IOP Conf. Series: Earth and Environmental Science **121** (2018) 032028 doi:10.1088/1755-1315/121/3/032028

Research on PM2.5 emission reduction path of China 's electric power industry based on DEA model

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Abstract. Based on the theory of data envelopment analysis, this study constructs the environmental performance evaluation model of the power industry, analyzes the performance of development of clean energy, the implementation of electricity replacement, and the development of coal-fired energy-saving and emission-reducing measures. Put forward technology path to reduce emission in the future. The results show that (1) improving the proportion of coal for power generation, speeding up the replacement of electricity is the key to solve the haze in China. (2) With the photovoltaic and other new energy power generation costs gradually reduced and less limit from thermal energy, by final of "thirteenth five-years plan", the economy of clean energy will surpass thermal energy-saving emission reduction. (3) After 2025, the economy of the electricity replacement will be able to show.

1. Introduction

In recent years, the frequent haze events in the eastern and central regions of China have brought great threat to the development of the national economy and the health of the people, which has aroused widespread concern in the whole society. Coal-fired PM2.5 and other air pollutants has become one of the main sources of haze [1]. Therefore, around the power industry to carry out air pollution reduction, to analyze future power industry emission reduction measures and effectiveness, which is of great significance to strengthen the prevention and control of air pollution.

At present, the research on PM2.5 emission control at home and abroad mainly focuses on PM2.5 control technology research, physical and chemical characteristics and related emission factors [2-5]. The research on the emission reduction path of the power industry mainly focuses on the emission reduction analysis of sulfur, nitrogen and carbon in the thermal power industry [6]. This study not only focuses on the development trend of energy saving and emission reduction in thermal power industry, but also focuses on the alternative emission reduction effect of clean energy and the synergistic haze effect of power industry and other industries. DEA (Data envelopment method) can carry out more objective evaluation of the effect， Park [7] uses DEA model and stochastic frontier analysis method respectively to evaluate the same efficiency of power generation environment, the results showed that the DEA method of the evaluation results more close to reality.

2. China's power industry emission reduction control measures

Based on the current development trend, China's future power industry emission reduction measures mainly include thermal power plant energy-saving emission reduction (ESER), clean energy development, electricity replacement (ER).

2.1. Thermal power plant ESER measure

Thermal power plant ESER measures include technical reduction, structural reduction and emission reduction and so on. Therefore, the main way to achieve ESER is to reduce the front-end consumption and improve end-use technologies such as reduce coal consumption and improve the emission standards. The specific measures include eliminating backward production capacity, shutting down small thermal power units, optimizing thermal power structure, reducing coal consumption and implementing ultra-low emission.

(1) Reduce power supply coal consumption

In 2015, power supply of China's large generating units per kilowatt-hour is about 285 to 305 grams of coal, coal consumption of small units is higher than large units about 25% to 17%. It is estimated that by 2020, the average coal consumption of the existing coal-fired generating units will be reduced by less than 310 g/kWh, among them, the 600 thousand kilowatts (except the air-cooled units) will be less than 300 g/kWh. After the transformation, air pollutant emissions concentration will basically reach the gas turbine emission limits [8].

(2) Ultra-low emission

At present, China's new emission standards of soot, nitrogen oxides, sulfur dioxide standards are 10 mg/ m³, 30 g/ m³, 50 mg/ m³. The power industry primary PM2.5 emissions are only 15% to 20% of the total emissions, the key to solve haze is to reduce the emissions of conventional air pollutants. According to estimates in 2015, coal unit average dust extraction, desulfurization, and denitrification reaching more than 99.95%, 98%, 85%. Data of the table 1 is from thermal power plant air pollutant emission standards (From GB 13223-2011).

Table 1 change of China's thermal power plant pollutant discharge standards (unit: mg / m³)

Pollutant species	Applicable conditions	2003 version of the standard	2011 version of the standard		Ultra low emission limits
			priority areas	Non - priority areas	
soot	all	50	20	30	10
sulfur dioxide	New boiler	400	50	100/200	35
	Existing boilers			200/400	
nitrogen oxide（NO2）	all	450	100	100	50

2.2. Clean energy development measure

At present, the proportion of non-fossil energy in developed countries is more than 80%, and conversion to electricity is the most important way to achieve the effective use of them. As of the end of 2016, China's hydropower, wind power, solar power installed capacity all ranked first in the world. It is expected in 2020 that, China's clean energy installed capacity will be about 800 million kilowatts, accounting for 44% of the national power installed capacity [9].

With the costs of PV module and system continue to decline, there is a large decline in space of the future of new energy power generation costs. According to the forecast, by 2030 China's wind power and photovoltaic power costs will reach 0.34, 0.32 RMB / kWh, lower than 53%, 33% compared with 2016, and has been lower than the current conventional coal-fired thermal power average electricity price, so it is with strong market competitiveness.

2.3. Electricity replacement measure(ER)

Direct combustion of coal causes serious air pollution problems, is the most important cause of haze. From the power production and utilization of the whole process, the thermal emissions of pollutants can be centralized treatment, the current thermal power plant desulfurization rate, denitrification rate, dust removal rate can reach more than 90%, 80%, 99% or more. Energy efficiency from the energy terminal, the use efficiency of electricity is the highest among all, up to 90% or more. The efficiency of scattered coal is even less than 20%.

The potential for energy substitution is affected by a variety of factors, including energy efficiency and economic factors, user habits, environmental factors. According to the relevant research [9], it is expected that the replacement of electricity in 2020 will be mainly distributed in the fields of industrial boilers, industrial furnaces and central heating, with an alternative power of about 600 billion kWh.

3. Environmental evaluation of emission reduction measures in power industry

3.1. Environmental performance assessment model

In this study, we use the input-oriented DEA model to evaluate and forecast the efficiency of reducing emissions of three measures from 2006 to 2030. By means of software DEAP2.1 analysis, the higher the efficiency of evaluation, the better the implementation of the measures, that is, with relatively little input to get more output. It is also an important boundary parameter to construct the environmental performance evaluation model

(1) Energy-saving and emissions-reduction benefits of thermal power

According to PM2.5 Emissions Accounting Technical Specifications, which issued by China Ministry of Environmental Protection, coal-fired units PM2.5 emissions computational formula is as follow:

$$E = M \times Aar \times \omega \times (1-\eta). \tag{1}$$

Where, M is coal consumption (ten thousand tons). Aar is ash share, here takes 20%.

$$\omega = (1 - Aar) \times f_{PM2.5} \tag{2}$$

ω is the conversion coefficient of coal ash to PM2.5, here takes 5.1%， Aar is same as (1).

Assuming the ash ratio and PM2.5 conversion coefficient unchanged, the implementation of energy-saving technologies and emission reduction technology, comprehensive emission reduction benefits can be expressed as

$$E_i = E - E'. \tag{3}$$

$$E_i = E \times \frac{M_i \times (1-\eta)}{M \times (1-\eta)}. \tag{4}$$

$$E_i = E \times \left[1 - \frac{d \cdot \alpha \cdot (1-\eta)}{d_i \cdot \alpha \cdot (1-\eta_i)} \right]. \tag{5}$$

Where E and E' are primary emission of PM2.5 of benchmark year and ith year in electricity industry. M d, α, η are coal consumption, power generation, unit coal consumption, dust removal efficiency respectively of benchmark year. M_i, d_i, α_i, η_i are the value of corresponding indicator of ith year.

(2) Clean energy reduction benefits

The Energy-saving benefit of development of clean energy can be expressed as:

$$\Delta F_t = \sum_{j=1}^{4} G_{j,t} \times h_{j,t} \times c_t. \tag{6}$$

The pollutant emission reduction benefits of development of clean energy can be expressed as:

$$\Delta F_{t,u} = \sum_{j=1}^{4} G_{j,t} \times h_{j,t} \times c_t \times e_{t,u}. \tag{7}$$

Where ΔF_t is clean energy alternative to coal consumption, j indicates hydropower, nuclear power, photovoltaic, wind power four kinds of clean energy, G is installed capacity, h is use hours, c_t is coal consumption coefficient of tth year. e is emission factor of SO_2 and NO_x.

So emission reduction of $PM_{2.5}$ can be written as:

$$\Delta PM_{2.5} = \Delta F_t \times 1.4 \times Aar \times \delta \times \varepsilon \times (1-\nu). \quad (8)$$

Where ash share Aar takes 20% here, fly ash ratio δ takes 85%, the proportion of $PM_{2.5}$ in fly ash δ takes 6%, removal efficiency of $PM_{2.5}$ ε takes 96.6%.

(3) Electricity replacement reduction benefits

$$\Delta E_{t,u} = \sum_{t=1}^{n} Coal_{t,i} \times e_{e,i,u} + \sum_{t=1}^{n} Petr_{t,i} \times e_{e,i,u} - Ele \times Str_t \times e_{t,u}. \quad (9)$$

Where $Coal_i$ is the saving coal of new technology, $Petr_i$ is the saving fuel, e is the $PM_{2.5}$ emission factor of new technology, Ele is total amount of replacement of electricity, Str is the proportion of coal power.

Data envelopment analysis (DEA), first proposed by Charnes et al. (1978) is a mathematical programming technique to evaluate the relative efficiency of a set of DMUs transforming multiple inputs into multiple outputs. Initially, it was mainly used to evaluate the efficiency of commercial banks, schools, hospitals, and other enterprises and institutions. As energy and environmental issues have become more and more prominent recently, it is also widely applied to evaluate the relative energy and environmental efficiency of a national, regional, and firm level. The input orientation is defined as not changing the number of outputs, how to minimize the input. This paper prefers to reduce input to gain more output, while the investment in these measures is relatively easier to adjust according to the specific conditions of energy conservation and emission reduction measures. So this paper adopts the input - oriented DEA evaluation method.

The input data of the decision-making unit in the environmental performance evaluation model of the power industry is the amount of capital x_j that invested in the haze control measures in the corresponding power industry. The output data are the reduced $PM_{2.5}$ emissions after the implementation of the measures, and the amount of raw coal. Assuming that there are j decision units and this model consists of 66 decision units. Any decision unit has an input vector X_j and two output vectors, thus the corresponding CCR planning model for the j_0th DMU is:

$$\begin{cases} \min[\theta - \varepsilon(e^T S^- + e^T S^+)] \\ \sum_{j=1}^{t} \lambda_j x_j + S^- = \theta x_{j0} \\ \sum_{j=1}^{t} \lambda_j y + S^+ = y_{j0} \\ S^-, S^+ \geq 0; \lambda_j \geq 0 \end{cases} \quad (10)$$

θ is the effective value of the evaluation unit, s^-, s^+ are slack variables, λ_j is equivalent to DMU_{j0} which corresponds to the combination ratio of the jth evaluation unit in a valid combination of the reconstructed.

Assuming that the optimal solutions of this model are. If $\theta^* = 1$, the evaluation unit DMU is weak and the DEA is valid; If $\theta^* = 1$ and $s^{*+} = s^{*-} = 0$, the evaluation unit DMU is valid for the DEA. Furthermore, it is both valid for the technology and scale; If $\theta^* < 1$, the evaluation unit DMU is invalid for the DEA.

Where S^-, S^+ mean relaxation variables and residual variable, ε and λ_j are weight. Here, input vector X_j is annual investment fee, output vectors Y_j are $PM_{2.5}$ emission reductions and annual coal savings.

As input variables, we use the annual investment fee (100 million RMB), use $PM_{2.5}$ emission reductions (million tons), and the annual coal savings (million tons). The data can be found on the China energy statistics yearbook. Four clean energy annual investment calculation method is the same, simply say, is annual new generation of electricity and electricity price product. The annual investment fee of electricity replacement is divided into two parts. The first part is direct investment, which is the product of new generation and electricity price. The second part is to transform investment. The annual investment fee of energy-saving emission reduction is also divided into two parts. The first part is cost of energy conservation reform, the cost of unit power renovation is 0.069 yuan/Kwh. The second part is desulfurization and denitration subsidies, which is related to the year's policy, not a fixed value.

3.2. Analysis of emission reduction methods

Based on analysis from 2006 to 2016, thermal power industry measures are the most efficient. Clean energy efficiency is also rising, with the declining costs. Because seriously abandoned wind and photovoltaic power in 2014 to 2016, it has declined. Due to the larger investment cost of ER the measure performance is relatively low. In the future, with increasing cost of hydropower and eco migration cost, hydropower emission reduction performance will decline; at the same time, wind power, solar energy and other new energy power generation technology is gradually mature, its power generation costs continue to decline, in years of 2019~2020, those performance will be higher than coal. As ER technologies developing and alternative scale effect, after 2025 its performance will be similar to coal energy conservation.

We include the following six emission reduction measures in our analysis: wind power (WIP), solar power (SP), water power (WAP), nuclear power (NP), electricity replacement (ER), energy-saving emission reduction (ESER). Figure 1 shows the economy of different measures to reduce emissions.

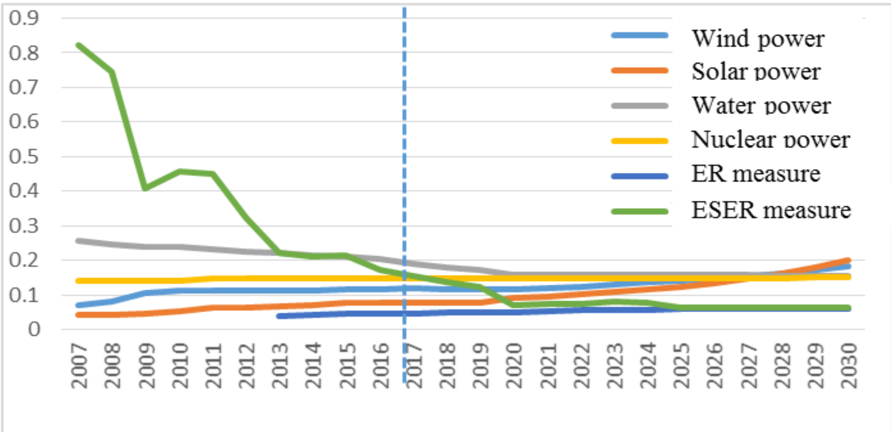

Figure 1. 2007-2030 emission reduction measures performance in electric power industry.

From emission reduction effect, with the change of power functions gradually into capacity provided by electricity providers after 2020 power plant scale emission reduction effect appears gradually. The results ofillustrate two conclusions, first, in 2020, the replacement size of the Beijing-Tianjin-Hebei Region and Yangtze River Delta energy will reach 200 gigawatts, which will reduce the local PM2.5 concentration by 25 percent. Second, the implementation of ultra-low emissions from thermal power plants will reduce PM2.5 concentrations by no more than 7 percent.

Considering reductions, environmental economics, technical feasibility, economic impact and other factors, from the electric power industry the future path, government should develop clean energy before 2020; and promote energy replacement and clean energy after 2025(table 2).

Table 2. 2007-2030 emission reduction measures performance.

	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018
WIP	0.071	0.08	0.106	0.112	0.114	0.114	0.114	0.113	0.115	0.115	0.118	0.116
SP	0.041	0.042	0.046	0.053	0.064	0.064	0.068	0.069	0.076	0.076	0.076	0.076
WAP	0.257	0.248	0.241	0.241	0.233	0.225	0.223	0.215	0.212	0.203	0.191	0.18
NP	0.142	0.142	0.142	0.142	0.147	0.147	0.148	0.148	0.148	0.148	0.148	0.147
ER							0.038	0.043	0.046	0.047	0.047	0.049
ESER	0.824	0.745	0.407	0.458	0.45	0.322	0.221	0.21	0.216	0.171	0.154	0.138
	2019	**2020**	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
WIP	0.116	0.116	0.12	0.125	0.13	0.136	0.142	0.148	0.155	0.163	0.172	0.182
SP	0.078	0.091	0.096	0.102	0.109	0.116	0.125	0.135	0.147	0.161	0.178	0.199
WAP	0.171	0.159	0.159	0.159	0.158	0.158	0.157	0.157	0.157	0.156	0.156	0.155
NP	0.147	0.147	0.147	0.147	0.148	0.148	0.148	0.149	0.149	0.149	0.15	0.15
ER	0.05	0.05	0.053	0.056	0.056	0.057	0.059	0.059	0.059	0.06	0.06	0.06
ESER	0.125	0.069	0.073	0.074	0.081	0.079	0.065	0.065	0.065	0.065	0.064	0.064

4. Summary

The choice of emission reduction path in the power industry depends on the level of emission reduction technology, national environmental protection and other policy factors. In this study, DEA model was used to analyze the haze of China's power industry in 2020 and 2030. The results show that, taking into account the environmental effects, economy and other factors, 12th and 13th Five-Year Plan period, to speed up the elimination of backward production capacity, energy conservation and ultra - low emissions should be the main means of haze the power industry; During the period of the 13th and the 14th Five-Year Plan period, the environmental protection economy of clean energy has been improved. Electricity replacement has reduced the effect of reducing coal waste in China, due to its economic reasons, large-scale power replacement technology will be able to apply after 2025.

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