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How to Deal with Existing Coal Production Capacity on a Low-Carbon Transition Pathway? A Case Study of China

Tianxiao Li, Pei Liu*, Zheng Li

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

In recent years, driven by climate change and air pollution, the global energy structure is on a low-carbon transition way. Coal production capacity is expected to gradually shrink. Without proper planning, mismatch between capacity shrinking and increasing demand would lead to over-tight energy supplies, on the contrary, it would lead to overcapacity and waste of social resources. A quantitative method considering an overall planning horizon is needed to facilitate policy-making. In this paper, a monthly-scale multi-period and multi-regional modelling and optimization framework of a coal supply system at a transient stage is proposed. China's coal supply system is taken as a case study. The optimal reduction path of China's coal production capacity and the optimal operation strategy of the coal supply system are obtained by minimising the overall cost by 2050. Results show that the capacity concentration policy would lead to more coal transmission, which results in higher total supply cost.

1. Introduction

Coal has been one of the main energy sources since the Industrial Revolution. The world's coal consumption in 2017 has reached 3,731.5 toe, accounting for 27.6 % of the world's primary energy consumption (BP, 2018). A complex coal supply system has been established to meet such huge coal demand. Costly infrastructure, including coal mines, railways, highways, ports, etc., is the core of the supply system to connect coal resources with coal demand.

A large quantity of coal consumption results in CO_2, which would lead to climate change. Coal consumption is expected to gradually decrease in the future. It indicates that the coal supply system would shrink after more than a century of expansion. Managing the coal supply system becomes more different at this transient stage because inappropriate strategies would lead to huge loss.

Managing the coal supply system economically is a challenging task at a low carbon transition way. On the one hand, coal resources and coal demand are mismatched in both space and time scale. Seasonal fluctuation of coal demand resulting from heating and power generation increases the complexity of the management. On the other hand, the timing of the coal supply system shrinking is the key to long-term planning. Too fast or too slow to shrink the system would lead to insufficient supply and waste.

The energy planning method is generally applied to solve these issues, which establishes mathematical models and then optimizes the objective function. Debnath and Mourshed (2018) reviewed and classified the most commonly used energy planning models for developing countries and pointed out that higher resolution in space and time scale was the direction of further researches. Zhang et al. (2016) developed a general framework to describe high-speed transport infrastructure from an energy perspective. Guo et al. (2015) developed a load-dispatch power generation optimization model, which described the fluctuation of renewable energy on an hourly scale. Mou and Li (2012) applied the linear programming method to establish a China's multi-region coal transportation model, and the optimal coal transportation plan among thirty regions was attained. Liu et al. (2018) developed China's coal transportation optimization model with 2,206 production nodes and 1,500 consumption nodes, which further improved the resolution in space scale.

However, some issues in energy planning researches need to be further studied. Firstly, existing researches generally focus on energy infrastructure expansion issues, while the energy planning at a transient stage is not

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well studied. Secondly, despite hourly matching of energy supply and demand attracts much attentions, seasonal fluctuation of energy demand is studied less.

China is the world's largest coal consumer. In 2017, China's coal consumption reached 1,892.6 toe, accounting for 50.7 % of the world's coal consumption (BP, 2018). China is a typical country with the significant regional disparity of coal resources and large fluctuation of coal demand, especially in north regions. Most regions need transport coal from other regions to meet their demand, which would lead to large-scale coal transportation across China.

China's coal demand is expected to decrease in the near future, and the overcapacity of coal production has become a serious problem. Wang et al. (2013) forecast China's coal demand before 2100 and pointed out that the mean peak was expected around 2024. Wang et al. (2018) believed that coal demand would decrease before 2020. The coal production capacity in operation and under construction reaches 4,500 Mt in 2018, which still exceeds nearly 18 % of national coal demand, after three years of capacity reduction dominated by China's government. Planning on coal production capacity reduction and coal transportation becomes a serious problem.

In this paper, a long-period multi-region monthly-scale optimization model on a coal supply system is developed under the expectation of a decline in coal consumption. This model could address production capacity planning at a transient stage and reflect monthly coal transportation. China's coal supply system is taken as a case study. The optimal reduction path of coal production capacity is obtained by minimising the overall cost by 2050. The coal transportation among regions in different months and years is also pointed out. The impact of current planning on coal production capacity projected by the government is analysed.

This paper is organized as follows. In Section two, the mathematical model is introduced. In Section three, scenarios are set based on China's coal supply system. In Section four, results are displayed and analysed. In Section five, the main conclusions are summarized.

2. Method

2.1 Generic framework of coal supply systems

A coal supply system generally comprises of four parts, namely resources, production capacity, transportation and import. Coal resources are different regionally. The production capacity depends on infrastructure, and it could change by building or shutting down coal mines year by year. The transportation methods mainly include road transportation, railway transportation and sea transportation. The transportation cost is determined by the transportation method and distance. The import capacity and methods in each region depend on the geographical location. Coastal regions could import coal by sea, and border regions could import coal by road and railway, while other regions could not import coal.

The coal demand in each period of each region could be met by different combinations of these four parts. Numerous strategies, including system design strategies and operation strategies, could be adopted when given the coal demand. A mathematical model would help to obtain the optimal strategy with the lowest overall cost.

2.2 Mathematical model

The Mixed Integer Programming (MIP) method is applied to describe a coal supply system. The generic MIP problem expression is shown in Eq(1). A MIP problem comprises of the objective function f , equality constraints h and inequality constraints g , where x,d,y,θ represents a vector of continuous operational variables, continuous design variables, binary variables and input parameters.

$$\begin{aligned} &\min f(x,d,y,\theta) \\ &s.t.\ \ h(x,d,\theta)=0\ ,\ g(x,d,y,\theta)\leq 0 \end{aligned} \tag{1}$$

In this model, coal production, transportation and import are operational variables. Coal production capacity yearly changes in each region are design variables. Coal demand, resources, transportation distance, geographical location, production capacity in base year and the cost in the supply chain are input parameters.

Objective function indicates the overall supply cost in a long period. Equality constraints describe the balance between coal supply and demand, and production capacity changes yearly. Inequality constraints comprise of resources limitation, geographical limitation, production capacity limitation and policy limitation.

The detailed mathematical process is listed below, and the notation is listed in Table 1 and Table 2. Subscripts $r(rr),t,m$ represent regions, year and month. All parameters and variables are non-negative values. The following Eq(2)-(14) make up a MIP problem, and the CPLEX solver is used to solve this problem.

Table 1: Parameters

Symbol	Meaning and unit	Symbol	Meaning and unit
$DT_{r,rr}$	Distance by train *km*	CO	Operation cost *yuan/t*
DR_r	Distance by road *km*	CI	Import cost *yuan/t*
$DS_{r,rr}$	Distance by ship *km*	CTx	Transportation cost *yuan/t*
$D_{r,t,m}$	Coal demand *Mt*	CE	Capacity expansion cost *yuan/t*
R_r	Coal resources *Mt*	CP_r	Production cost *yuan/t*
DIS	Discount rate		

Table 2: Variables

Symbol	Meaning and unit	Symbol	Meaning and unit
pro_r	Coal production *Mt*	ccp_t	Total production cost *10^9yuan*
imp_r	Coal import *Mt*	cco_t	Total operation cost *10^9yuan*
$cap_{r,t}$	Capacity in operation *Mt*	cci_t	Total import cost *10^9yuan*
$trs_{r,rr}$	Transportation by ship *Mt*	cct_t	Total transportation cost *10^9yuan*
$trt_{r,rr}$	Transportation by train *Mt*	cce_t	The total capacity expansion cost *10^9yuan*
$cex_{r,t}$	Capacity expansion *Mt*	c	Overall cost *10^9yuan*
$csh_{r,t}$	Capacity shut down *Mt*		

2.2.1 Equality constraints

In each region, total coal supply comprises of domestic production, net transportation from other regions and net import from foreign areas. The balance between demand and supply in each period and in each region is shown in Eq(2). The production capacity is set to change in yearly scale in each region. The change of production capacity year by year is described in Eq(3).

$$D_{r,t,m} = pro_{r,t,m} + \sum_{rr}(trt_{rr,r,t,m} - trt_{r,rr,t,m} + trs_{rr,r,t,m} - trs_{r,rr,t,m}) + imp_{r,t,m} \quad (2)$$

$$cap_{r,t} = cap_{r,t-1} + cex_{r,t} + csh_{r,t} \quad (3)$$

2.2.2 Inequality constraints

Resources limitation indicates that overall production could not exceed its resources, as shown in Eq(4). Production capacity limitation indicates that coal production is lower than the production capacity, as shown in Eq(5).

$$R_r \geq \sum_{m,t} pro_{r,t,m} \quad (4)$$

$$pro_{r,t,m} \leq cap_{r,t} / 12 \quad (5)$$

Geographical limitation describes coal transportation and import. In this model, transportation by road describes coal transportation within a region, and transportation by train and ship describes transportation between regions. Transportation by train is set to only transport between adjacent regions, and transportation by ship is set to only transport among coastal regions. Take train transportation as an example, binary variables $b_{r,rr}$ are applied to describe the location of two regions. It is set to 1, when two regions are adjacent. Otherwise it is set to 0. Then, the train transportation limitation could be described in Eq(6) - (7), where L represents a large positive value. Accordingly, ship transportation limitation and import limitation could be described.

$$-L \times b_{r,rr} \leq trt_{r,rr,t,m} \leq L \times b_{r,rr} \quad (6)$$

$$(b_{r,rr} - 1) \times L \le trt_{r,rr,t,m} \tag{7}$$

Besides previous constraints, policy on coal production capacity is also considered in this study (Ministry of Land and Resources of China, 2016). This can also be understood as a capacity concentration policy. It plans to concentrate a certain percentage $A\%$ of coal production in a few resource-rich regions in the future. This constraint could be described in Eq(8), where $r1$ it represents the aggregation of those resource-rich regions.

$$\sum_{r,t,m} pro_{r,t,m} \times A\% \le \sum_{r1,t,m} pro_{r1,t,m} \tag{8}$$

2.2.3 Objective function

The objective function in this model is the overall cost of the coal supply system during a long period, including production cost, import cost, transportation cost, capacity expansion cost and capacity operation cost. The overall cost and each cost are calculated in Eq(9) - Eq(14).

$$c = \sum_{t} ((cci_t + ccp_t + cct_t + cco_t + cce_t) / (1 + DIS)^{t-t0}) \tag{9}$$

$$cci_t = \sum_{r,m} (imp_{r,t,m} \times CI) \tag{10}$$

$$ccp_t = \sum_{r,m} (pro_{r,t,m} \times CP_r) \tag{11}$$

$$cct_t = \sum_{r,rr,m} (trt_{r,rr,t,m} \times DT_{r,rr} \times CTT + trs_{r,rr,t,m} \times DS_{r,rr} \times CTS) + \sum_{r,m} D_{r,t,m} \times DR_r \times CTR \tag{12}$$

$$cco_t = \sum_{r} cap_{r,t} \times CO \tag{13}$$

$$cce_t = \sum_{r} cex_{r,t} \times CE \tag{14}$$

3. Case study

China's coal supply system is used as a case study. The planning period covers from 2018 to 2050. This model contains thirty provinces in China, where Hong Kong, Macau, Taiwan and Tibet are excluded because of lack of data. The coal demand in each region and each period are input parameters, the assumption of national coal demand before 2050 is listed in Table 3 (BP, 2019).

Table 3: China's coal demand assumptions (10^9 t)

Year	2018	2020	2025	2030	2035	2040	2045	2050
Demand	39.67	40.11	39.74	35.93	32.23	28.15	24.80	21.62

Three scenarios are set to analyse the impact of the capacity concentration policy. In this policy, top three, eight and fourteen provinces which are resource-rich regions are marked. In business as usual (BAU) scenario, the policy would not be considered. Another two scenarios, marked as L and H, consider the policy and the lower bound of their shares in national coal production in 2050 is set in Table 4.

Table 4: The lower bound of share in China national coal production in 2050

Scenarios	Top 3	Top 8	Top 14
L	70 %	90 %	99.5 %
H	77 %	97 %	99.7 %

4. Results and discussion

4.1 The optimal capacity reduction timetable in BAU

Total coal production capacity would be gradually decrease because the coal demand in China is expected to fall after peaking. The optimal capacity reduction timetable by 2050 in the BAU scenario is shown in Figure 1. Results show that coal production capacity would be concentrated more in a few provinces, where the production cost is lower. Other regions would keep less capacity because importing coal from other regions would cost less than domestic production.

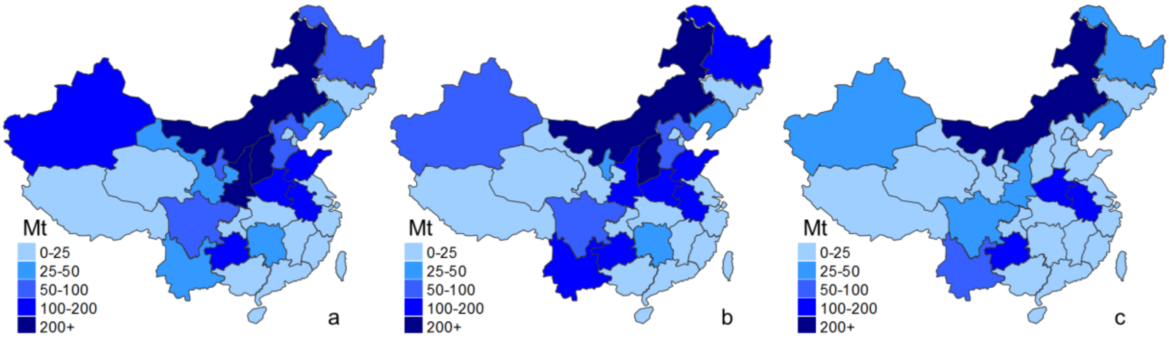

Figure 1: Regional coal production capacity in 2020 (a), 2035 (b) and 2050 (c) (Mt)

4.2 The optimal coal transportation strategy in BAU

In the BAU scenario, the optimal coal transportation strategy could be obtained by minimising the overall cost, as shown in Figure 2. Results show that coal flow among regions would not change much, while south regions would import more because import would cost less than transport from north regions.

Figure 2: The optimal transportation strategy in 2018 (a), 2035 (b) and 2050 (c) (Mt)

Seasonal fluctuation of coal demand in different regions would have impacts on coal flow across China, as shown in Figure 3. Results show that coal import would increase, and transportation by ship would decrease in summer and winter because coal demand would increase in north regions resulting from more heating demand in winter and more power generation demand in summer.

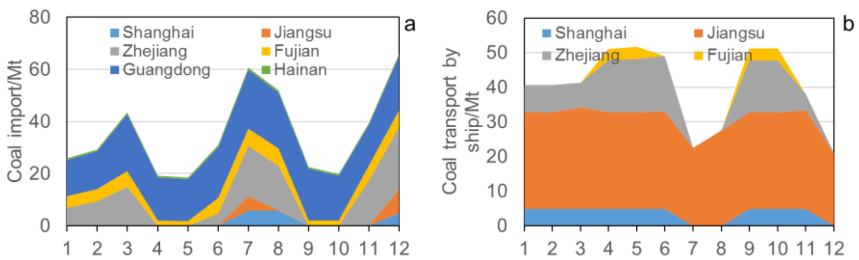

Figure 3: Monthly coal import (a) and transportation by ship (b) in 2018 (Mt)

4.3 Impacts of the capacity concentration policy

In the BAU scenario, the capacity concentration policy is not considered, which means the capacity reduction depends on the market. Results show that shares in national coal production of top three, eight and fourteen provinces in the BAU scenario are 62.3 %, 88.1 % and 96.6 %. Results show that the capacity concentration policy would increase coal transportation and transportation costs undoubtedly. In L and H scenarios, production capacity would concentrate more in northern regions. Figure 4 shows that in L and H scenarios the capacity concentration policy would increase the transportation cost by 24.9 % and 30.2 %. Results indicate that the capacity concentration policy would increase the amount of coal transported by train. In China, coal transportation by train accounts for 42 % of total railway transportation. It indicates that capacity concentration has great effects on railway transportation.

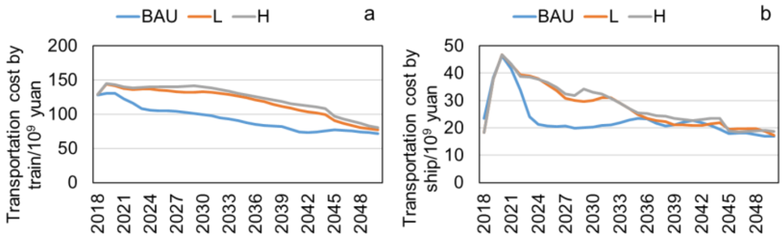

Figure 4: Transportation cost by train (a) and ship (b) in BAU, L, H scenarios (10^9 yuan)

5. Conclusions

In this paper, a multi-region multi-period and monthly-scale modelling and optimisation framework of a coal supply system at a transient stage is proposed. China's coal supply system is taken as a case study. The optimal timetable on coal production capacity reduction and coal transportation strategy could be attained by minimising the overall cost. Scenarios are set to analyse the impact of the capacity concentration policy. Results show that coal production capacity would concentrate more in resource-rich regions. Southern regions would import more rather than transport from northern regions. Furthermore, the capacity concentration policy would significantly increase the transportation cost, which would have impacts on railway transportation. In the L and H scenarios, the transportation cost would increase by 24.9 % and 30.2 %.

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