CHEMICAL ENGINEERING TRANSACTIONS
VOL. 70, 2018

A publication of
AIDIC
The Italian Association
of Chemical Engineering
Online at www.aidic.it/cet

Guest Editors: Timothy G. Walmsley, Petar S. Varbanov, Rongxin Su, Jiří J. Klemeš

**ISBN** 978-88-95608-67-9; **ISSN** 2283-9216
DOI: 10.3303/CET1870104

# Regional Analysis of Air Quality Control in China's Power Sector

Siyuan Chen, Pei Liu*, Zheng Li

State Key Lab of Power Systems, Department of Energy and Power Engineering, Tsinghua University, Beijing, 100084, China
liu_pei@tsinghua.edu.cn

Air pollutants emissions are mainly from energy-related sectors. Among these sectors, power sector has the greatest air pollutants mitigation potential as the emissions are centralized from power plants which are easier to control. In order to decrease air pollutants emissions from the power sector, the Chinese government started to vigorously promote ultra-low emission technologies in 2015. However, power supply and demand in China exhibit a feature of uneven spatial distribution, which should be taken into account by policy makers in power sector planning. In this paper, a "most-likely" scenario of air quality control in China's power sector is presented based on a multi-regional, load-dispatch and grid-structure based power generation planning model, illustrating the development of power generation technologies and changes in their spatial distribution. The impact on regional air pollutants emissions and power transmission among regions is also illustrated.

## 1. Introduction

Air pollution has become a severe problem in China during the past few years, especially the haze problem. Many factors are responsible for air pollution problem, including vehicle exhaust, construction dust, factory fumes and coal combustion. In China, more than half of the coal consumption is for electricity generation. Under the circumstances, ultra-low emission technologies of coal-fired power plants are developed and first applied in 2014, drawing great attention from the government and industry. $SO_2$ and $NO_x$ emissions from coal-fired power plants equipped with these emission control devices are lower than 35 and 50 mg/m$^3$ with 6% oxygen content respectively, which is as clean as gas-fired power plants. In order to address the air pollution problem, the Chinese government planned to retrofit all qualified coal power plants with ultra-low emission technologies by 2020 (NDRC, 2016). However, natural resources are mainly located in western China whilst electricity demand is centred in eastern China. Therefore, it is important to find a cost-effective clean production pathway for China's power sector whilst considering regional characteristics.

Power generation expansion planning is to determine the optimal type, location and construction time of power generation technologies whilst ensuring that the increasing power demand is met (Cerón et al., 2017). Recently, environmental issues have been taken into consideration due to the growing concern about global warming and air pollution. Becker et al. (2011) used WASP-IV model to estimate the impact of several environmental externality costs on the power sector development plan of Israeli. Chen et al. (2016) established a linear programming optimization model incorporating the external effects of $SO_2$, $NO_2$ and PM into the power planning and applied the model to the case study of China's power sector. Mavalizadeh and Ahmadi (2014) proposed a multi-objective optimization method for hybrid generation and transmission expansion planning which simultaneously minimizes total cost as well as $NO_x$ and $SO_2$ emissions. However, these studies usually regard the country as a whole entity and neglect regional differences. In order to solve this problem, Wang et al. (2014) developed a multi-period multi-region optimization model and used China as the target of a case study to investigate the extra cost caused by the local air pollution control target. In this model, China's power sector is divided into six regional power grids and inter-regional power transmission is considered. Yi et al. (2016) further divided China's original six power grids into twelve and developed a multi-region power sector optimization model. The impact of inter-regional power transmission on pollutant emissions of China's power sector is analysed. Nevertheless, power supply and demand are balanced only on a yearly basis in these multi-region

Please cite this article as: Chen S., Liu P., Li Z., 2018, Regional analysis of air quality control in china's power sector , Chemical Engineering Transactions, 70, 619-624 DOI:10.3303/CET1870104

models. Nowadays, integration of higher percentage of intermittent renewable energy increases peak load regulation requirements of power grids and has a great significance for changing the power structure (Li et al., 2017). Therefore, the optimal power generation structure neglecting temporal variation would be biased.
In this paper, a “most-likely” scenario of air pollutants emission reduction in China’s power sector is presented based on a multi-regional, load-dispatch and grid-structure based power generation planning model. Section 2 represents details of the planning model, followed by results and discussions in Section 3. Finally, Section 4 summaries the results of this research and gives policy suggestions.

## 2. Methodology

### 2.1 Model structure and assumptions

### 2.1.1 Power generation technologies

Nine types of power generation technologies are considered in this model: Subcritical and Supercritical Pulverized Coal (SPC), Ultra-Supercritical Pulverized Coal (UPC), coal plants with ultra-low emission retrofitting (SPCL, UPCL), Natural Gas Combined Cycle (NGCC), Nuclear (NU), Hydropower (HD), Wind (WD) and Solar Photovoltaic (PV). This model assumes that existing SPC and UPC plants can retire earlier than its expected lifespan or be retrofitted with ultra-low emission technologies. Other power generation technologies are set to be decommissioned at the end of their lifespan.

### 2.1.2 Spatial module

Natural resource and electricity demand in China exhibit an uneven spatial distribution. China has abundant resource endowment in western areas, such as fossil fuel and non-hydropower renewables in Xinjiang and Inner Mongolia and hydropower in Yunnan and Sichuan. However, power demand in eastern coastal areas occupies a much larger share than these resource-rich regions. Based on these regional characteristics, China is divided into seventeen areas reflecting power demand and natural resources as shown in Figure 1. Tibet, Hainan and Taiwan grids are neglected as they are relatively independent whilst international power transmission is neglected due to its small amount.

*Figure 1: Regional division of China based on natural resources and power demand*

### 2.1.3 Temporal module

Electricity demand has high volatility within one day and among different seasons, which needs accurate electricity supply to match. For electricity supply side, renewable energy also has a high temporal variation and can be used only when resources are available, which increases the uncertainty of power system. In order to handle this problem, temporal module is introduced. Each year is divided into four seasons and each day is divided into twenty-four hours to capture the high time resolution of power system.

### 2.1.4 Grid-structure module

With the rapid development of long-distance Ultra-High-Voltage power transmission lines in recent years, eastern coastal areas of China are capable of importing electricity from western areas which have abundant natural resources, instead of constructing power generation facilities locally. Long-distance cross-region power transmission options would have great influence on regional power generation structure and give new insights to policy makers for air quality control.

### 2.2 Mathematical formulas

Mathematical formulas of the optimization model are presented in this section, including objective function and physical constraints. Five sets, t, r, g, f and s stand for year, region, power generation type, fuel type and time block, respectively. Besides, parameters and variables are distinguished with upper and lower cases, respectively.

#### 2.2.1 Objective function

The objective function of this model is to minimize the accumulated total cost of the power generation sector from 2016 to 2020. The accumulated total cost is expressed as Eq(1). The total cost each year can be classified into five categories: capital cost for construction, capital cost for retrofit, operation and maintenance cost, fuel cost and power transmission cost. The calculation of the five parts of costs is based on previous work (Guo et al. 2017).

$$atc = \sum_{t=2016}^{2020} \sum_{r} \frac{tinv^{nb}_{r,t} + tinv^{rf}_{r,t} + tom_{r,t} + tfc_{r,t} + tptrc_{r,t}}{(1+I)^{t-2016}} \tag{1}$$

#### 2.2.2 Physical constraints

**Power balancing**

The model requires that electricity demand of the ninety-six time blocks in each year should be satisfied by regional power generation and inter-regional power transmission as shown in Eq(2).

$$PD^{s}_{r,t} = \sum_{g} pg^{s}_{r,t,g} + ptr^{s}_{r,t} \tag{2}$$

Operating hours of each kind of power generation technologies in each time block are variables constrained by peak regulation capacity requirements and resource availability, as presented in Eq(3).

$$MINOH^{s}_{r,t,g} \cdot ic_{r,t,g} \le pg^{s}_{r,t,g} \le MAXOH^{s}_{r,t,g} \cdot ic_{r,t,g} \tag{3}$$

Net power imports in each region equal power transmitted in from other regions minus power transmitted out from the region itself. It is noteworthy that power transmitted into the region would decrease a little due to the line loss, which is taken into account in Eq(4). Power transmission among regions is also a variable to be optimized.

$$ptr^{s}_{r,t} = \sum_{r',r''\neq r} [ideaptr^{s}_{r',r,t} \cdot (1 - TRLOSS_{r',r}) - ideaptr^{s}_{r,r'',r}] \tag{4}$$

**Installed capacity**

This model assumes that existing SPC and UPC plants can retire earlier than its expected lifespan or be retrofitted with ultra-low emission technologies. Other power generation technologies are set to be decommissioned at the end of their lifespan. Therefore, installed capacity of technologies excluding SPC and UPC is the sum of newly-built capacity during the past several decades, as presented in Eq(5).

$$ic_{r,t,g} = \sum_{t'=t-TLT_g+1}^{t} nb_{r,t',g} \tag{5}$$

In contrast, installed capacity of SPC and UPC plants is the sum of newly-built capacity minus early-retired and retrofitted capacity, as presented in Eq(6).

$$ic_{r,t,g} = \sum_{t'=t-TLT_g+1}^{t} nb_{r,t',g} - \sum_{t'=t-TLT_g+1}^{t} \sum_{t''=t'+1}^{t} (rf^{t''}_{r,t',g} + er^{t''}_{r,t',g}) \tag{6}$$

**Other constraints**

Other constraints in terms of economic and technological factors are introduced in the form of inequality constraints, such as regional maximum total installed capacity of renewable energy, annual newly-built capacity limits, fuel supply limit and power transmission limits among regions. The formulas are imported from previous work (Guo et al., 2017). Moreover, the government’s policy targets for renewable energy utilization and ultra-low emission retrofitting of coal-fired power plants are also introduced as inequality constraints. Physical meanings of the symbols used in equations are presented in Table 1.

*Table 1: Physical meanings of parameters and variables*

| Symbol | Unit | Physical meaning |
|---|---|---|
| $MINOH^{s}_{r,t,g}$ | hour | Minimum operating hours for plants of type g during time block s in year t, in region r |
| $MAXOH^{s}_{r,t,g}$ | hour | Maximum operating hours for plants of type g during time block s in year t, in region r |
| $TRLOSS_{r',r}$ | % | Loss ratio of power transmitted from region r' to region r |
| $nb_{r,t,g}$ | GW | New-build capacity of power plants of type g in region r in year t |
| $er^{t'}_{g,t,r}$ | GW | Early retiring capacity of power plants of type g (built in year t) in region r in year t’ |
| $rf^{t'}_{g,t,r}$ | GW | Retrofitted capacity of power plants of type g (built in year t) in region r in year t’ |

### 2.3 Data input

Input data are imported from previous work, such as regional power demand in each time block and limits of operating hours for power generation technologies (Guo et al., 2017), as well as costs and lifespans of power generation technologies, regional fuel prices and fuel supply capacity, regional maximum capacity for renewable energy and annual newly-built capacity limits, and inter-regional power transmission limits and losses (Guo et al., 2016). $SO_2$ and $NO_X$ emission factors refer to the study of Wang et al. (2014). For example, capital costs of power generation technologies are shown in Table 2.

*Table 2: Capital costs of power generation technologies*

| Plant type | SPC | UPC | NGCC | NU | HD | WD | PV |
|---|---|---|---|---|---|---|---|
| Capital cost in 2015 (RMB/kW) | 4,000 | 3,373 | 2,973 | 1,7246 | 5,985 | 8,356 | 9,526 |
| Annual decreasing rate | 0.2 % | 0.2 % | 1.0 % | 0.1 % | -0.1 % | 3.0 % | 5.0 % |

## 3. Results and discussions

The Linear Programming Solver of the General Algebraic Modelling System (GAMS, GAMS Development Corporation, Washington DC, USA) was used for modelling and optimization. The results of “most-likely” scenario is presented in this section.

### 3.1 Installed capacity mix

Installed capacity of NGCC, nuclear, hydropower, wind and PV would reach 110 GW, 58 GW, 340GW, 223 GW and 140 GW by 2020, respectively. Meanwhile, capacity of coal power plants would reach 1060 GW by 2020 and are still the main contributor of electricity in China’s power system. Among coal power plants, installed capacity of ultra-low emission coal power plants (SPCL and UPCL) increases from 169 GW in 2016 to 641 GW in 2020 due to the strong policy target, as presented in Figure 2. By 2020, national ultra-low emission coal power plants would account for 60.5 % of total coal power plants whilst this percentage is over 45% in most regions.

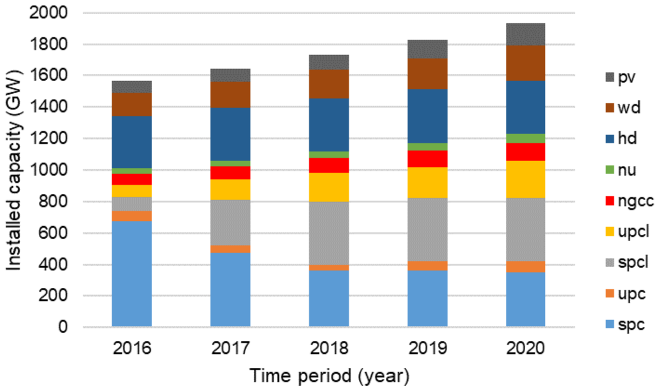

*Figure 2: Installed capacity mix from 2016 to 2020*

### 3.2 Air pollutants emissions

Due to the large-scale employment of ultra-low emission technologies in coal power plants and rapid growth of renewable energy, $SO_2$ and $NO_x$ emissions decrease by 44 % and 21 % in 2020 compared to the 2016 level. From regional perspective, air pollutants emissions decline in all regions except Inner Mongolia as shown in Table 3. The result shows that thermal power generation of coal power plants in Inner Mongolia grows rapidly, which is responsible for the increasing air pollutants emissions. Moreover, about half of the generated power is transmitted to other regions. Power exporting from Inner Mongolia increases due to the newly-built Ultra-High-Voltage long-distance transmission lines. Exporting destinations are East, Jing-Jin-Ji and Northeast.

*Table 3: Change rate of regional air pollutants emissions (2020 compared to 2016)*

| Region | Inner Mongolia | Xinjiang | Ningxia | Shanxi | Chuan-Yu | Hubei | North-east | Jing-Jin-Ji | Shan Dong |
|---|---|---|---|---|---|---|---|---|---|
| $SO_2$ | 28.5 % | -27.3 % | -40.9 % | -40.9 % | -44.1 % | -66.0 % | -61.4 % | -12.7 % | -92.5 % |
| $NO_x$ | 75.4 % | -3.9 % | -7.0 % | -11.5 % | -37.7 % | -30.6 % | -40.5 % | -37.2 % | -77.7 % |
| Region | North-west | Henan | Central | East | Yunnan | Guizhou | Guangxi | Guang dong | |
| $SO_2$ | -1.8 % | -67.7 % | -58.5 % | -50.7 % | -20.3 % | -14.6 % | -39.9 % | -49.8 % | |
| $NO_x$ | -5.6 % | -35.3 % | -34.4 % | -22.3 % | -3.5 % | -5.2 % | -12.4 % | -29.3 % | |

### 3.3 Power transmission

Power transmission routes among regions in 2020 are presented in Figure 3, in which thicker lines mean more electricity is transmitted through them. Jing-Jin-Ji imports electricity from Inner Mongolia and Shanxi and exports to Shandong. By 2020, Jing-Jin-Ji's external dependence on electricity increases to nearly 50 %. Shandong, East and Henan also import much electricity from Northwest, Inner Mongolia and Xinjiang, which helps them decrease local air pollutants emissions accordingly.

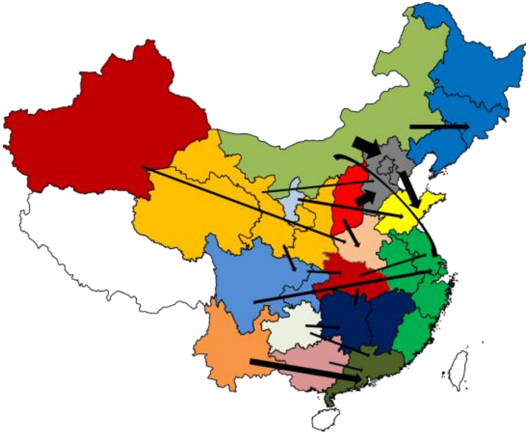

*Figure 3: Power transmission routes in 2020*

### 3.4 Emerging problems and policy suggestions

Load-centred areas like Jing-Jin-Ji, Shandong and East realize great air pollutants emissions reduction. On the one hand, large-scale employment of ultra-low emission technologies plays an important role in emission reduction. On the other hand, a large part of power demand in these regions is satisfied with electricity transmitted from northern and western areas, which can ease the increase of local power generation. In order to ensure enough power transmission, the government planned nine large-scale coal power bases (10 GW) in northern and western areas. However, air pollutants emissions would increase with the increasing thermal power generation, such as Inner Mongolia. The result in Figure 4 shows that $SO_2$ emission in Inner Mongolia in 2020 has exceeded local carrying capacity, which poses great threat to local environment.

Therefore, the emerging problem in this "most-likely" scenario is that air pollutants emissions are transferred along with power transmission. For example, Inner Mongolia exports electricity at the expense of local environment. Policy makers should take into account regional environmental carrying capacities when making air pollution control policies. When promoting cross-regional power transmission, policy makers should plan reasonable scale of coal power bases based on regional carrying capacity. Besides, ultra-low emission retrofitting progress of coal power plants should be enhanced as it proves to be very effective.

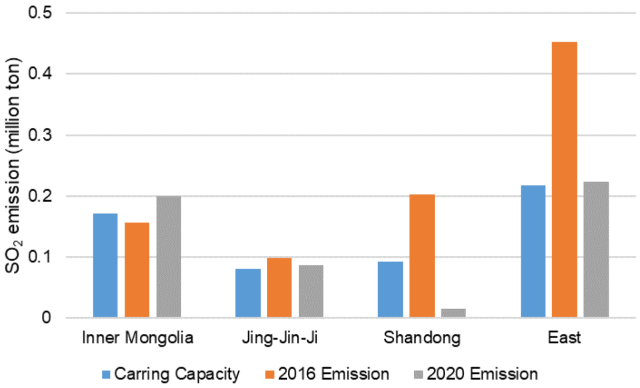

*Figure 4: Comparison of $SO_2$ emission with carrying capacity in representative areas*

## 4. Conclusions

The results show that the national projected working plan of ultra-low emission retrofitting for coal plants can significantly achieve air pollutants emissions mitigation in the power sector. Installed capacity of coal power plants equipped with ultra-low emission devices accounts for 60.5 % of total coal plants so that $SO_2$ and $NO_x$ emissions decrease by 44 % and 21 % in 2020 compared to the 2016 level. Eastern load-centred areas realize great emission reduction due to employment of ultra-low emission devices as well as importing more electricity from western areas. However, air pollutants emissions are transferred along with power transmission. With higher power supply task and construction of coal power bases, western China exports electricity at the expense of local environment, especially Inner Mongolia. Therefore, policy makers should take into account regional environmental carrying capacities when making air pollution control policies and enhance the progress of ultra-low emission retrofitting for coal power plants.

## Acknowledgments

The authors gratefully acknowledge the support by The National Key Research and Development of China (2016YFE0102500), Shanxi Key Research and Development Program (201603D312001), National Natural Science Foundation of China (71690245), Beijing Key Laboratory for Industrial Bigdata System and Application, and the Phase III Collaboration between BP and Tsinghua University.

## References

Becker N., Soloveitchik D., Olshansky M., 2011, Incorporating environmental externalities into the capacity expansion planning: an Israeli case study, Energy Conversion & Management, 52(7), 2489-2494.

Cerón A. M. R., Kafarov V., Latorre-Bayona G., 2017, A fuzzy logic decision support system for assessing sustainable alternative for power generation in non-interconnected areas of colombia-case of study. Chemical Engineering Transactions, 57, 421-426.

Chen H., Tang B.J., Liao H., Wei Y.M., 2016, A multi-period power generation planning model incorporating the non-carbon external costs: a case study of china, Applied Energy, 183, 1333-1345.

Guo Z., Cheng R., Xu Z., Liu P., Wang Z., Li Z., Jones I., Sun Y., 2017, A multi-region load dispatch model for the long-term optimum planning of china’s electricity sector, Applied Energy, 185, 556-572.

Guo Z., Ma L., Liu P., Jones I., Li Z., 2016, A multi-regional modelling and optimization approach to china's power generation and transmission planning, Energy, 116, 1348-1359.

Lu J., Li R., Wang J., 2017, Effect of collaborative utilization of energy storage and wind power on wind power grid-connected and carbon emission. Chemical Engineering Transactions, 62, 1117-1122.

Mavalizadeh H., Ahmadi A., 2014, Hybrid expansion planning considering security and emission by augmented epsilon-constraint method, Electrical Power & Energy Systems, 61(61), 90-100.

NDRC (National Development and Reform Commission), 2016, The 13th five-year plan for electric power development (in Chinese), NDRC, Beijing, China.

Wang C., Ye M., Cai W., Chen J., 2014, The value of a clear, long-term climate policy agenda: a case study of china’s power sector using a multi-region optimization model, Applied Energy, 125, 276-288.

Yi B.W., Xu J.H., Fan Y., 2016, Inter-regional power grid planning up to 2030 in china considering renewable energy development and regional pollutant control: a multi-region bottom-up optimization model, Applied Energy, 184, 641-658.