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A multi-regional energy transport and structure model for China's electricity system

Yaru Zhang [a], Tieju Ma [a, b, *], Fei Guo [b]

[a] School of Business, East China University of Science and Technology, Meilong Road 130, Shanghai 200237, China
[b] International Institute for Applied Systems Analysis, Schlossplatz 1, A-2361, Laxenburg, Austria

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ABSTRACT

The imbalance between the distribution of coal resources and electricity demand makes the transport of energy a significant challenge for China's electricity system. Moreover, with China's air pollution control policies, more clean energy resources will be used to generate electricity, which will change regional power generation structures and influence the energy transport among regions. In this paper, a multi-regional model is developed to optimize the long-term generation and transmission structure of China's electricity system by minimizing the accumulative system cost and considering regional resource endowments and air pollution control polices in four key areas. Results indicate that 1) the share of power generation from clean energy will increase from 24% in 2015 to 62% in 2050, 2) the structure of power generation in each region will be influenced by local water resource availability, and the total CO_2 emission will be reduced by around 16% in 2030 owing to the air pollution control policies, and 3) by 2050, coal will be mainly transported from the North to the Central, the South, the East and the Northeast, while the electricity will be transmitted to the Central, the South and the East from the Northwest, the North, the Southwest and the Central.

1. Introduction

China's fast industrialization and urbanization have led to significant growth in electricity consumption, reaching 5919.8 TWh in 2016, approximately twenty times the consumption in 2006 [1,2]. In terms of energy resources, China is rich in coal and poor in both oil and gas [3], which implies that coal accounts for a majority of electricity generation, nearly 67% in 2016. However, the distribution of coal resources and the demand for electricity are geographically unbalanced in China. Most of the country's coal is located in its north and northwest regions, such as Inner Mongolia, Shanxi, Shaanxi and Xinjiang, while a considerable number of coal-fired power plants are in the eastern and southern coastal regions, near demand centers and far away from coal mining areas [4]. At present, approximately 80% of inter-regional energy transport is about transporting coal and the remaining 20% is by electricity transmission [5]. However, the capacity for coal transportation by railway is limited. In addition, it is not well accepted to build new large-scale coal power plants at the demand regions because the population densities at these regions are quite high, and coal power plants could cause serious air pollution in these regions. The Chinese government is planning to build an inter-regional and smart electricity transmission grid [6]. Ultra-high voltage (UHV) is now being viewed as an emerging technology in China with the aim of meeting the need for large amounts of power transportation over long distances at lower loss and costs [7].

With the implementation of various China's air pollution control policies, more clean energy resources, such as hydro and photovoltaic (PV), are used to generate electricity [8]. This means that the power generation structure is changing, which will lead to a new challenge to energy transport between regions. In addition, China is adopting new energy transport technologies and new power generation technologies, which provides a chance to reconfigure the electricity system both technologically and spatially. Therefore, what should be the cost-effective energy transport and structure in China's electricity system have become important problems to explore.

Many studies have investigated the energy transport in China's electricity system. Mou and Li [9] studied China's coal flows by a linear programming method and considered future shifts in coal

* Corresponding author. School of Business, East China University of Science and Technology, Meilong Road 130, Shanghai 200237, China.
E-mail address: tjma@ecust.edu.cn (T. Ma).

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supply zones and their influence on coal transportation arteries. Zhou et al. [10] provided a comprehensive introduction to China's power transmission systems and grids, as well as some issues faced by China's power grids. Cheng et al. [11] developed a multi-regional optimization model to optimize the planning of China's power sector by minimizing the total cost of China's power sector whilst considering inter-regional power transmission and the impact of carbon policies. Chen et al. [12] performed a case study to quantify life cycle carbon emission flows concurrent with electricity coal flows and electricity flows in China. Yi et al. [13] established a multi-regional power dispatch and capacity expansion model to analyze China's future inter-regional power transmission planning and its influences on each region. Zheng et al. [14] proposed the IRSP (Integrated Resource Strategic Planning) smart grids model to study the impact of cross-region transmission on China's low carbon electricity development until 2035. Zhang et al. [15] built a novel source–grid–load coordinated planning model considering the integration of wind power generation. Zhang et al. [16] presented an integrated source-grid-load planning model for China's whole power system. The above-mentioned studies mainly focused on either a single electricity transmission system or scenario analyses from a short-term perspective but seldom focused on the alternative relationship between coal transportation and electricity transmission, as well as the energy transport among regions from a long-term perspective.

There are also many existing studies on the energy structure of China. Zhang et al. [17] presented a multi-period modeling and optimization framework for the future pathway planning of China's power sector, considering CO_2 mitigation between 2010 and 2050. Zeng et al. [18] gave an overall review of China's thermal power development based on industry data of 2014 and 2015. Guo et al. [19] proposed a multi-regional model that reflects actual grid infrastructure with an objective function to maximize accumulated total profits gained by the power generation sector from 2013 to 2050. Niu et al. [20] studied the current development status of electric power substitution in China and adopted a SWOT (Strengths, Weaknesses, Opportunities and Threats) model to analyze the electric power substitution. Zhou et al. [21] used LBNL (Lawrence Berkeley National Laboratory) China end-use energy model to assess the role of energy efficiency policies and structural change in industry for transitioning China's economy to a lower emission trajectory. Gao et al. [22] applied portfolio theory to optimize China's energy structure, considering the learning curve effect of renewable energy cost and the increasing fossil energy cost over time. In these studies, few considered the regional resource endowments and the impact of regional water resource and air pollution control policies on multi-regional energy structures.

The main difference between our research and previous studies is that we built a system optimization model to analyze long-term and multi-regional energy transport (i.e., coal transportation and UHV transmission) and electricity generation structure for each region, which has specific resource endowments and air pollution control polices. The rest of the paper is organized as follows. Section 2 presents our optimization model of China's electricity system. Section 3 introduces the data used in the model. Section 4 shows the analysis results of optimal strategies for regional energy structure and inter-regional long-distance energy transport pathways for China's electricity system. Section 5 gives conclusions of the study.

2. Methodology

2.1. Model descriptions and assumptions

China's power grid is divided into seven regions according to the State Grid Corporation of China (SGCC) and the China Southern Power Grid (CSG) [23,24]. As shown in Fig. 1, the seven regions are the Northwest (Xinjiang, Gansu, Qinghai, Ningxia, and Shaanxi), the Southwest (Sichuan, Chongqing, and Tibet), the Northeast (Liaoning, Jilin, Heilongjiang, and East inner Mongolia), the North (Beijing, Tianjin, Hebei, Shanxi, Shandong, and West inner Mongolia), the Central (Hubei, Hunan, Jiangxi, and Henan), the South (Guangdong, Guangxi, Yunnan, Guizhou, and Hainan), and the East (Shanghai, Jiangsu, Zhejiang, Fujian, and Anhui).

These seven regions differ greatly in respect to economic development level, power demand, resource endowment, and power generation structure. Even within the same region, there are also significant differences in the distribution of coal resource. There are 14 large-scale coal bases in China: Shendong, Eastern Mongolia, Eastern Ningxia, Northern Shanxi, Middle Shanxi, Eastern Shanxi, Northern Shaanxi, Huanglong, Xinjiang, Henan, Lianghuai, Western Shandong, and Yungui. These large-scale coal bases supply over 90% of China's coal consumption [25]. In this study, these 14 large-scale coal bases are grouped into 9 major coal bases: Cnw1, Cnw2, Cn1, Cne1, Cne2, Cne3, Cc1, Cs1 and Ce1 (see Fig. 1), according to their geographical location in the seven regions. Besides these 9 major coal bases, for each grid region, all the rest relatively small coal mines in it are treated as a small coal base, namely Cnw3, Csw1, Cne4, Cn2, Cc2, Cs2 and Ce2 (see Fig. 1). In short, each region typically includes a small coal base and a few major coal bases (1–3 depends on regions and no major coal base for the Southwest). For example, in the Northwest, there are two major coal bases (Cnw1 and Cnw2) and one small coal base (Cnw3).

Recently, UHV lines (over 1000 kV UHVAC and ±800 kV UHVDC) have been adopted in China to significantly increase the electricity transmission capability [26]. A previous study [20] found that the UHV would surpass other power transmission ways in terms of cost-effectiveness when the transmission capacity exceeds the 2400 MW and the transmission distance exceeds 800 km. According to the plans released by the SGCC [23] and CSG [24], 28 UHV lines are planned to be constructed by 2020. As shown in Table 1, 18 of them are inter-regional transmission lines, while the rest 10 are intra-regional lines. In our study, a region's energy consumption is supplied by energy generated inside this region and the energy transported to it from other regions. Like some previous modeling practices (including some non-bottom-up system optimization model, i.e., Ref. [27]), we treated the energy transport inside each region in an accumulative way to make the scale of the optimization model suitable for solving and analysis. Of course, it will be more credible to consider more details of the intra-region energy supply, which will be considered in our future work with this study as a starting point. The UHV planning by 2020 shown in Table 1 is treated as the initial status for our analysis of building suitable potential UHV grids by 2050 with the model.

In China, the inter-regional coal transportation is mainly by railways and waterways [13]. Therefore, it is assumed that there are only two ways to transport coal between regions in our model. Given the geographical conditions, coal would be transported from the North to the East and from the North to the South by waterways, while all the others by railways.

In addition, we assume that all coal bases are able to supply intra-regional coal demand and inter-regional coal transportation, and power can be transmitted by UHV among regions. Theoretically, the model would allow any location being the potential site for power plants, and then the optimization process would find the optimal locations. However, in this sense, the number of potential locations will be infinite and the optimization model will become extremely difficult to solve. Therefore, we made a reasonable constraint to the model: considering the economy-of-scale, the new built coal power plants which generate electricity for the UHV