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Scenario analysis for optimal allocation of China's electricity production system

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ABSTRACT

Electricity production is an important source of CO_2 emissions in China. Using a multi-objective model and a fuzzy multi-objective optimization linger programming method, this paper analyzes different scenarios for optimal allocation of China's power system in 2020. The results suggest that under low CO_2 reduction target, the fuel power plant should be highly developed besides coal-fired conventional plants, which in fact is impossible to form a fuel-driven power plant structure in China. When CO_2 reduction target is increased, natural gas combined cycle power plants should be developed vigorously. The coal-fired conventional power plants, hydropower plants and fuel power plants should play a lesser role in electricity generation. It is noteworthy that higher emission reduction targets do not cause greater generating cost. It is necessary for China to adjust its power generation structure from traditional coal-driven power plants to a diverse generation mix especially the development of plants using clean energy such as natural gas and hydropower. With rapid economy growth, China's power industry must develop strict CO_2 reduction targets, and emission reduction technology should be promoted in large-scale in China's electricity sector, as it does not lead to a higher increase in generating costs.

1. Introduction

After the enactment of Kyoto Protocol, the issue of global warming has been concerned by public increasingly, especially energy-related CO_2 emission which is the main greenhouse gas. Electricity production is an important source of CO_2 emissions in China, accounting for about 50% of the total CO_2 emissions, mostly from thermal power emissions. China's power structure is coal-based, in which the proportion of coal-fired generating capacity in the total generating capacity is more than 80%. CO_2 emissions will become a major constraint for the development of China's electricity production system. Therefore, it is necessary to change the development mode of power industry in China.

Many authors have applied the tools of multi-objective programming to the energy and environmental problems. Loucks (1975) analyzed the resource utilization and economic development decisions using a multi-objective programming, with each objective being a trade-off itself. Hafkamp and Nijkamp (1982) applied the multi-objective programming to the issue of integrated resource planning. They supposed that a single-objective approach can not evaluate social welfare changes accurately. Hsu and Chou (2000) used a multi-objective programming approach integrated with a Leontief inter-industry model to evaluate the impact of energy conservation policy on the cost of reducing CO_2 emissions and undertaking industrial adjustment in Taiwan, also this integrated model is applied to investigate the impact of mitigating CO_2 emissions on Taiwan's economy by Chen (2001).

The purpose of this study is to analyze the structure allocation of electricity sector to meet different CO_2 mitigation targets in China by using a multi-objective programming method. The remainder of this paper is organized as follows. In the next section, we present the multi-objective programming method and model in this paper. Section 3 states the related data used in this paper and designs three scenarios. Results are presented in Section 4. Finally, we conclude this study.

2. Methodology

2.1. Fuzzy multi-objective linear programming

The mathematical model of multi-objective linear programming (MOLP) is as follows,

$$\begin{cases} \text{Minimize}\, Z(X) = C(X) \\ \text{Subject to} \quad A(x) \le b, \quad X \ge 0 \end{cases} \tag{1}$$

where $Z(x) = (Z_1(x), Z_2(x), Z_3(x), \ldots Z_k(x))^T$ is a k-dimension vector, $C = (C_1, C_2, C_3, \ldots C_k)$ is a $k \times n$ matrix. The optimal solution of the single-objective can be obtained using any ordinary single-objective optimization method, named as X_k^*, thus the minimum is $f_k(X_k^*)$, and the value of other target equation is $f_1(X_k^*)$ ($l = 1, 2, 3\ldots,$

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Table 1
The basic situation of China's power plant.

Generation type	Abbreviation	Efficiency (%)	Fixed capital investment ($/KW)	Operating cost ($/kWh)	Economic operation life	Annual operating hours
Conventional coal-fired	CC	30	700	7.23	20	5573
Pressurized fluidized bed	PF	35	1090	4.89	30	5573
Circulating fluidized bed	CF	41	1025	11.07	30	5573
Nuclear	N	33	1750	13.21	40	7670
Natural Gas combined cycle	NG	58	625	6.59	25	3500
Fuel	F	45	750	5.82	25	5573
Hydropower	W	85	1340	11.04	50	3700
Wind	WI	17	1419	37.06	20	4000

Source: Gnansounou et al. (2004). Peng and Daiqing (2011); authors' deliberation.

$q, l \neq k$). Solving the other equation $f_k(X)$ ($k = 1, 2, 3, \ldots, q$) in accordance with the above method. Then find the possible maximum (M_k) and minimum (m_k) of a single target equation, that is,

$$\begin{cases} m_k = \min_{1 \le l \le q} f_k(X_l^*) = f_k(X_k^*) \\ M_k = \min_{1 \le l \le q} f_k(X_l^*) \quad (k = 1, 2, 3, \ldots, q) \end{cases} \tag{2}$$

Membership function is defined as,

$$G_k(X) = \frac{M_k - f_k(X)}{M_k - m_k} = \frac{M_k - f_k(X)}{d_k}, \quad 0 \le G_k(X) \le 1 \tag{3}$$

By the definition of $G_k(X), \forall \lambda \in [0, 1], G_k(X) \ge \lambda \Leftrightarrow f_k(X) + d_k\lambda \le M_k$

$$\begin{cases} \text{Max}\,\lambda \\ \text{s.t.}\, f_k(X) + d_k\lambda \le M_k \quad (k = 1, 2, 3 \ldots, k) \\ A(x) \le b, \quad X \ge 0 \end{cases} \tag{4}$$

2.2. The model in this paper

Objective functions:

$$\begin{cases} \text{Min} \ \ Z_1 = \sum_{j=1}^{n} (FC_j \times IC_j + VC_j \times X_j) = \sum_{j=1}^{n} (FC_j/8760\rho_j + VC_j) \times X_j \\ \text{Min} \ \ Z_2 = \sum_{j=2}^{n} X_j \times ef_j \end{cases} \tag{5}$$

Constraint functions:

1. Total generating capacity constraints. The output of each type of power generation unit should exceed the total capacity of the existing units of this type, multiplied by the corresponding availability factor:

$$X_j - af_j \times C_j \times N_j \ge 0 \tag{6}$$

where af_j is the availability factor of the jth type of units and C_j is capacity of the jth type of units.

2. Total energy consumption constraint

$$\sum X_j \times V_l \le E_m \tag{7}$$

3. Demand satisfaction

$$\sum X_j \ge P \tag{8}$$

4. CO_2 emission satisfaction

$$Z_2 \le \frac{GDP_{2020}}{GDP_{2005}} Z_{2005}(1 - r\%) \tag{9}$$

where j indicates the generator type, C_j is fixed cost per kWh, VC_j means variable cost, X_j is net generation, ef_j is CO_2 emission coefficient per kWh, P is the total electricity of demand in the forecast period, and V_j denotes energy consumption per kwh.

Table 2
Alternative scenarios for CO_2 reduction target.

Scenario	2020 GDP (10^8 yuan)	Electricity demand forecast of 2020 (10^{12} kWh)	CO_2 reduction target of power sector (%)
Case I	712,726.94	5.64	$r = 35$
Case II			$r = 40$
Case III			$r = 45$

3. Data resource

The data used in this paper is given by China Statistical Yearbook (CSY, 2011), China Electric Power Yearbook (CEPY, 2010), literature reviews and authors' calculation. In this paper, eight kinds of promising power generation technologies are considered, namely conventional coal-fired power plant, coal pulverized with FGD power plant, coal with PFBC, nuclear power plant, natural gas combined cycle power plant, fuel power plant, water plant and wind plant. The specific data of the different generation technologies are stated in Table 1. The target year is set as the year of 2020, and we assume that the relative cost of different power generation technologies is unchanged.

We adopt three different CO_2 reduction targets of 35%, 40%, 45% respectively in every scenario, as shown in Table 2.

4. Results analysis

China is one of the few coal-dominated countries in the world, whose energy resource endowment and energy consumption characteristics bring tremendous pressure to the country for reducing its greenhouse gas emissions. China's power generation industry is the principal coal consumption sector in China. As shown in Fig. 1, both CO_2 emissions of power generation sector and its shares to China's total energy-related CO_2 emissions increased during 2000

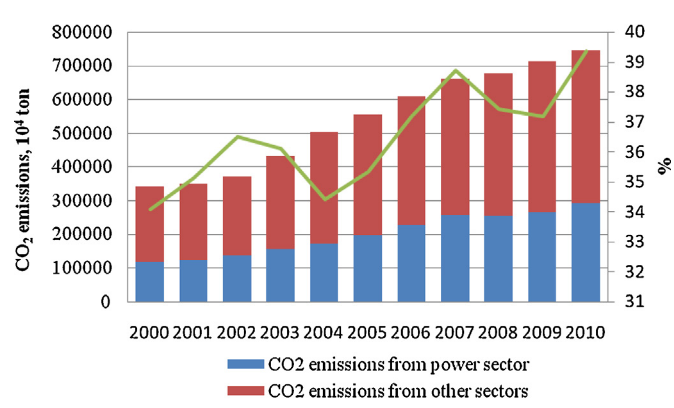

Fig. 1. CO_2 emissions from power sector and its shares to China's total CO_2 emissions during 2000 and 2010.