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A Multi-Period Multi-Region Optimization Model of China's Power Sector Considering Synergetic CO_2 and Air Pollutants Control

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Abstract

China will soon be under the pressure of controlling the emissions of CO_2 and various air pollutants simultaneously. Power sector as the largest contributor is the key sector to fulfill this task, which makes a power sector model with consideration of multiple air emissions control in great need for supporting policy making. This study built a multi-period optimization model for China's power sector with considerations of SO_2, NO_X and CO_2 emission control and accounting of Hg emissions, based on six regional power grids with growing inter-connections. A case study of technology development and emission trends in China's power sector between 2010 and 2030 follows, using regional technology and fuel data in 2010, and advices for further model development come last.

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Keywords: optimization model; CO_2; SO_2; NO_X; Hg; regional power grids; emission mitigation; carbon intensity

1. Introduction

Because of the predominance of coal in China's fossil resource structure, China's power sector accounts for more than half of the national industrial coal consumption, and approximately 42%, 40% and 50% of China's emissions of SO_2, NO_x and CO_2 respectively in 2010 and 43% of China's Hg emissions in 2007 [1-3]. It's no surprise that power sector is identified as the key sector for emissions control. Mitigation targets of SO_2 and NO_X for China's thermal power industry have already been included in the 12th five-year energy-saving plan of industry. International negotiation of dealing with climate change

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achieved decisions to establish a new international agreement requiring all parties, including developing countries like China and India, to make emissions reduction commitments after 2020. Meanwhile, international negotiation of Hg emission control is undergoing with an aim of adopting a treaty in 2013[4]. Based on the above facts, China's power sector will be required to control emissions of air pollutants and greenhouse gas at the same time in a foreseeable future, which makes a power sector modeling tool with considerations of the co-control of CO_2 and air pollutants in great need for supporting policy making.

China's power sector is divided into six regional power grids, which have limited interconnections among them [5]. Besides, great differences exist in the characteristics of power sector among regions, including the amount and exploitation difficulty of renewable energy resources, physic-chemical properties of fuels, technology costs and current penetration rates of air pollutants control devices et al. Based on the fact that regions with sufficient, and often clean, energy resource are usually not the electricity load centers, and the fact of growing inter-connections among regions due to the Strong Smart Grid plan, a power sector model without consideration of inter-regional power transmissions will not be able to capture the great mitigation potential of it and bias the projection of future emission trajectory.

Multi-period multi-region optimization models have been proposed and used for power sector analysis since late 1980s. Hoster [7] and Voorspools and D'haeseleer [8] developed a multi-region model of power sector based on the inter-connections of European countries' power grids and used it to analyze the CO_2 emission control policies. Watcharejyothin and Shrestha [9] modeled the electricity trading between Laos and Thailand and focused on the environmental impacts of CO_2, NO_X and SO_2 emissions. As for the studies on China, Chen et al [10] built the Western China Sustainable Energy Development Model to model the energy sector of China in two separate regions (west and east) and analyzed how the west to east energy transfer would impact the regional CO_2 and SO_2 emissions. Zhang et al [11] presented a multi-period optimization model of China's power sector with consideration of only CO_2 mitigation. Mao and Wang [12] developed BOMCES model based on China's regional power grids and used it to analyze CO_2 mitigation policies, but the model didn't consider inter-regional power transmissions.

Compared with previous studies, this paper will present a multi-period optimization model for China's power sector with the following distinctive characteristics: (1) considering the emission accounting and control technologies of CO_2 and air pollutants including SO_2 and NO_X; (2) considering the synergetic removal of Hg emission caused by SO_2 and NO_X control devices; (3) modeling the China's power sector based on six inter-connecting regional power grids with regionl parameters. Next, we will first describe the model structure, followed by a case study of China's power sector under emission control policies from 2010 to 2030. Some advices for further model development are given at last.

2. Model description

Fig. 1 presents an illustrative model structure. 13 generation technologies and 5 emission control devices are currently considered in the model.

Module 1: Objective function of minimizing the total cost. The objective function is to minimize the total discounted, cumulated cost of generation and interregional transmission for all the six regions during the whole planning horizon. Total generation costs are the sum of capital investment costs (*CAP*), fixed non-fuel operation and maintenance (*FOM*) costs, variable non-fuel operation and maintenance (*VOM*) costs and fuel costs (*FUEL*), with *i* being the discount rate, *n* being the technology and *t* being the year:

$$Z = \min \sum_t [\sum_n (CAP_{n,t} + FOM_{n,t} + VOM_{n,t} + FUEL_{n,t} + TRANS_{n,t}) / (1+i)^{t-1}] \quad (1)$$

The capital investment cost of a generation unit is pertinent to the starting year of operation, and is considered as a loan that should be paid off equally each year during its whole lifecycle. A generation technology's *FOM* and *VOM* costs are estimated basing on the installed capacity and the electricity generation of the year respectively. Fuel costs are estimated on the basis of electricity generation, fuel consumption rates and fuel prices. Among the above costs, regional variation of capital investment costs for coal-fired, hydro and wind power are considered, as well as the fuel price.

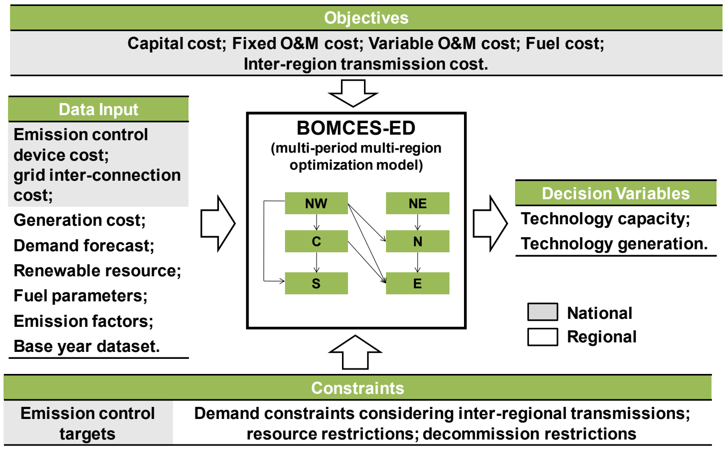

Fig. 1. Model structure.

Interregional transmission costs (*TRANS*) is calculated as follows, with *p* as the transmission line, *freg* and *reg* as the export and import region of transmission line *p*, *LEN* as the length of the transmission line, *unitTRC* as the cost of transmission per kWh, *al* as the power losses within the power plant:

$$TRANS_{n,t} = \sum_{p} \left\{ unitTRC(LEN_p) \cdot \sum_{n} [OUTGELEC_{freg,reg,n,t} \cdot (1 - a1_{n,t})] \right\} \tag{2}$$

Module 2: Constraints of meeting electricity demand considering inter-regional transmissions. The expected electricity demand (*DELEC*) of a region is met by the electricity supply within the region, which equals to the electricity generation within the region (*SUMGELEC*) minus the electricity transmitted to other regions (*SUMOUTGELEC*) as well as the losses within the power plant (*al*) and the region power grid (*gl*), and the electricity imports to the region (*SUMINGELEC*), which equal to the electricity transmitted from other regions minus the transmission loss (*tl*).

$$(SUMGELEC_{reg,t} - SUMOUTGELEC_{reg,t}) \cdot (1 - gl_{reg,t}) + SUMINGELEC_{reg,t} \geq DELEC_{reg,t} \tag{3}$$

$$SUMGELEC_{reg,t} = \sum_{n} [GELEC_{reg,n,t} \cdot (1 - a1_{n,t})] \tag{4}$$

$$SUMOUTGELEC_{freg,t} = \sum_{n} [\sum_{reg} OUTGELEC_{freg,reg,n,t} \cdot (1 - a1_{n,t})] \tag{5}$$

$$SUMINGELEC_{reg,t} = \sum_{freg} [\sum_{n} OUTGELEC_{freg,reg,n,t} \cdot (1 - a1_{n,t}) \cdot (1 - tl_{freg,reg,t})] \tag{6}$$

Constraints to interregional transmissions due to technological and constructional limitations are considered by setting upper threshold values (*HQTR*) to transmission capacities (*OUTQCAP*) of each interregional transmission lines:

$$\sum_{n} OUTQCAP_{freg,reg,n,t} \le HQTR_{freg,reg,t} \quad (11)$$

Module 3: Constraints of emission control. A pollutant's (*pol*) emission of an electricity generation technology is estimated by multiplying the electricity generation (*GELEC*), the fuel consumption rate (*fcr*) and the pollutant's emission factor per unit fuel consumption (*ef*). Constraints of total emissions (*EMIT*) and emission intensities (*unitEMIT*) of air pollutants including SO_2, NO_x and CO_2 for national power supply can be considered using this model by setting a mitigation target (*CAP*, *unitCAP*) compared to the starting year:

$$\sum_{reg}(GELEC_{reg,n,t} \cdot fcr_{n,t} \cdot ef_{pol,n,t}) \le EMIT0_{pol} \cdot (1 - CAP_{pol,t}) \quad (12)$$

$$\sum_{reg}\sum_{n}(GELEC_{reg,n,t} \cdot fcr_{n,t} \cdot ef_{pol,n,t}) / \sum_{reg} DELEC_{reg,t} \le unitEMIT0_{pol} \cdot (1 - unitCAP_{pol,t}) \quad (13)$$

The emission factor per unit fuel consumption (*ef*) of a certain generation technology is calculated following the equation (14), with *uef* as the emission factor without emission control technologies, β as the removal rate of a pollutant caused by one kind of emission control device (*ecd*), γ as the operation rate of the emission control device:

$$ef_{pol,n,t} = uef_{pol,n,t} \cdot \prod_{ecd}(1 - \beta_{ecd,pol} \cdot \gamma_{ecd,t}) \quad (14)$$

Module 4: Constraints of regional energy resources. Resource restrictions due to technology and natural limitations for renewable and nuclear energies are considered in this model by setting a maximum installed capacity (*SQCAP*) pertinent to the time and regional grids:

$$QCAP_{reg,n,t} \le SQCAP_{reg,n,t} \quad (15)$$

The utilization hours of generation technologies are limited between lower (*HMIN*) and upper (*HMAX*) threshold values varied by regions:

$$HMIN_{reg,n} \cdot QCAP_{reg,n,t} \le GELEC_{reg,n,t} \le HMAX_{reg,n} \cdot QCAP_{reg,n,t} \quad (16)$$

$$HMIN_{reg,n} \cdot OUTQCAP_{reg,n,t} \le OUTGELEC_{reg,n,t} \le HMAX_{reg,n} \cdot OUTQCAP_{reg,n,t} \quad (17)$$

Module 5: Considerations of decommissions. Generation units operating at the base year may be decommissioned during the planning horizon. Decommissioned plants can be further categorized into two groups: (1) For those which lifecycle have been fulfilled, we assume the residual value is zero; (2) For those which are forced to decommission in advance due to emission control policies, we assume the residual value will be continued to be paid as a loan during its original lifecycle and their remaining generation rights will be traded to other plants with higher efficiency. We further assume no extra cost will be caused by the generation rights trading. An annual decommission plan (*DQCAP1* for group 1 and *DQCAP2* for group 2) could be set in the model. The total new-built capacities (*NQCAP*) and total capital investment cost (*CAP*) of year *t* can be calculated as follows, with *capex* as the annual equal payment of the capital investment cost per kW capacity of technology *n*:

$$NQCAP_{reg,n,t} = QCAP_{reg,n,t} - QCAP_{reg,n,t-1} + DQCAP1_{reg,n,t} + DQCAP2_{reg,n,t} \quad (18)$$

$$CAP_{reg,n,t} = CAP_{reg,n,t-1} + NQCAP_{reg,n,t} \cdot capex_{reg,n,t} - DQCAP1_{reg,n,t} \cdot capex_{reg,n,0} \quad (19)$$

3. Case study and discussions

3.1. Scenario settings

A scenario of China's power sector from 2010 to 2030 based on regional data in 2010 is analyzed as a case study. Control targets of SO_2, NO_X and CO_2 emissions by national power generation are set according to current policies, industrial plans and related discussions [13-15]. The capacity development of inter-regional power transmissions is assumed based on the strategic planning research of ultra-voltage power transmission lines [16]. Regional physic-chemical parameters of coal are obtained from [2, 17, 18]. Selected parameters of the case study are shown in Table 1 and Table 2.

3.2. Results and discussions

Fig. 2 shows the optimization results of the installed capacities for the generation technologies (a) and emission control devices (b) from 2010 to 2030. As we can see in Fig. 2a, ultra-supercritical pulverized coal (USC) will be a dominant generation technology in the future mainly due to its low generation cost and high efficiency. Coal-fired generation technology will continue to account for more than 70% of the total installed capacities in 2020 but the ratio decreases to 51.7% in 2030, mainly resulting from the CO_2 intensity mitigation target set after 2020. The CO_2 intensity mitigation target also induce a major growth of natural gas power to account for approximately 16.6% of the total installed capacities in 2030. A significant growth of renewable and nuclear power and an approximately 400 GW of CCS deployment in 2030 are also needed to achieve the carbon intensity mitigation targets.

The above changes also contribute to fulfill the SO_2 and NO_X emission mitigation targets. Meanwhile, 90% of coal-fired capacities need to install Flue Gas Desulfurization (FGD) for pulverized coal units or in-furnace desulfurization for CFBC (also calculated as "FGD" in Fig. 2b) in 2030, 94% to be Low-NO_X Boilers (LNB), and 82% to install Selective Catalytic Reduction (SCR) for flue gas de-nitrification.

The regional emissions of Hg and CO_2 in 2010 and 2030 are shown in Fig. 3a, from which we can see

Table 1. Emission Mitigation Targets.

Substance	SO_2 (total emission compared to 2010)	NO_X (total emission compared to 2010)	CO_2 (intensity compared to 2020)
2015	16%	29%	-
2020	16%	29%	-
2030	22%	30%	20%

Table 2. Physic-Chemical Parameters of Coal.

Region	N	NE	E	C	NW	S
LHV (kcal/kg)	4499	3896	5069	4380	4630	4806
S content	0.89%	0.52%	0.89%	1.07%	0.90%	1.04%
Hg content (mg/kg)	0.1691	0.1689	0.1789	0.2120	0.1125	0.2020

that Region E, N and C are the major contributors, accounting for more than 70% of the national emissions. Despite of the existence of carbon intensity mitigation targets, CO_2 emission of China's power sector will experience a significant growth of 144.9% compared to the one in 2020 to achieve 7253.5 Mt in 2030. However, only a 34.4% growth of Hg emission from 2010 to 2030 can be observed, indicating the large mitigation potential of Hg emission provided by the synergetic removal of FGD and SCR.

Shown in Fig. 3b, an amount of 0.102 trillion RMB of the national total power supply cost during 2010 and 2030 can be saved with the inter-regional power transmissions mainly because it allows more coal-fired generation units to be built near the producing area of coal, saving the long distance transportation cost which will significantly increase the coal price. As the region expected to export the most electricity to other regions, Region NW's emissions in 2030 of SO_2, NO_X, CO_2 and Hg will experience a growth of 169%, 133%, 58% and 167% respectively caused by the inter-regional power transmissions, calling for policy makers' attentions to deal with the potential conflicts between power export and import regions about the environmental and health loss transfer along with the transmissions.

4. Conclusions

A multi-period optimization model for China's power sector based on six inter-connected regional

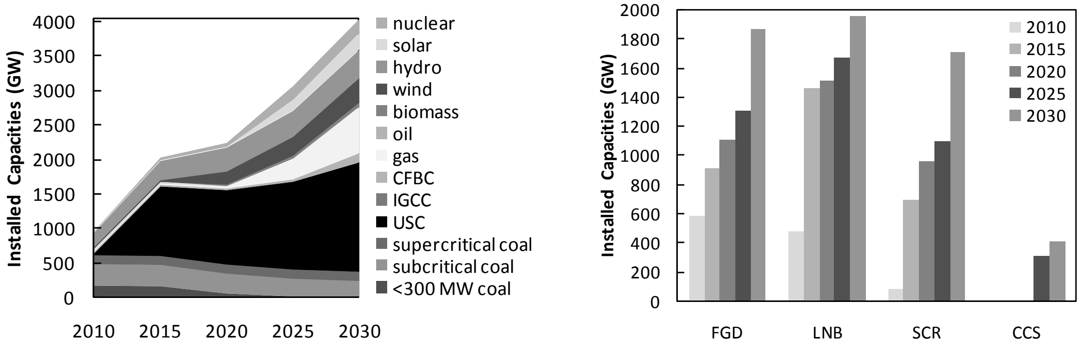

Fig. 2. (a) Installed Capacities of Generation Technologies in China; (b) Installed Capacities of Emission Control Devices in China.

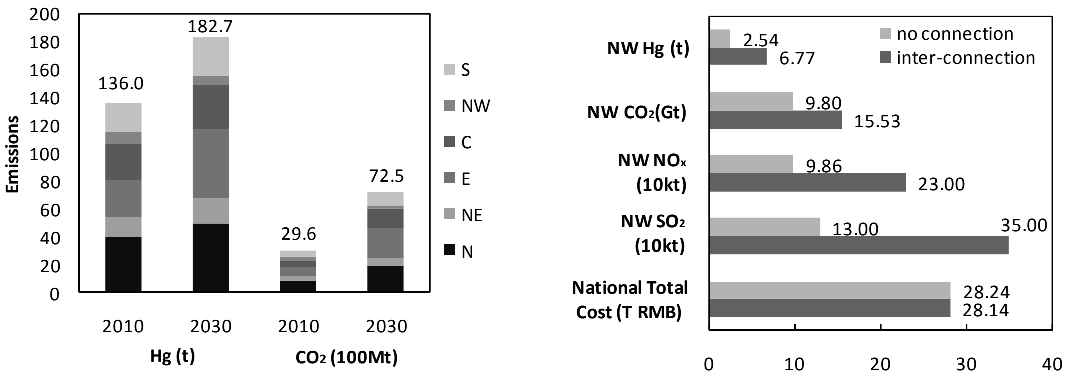

Fig. 3. (a) Regional Emissions of Hg and CO_2; (b) Comparison of National Total Cost and Emissions in Region NW in 2030 with or without inter-regional power transmissions.

power grids considering sectoral emissions of SO_2, NO_X, CO_2 and Hg is presented in this paper, together with a case study of China's power sector from 2010 to 2030 to briefly show the possible applications of the model. Results show that the model is suitable for emission mitigation analysis of power sector when CO_2 and various air pollutants need to be addressed simultaneously, and when regional implications are needed. For further development of the model, integrated resource planning could be included to capture the impacts of demand-side management potential with low cost and great co-control effect of various emissions. The energy-saving retrofitting potential of commissioning generation units could also be considered in a further version of the model.

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