEA models. International Journal of Mining Science and Technology 25:861–864

Du L, Mao J (2015) Estimating the environmental efficiency and marginal CO_2 abatement cost of coal-fired power plants in China. Energy Policy 85:347–356

Du L, Hanley A, Zhang N (2016) Environmental technical efficiency, technology gap and shadow price of coal-fuelled power plants in China: a parametric meta-frontier analysis. Resource and Energy Economics 43:14–32

Färe R, Grosskopf S (2010) Directional distance functions and slacks-based measures of efficiency. Eur J Oper Res 200:320–322

Guo Y, Li N, Mu H, Li L, Duan Y (2017a) Regional total-factor coal consumption efficiency in China: a meta-frontier SBM-undesirable approach. Energy Procedia 142:2423–2428

Guo Y, Liu W, Tian J, He R, Chen L (2017b) Eco-efficiency assessment of coal-fired combined heat and power plants in Chinese eco-industrial parks. Journal of Cleaner Production 168:963–972

Guo X, Lu CC, Lee JH, Chiu YH (2017c) Applying the dynamic DEA model to evaluate the energy efficiency of OECD countries and China. Energy 134:392–399

Guo P, Qi X, Zhou X, Li W (2018) Total-factor energy efficiency of coal consumption: an empirical analysis of China's energy intensive industries. Journal of Cleaner Production 172:2618–2624

Lin X, Zhu X, Han Y, Geng Z, Liu L (2020) Economy and carbon dioxide emissions effects of energy structures in the world: evidence based on SBM-DEA model. Science of the Total Environment 138947.

Liu J, Liu H, Yao X, Liu Y (2016) Evaluating the sustainability impact of consolidation policy in China's coal mining industry: a data envelopment analysis. Journal of Cleaner Production 112:2969–2979

Liu X, Chu J, Yin P, Sun J (2017) DEA cross-efficiency evaluation considering undesirable output and ranking priority: a case study of eco-efficiency analysis of coal-fired power plants. Journal of Cleaner Production 142:877–885

Long R, Wang H, Chen H (2016) Regional differences and pattern classifications in the efficiency of coal consumption in China. Journal of Cleaner Production 112:3684–3691

Luenberger D (1992) Benefit functions and duality. Journal of Mathematical Economics 21:461–481

Meng F, Su B, Thomson E, Zhou D, Zhou P (2016) Measuring China's regional energy and carbon emission efficiency with DEA models: a survey. Applied Energy 183:1–21

Ren F R, Tian Z, Chen H S, Shen Y T (2020a) Energy consumption, CO_2 emissions, and agricultural disaster efficiency evaluation of China based on the two-stage dynamic DEA method. Environ Sci Pollut Res 1–18.

Ren J, Gao B, Zhang J, Chen C (2020b) Measuring the energy and carbon emission efficiency of regional transportation systems in China: chance-constrained DEA models. Mathematical Problems in Engineering 2020.

Shephard R (1970) The theory of cost and production functions. Princeton University Press, Princeton

Song C, Li M, Zhang F, He Y, Tao W (2014) Analysis of energy efficiency for coal-fired power units based on data envelopment analysis model. Energy Procedia 61:904–909

Wang LW, Le KD, Nguyen TD (2019) Assessment of the energy efficiency improvement of twenty-five countries: a DEA approach. Energies 12:1535

Wu Y, Ke Y, Xu C, Xiao X, Hu Y (2018) Eco-efficiency measurement of coal-fired power plants in China using super efficiency data envelopment analysis. Sustainable Cities and Society 36:157–168

Zhang D, Li M, Ji X, Wu J, Dong Y (2019) Revealing potential of energy-saving behind emission reduction. Manag Environ Qual

Publisher's note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.