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A multi-regional modelling and optimization approach to China's power generation and transmission planning

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ABSTRACT

Power demand in China has increased rapidly in the past decade, and it is projected to grow even further. To gain insights into how this demand growth could optimally be met, addressing regional differences such as resource distribution and power demand, is crucial. For long-term planning purposes, using a multi-regional mathematical model that divides China's power sector into regions overcomes the limitations of viewing as a single network. Reflecting how inter-regional power transmission could best be utilized is critical in understanding how flows between regions could be optimised. In this paper, 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 is proposed. A case study is provided to illustrate how inter-regional power transmission could influence the regional deployment of technologies under different policy scenarios. The results show that energy subsidies and national targets will remain important to the deployment of renewable energy in both the short and long term. In addition, potential downside implications of lower demand growth on the long-term prospects of long-distance inter-regional power transmission and options, such as more flexible electricity pricing mechanisms, to limit the effects are discussed.

1. Introduction

Alongside its rapid economic growth, power demand in China has increased sharply from 1347.3 TWh in 2000 to 5342.3 TWh in 2013 [1], and it is expected to further increase in the future [2]. Large and varied coal, natural gas, nuclear power, hydropower, and renewable generation options make determining optimal planning pathways challenging. Options for high voltage transmission to link resource-rich regions to regions with large energy demand adds further complexity when considering a territory as large as China with its uneven geographical distribution of energy resources and demand [3].

Existing studies that analyse development pathways for China's power sector can generally be divided into two groups - those that treat the whole country as a single entity, and those that consider regional variations. In studies following the “single entity” approach, they generally adopt “bottom-up” models such as the Long-range Energy Alternatives Planning System (LEAP) in which the development of China's power sector under various policy scenarios are analyzed [4], and the Integrated Policy Assessment Model developed by the Energy Research Institute of the National Development and Reform Commission (NDRC) of China that assesses China's power sector under three demand scenarios [2]. In addition to the bottom-up models, Zhu et al. apply the portfolio theory to the optimization of China's power sector under three scenarios [5]. Chen et al. adopt scenario analysis to discuss roadmaps for China's future carbon reduction pathways by using the power mix planning model which minimizes total system costs [6]. Zhang et al. developed an optimization model for China's power sector aiming at minimizing total system costs whilst considering carbon markets and Carbon Capture and Storage (CCS) technologies [7]. This work demonstrates two carbon emissions mitigation scenarios and the contributions of different technologies to carbon mitigation in each scenario by 2050. However, these studies do not consider regional differences such as demand variations and natural resource distribution, quality and cost, and thus have limited application in analyzing regional power development challenges.

For studies reflecting regional differences, Gnansounou and Dong's work discusses integrating power markets in Shanghai and

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Shandong by enabling power transmission to minimize total system costs [8]. Wang et al. divide China into coastal and inland areas to consider their regional differences in energy independence [9]. It discusses the effects of environmental policies on the development of clean coal technologies. However, simply dividing China into two macro regions limits the extent to which regional characteristics can be reflected in detail and overlooks the complexity of China's power sector.

In our previous work, Cheng et al. built a multi-regional model and divided China into ten regions according to physical grid infrastructure. The model minimizes total system costs and considers regional demand and resource differentials and neighbouring-region power transmission interconnections. The results highlight the importance of inter-region transmission to the balance of regional power demand and supply and the better utilization of natural resources [10]. Nevertheless, this work does not consider inter-regional transmission capacity and long-distance cross-region transmission, which is an important factor in connecting the resource-rich west areas to the load-centred east areas of China. Although studies for India [11] and Greece [12] take inter-regional electricity transmission capacity into account, electricity markets and policies in these countries are quite different from China. Thus, in order to give an insight into the long-term development of China's power sector, this paper presents a grid-structure based multi-region modelling. Based on our previous single-regional model (Zhang et al.'s work) and the subsequent multi-regional model (Cheng et al.'s work), this grid-structure based, multi-regional model includes existing and proposed transmission lines and incorporates nationwide energy subsidy policies. An important departure for this model is its requirement to maximize total profits generated by power generators in order to try to give insights into the impacts of China's electricity market mechanism on installed generating capacity and power transmission.

This paper is organized as follows:

Section 2 explains the methodology and key assumptions used in this study.

Section 3 provides a case study based on regional specific assumptions.

Section 4 concludes the main findings and proposes optimal pathways for capacity expansion and power transmission.

2. Methodology

2.1. Model structures and assumptions

2.1.1. Power transmission

Power transmission has always been an important issue in meeting China's regional power demand and better allocating natural resources, especially from the west to the east, or from the resource-rich regions to the load-centred regions. In this work, we focus on the division of China's grid in this model based on the physical infrastructure, both existing and planned power transmission lines, and varying regional characteristics.

After years of development, nine main regional power grids in the main land of China are formed as follows: Northeast, North, Central, East, South, Northwest, Xinjiang, Tibet and Hainan [13]. Amongst these grids, Tibet and Hainan grids are relatively independents and their demand loads are almost negligible compared to the others. Consequently they are not considered in this model. International transmission is also neglected due to its relatively small amount compared to domestic power demand [14].

Recently, the rapid construction of large capacity high voltage transmission lines has accelerated the development of China's grid. As listed in Table 1, Extra-High Voltage (EHV) and Ultra-High Voltage (UHV) transmission lines have been extensively constructed from 2000. These power transmission facilities aim to unlock hydropower and coal reserves in the west, and transmitting them to the east where the major demand centres are located. In order to reflect power transmission and resource endowment, we divide China into eight areas as shown in Fig. 1. In areas with rich hydroelectric resources, hydropower exporting largely relies on the transmission lines i.e. Sichuan (line No.14, 15, 17), Hubei (line No.1,3,6) and Yunan (line No.18,19) provinces. For regions with abundant coal reserves, such as Xinjiang, Northwest region and Inner Mongolia, more coal power plants have been constructed accompanying the development of the grid in order to deliver electricity from these areas of low fuel costs.

According to the plans released by the State Grid Corporation of China (SGCC) [15] and announced by the government [16], as listed in Table 2, eighteen UHV lines have been proposed and lines No.1–3 are under construction. As shown in Fig. 2, the eighteen lines are denoted by dashed lines with black and blue colours indicating UHV DC and AC lines, respectively. The UHV DC lines are for long-distance power transmission, enabling abundant coal resource in Inner Mongolia and northwest areas as well as rich hydroelectric power in Yunnan and Sichuan to be accessed. On the other hand, the UHV AC lines link the North, East and Central regions provide better inter-regional power transmission capacity. These proposed lines further certify the importance of power transmission to future power generation and supply, and thus this model considers the optimal development of transmission facilities and inter-regional power transmission to closely reflect the real-world actual situations.

As discussed above, the development of power transmission facilities will have great impacts on China's power generation and supply. Thus, to reflect regional differences in power demand, resource endowment and transmission facilities, China is divided into 17 areas according to these characteristics, as shown in Table 3 and Fig. 3. These characteristics are summarized from the Twelfth Five-year Plan for Energy Development [17], in which coal, hydropower, wind and solar energy bases are defined.

2.1.2. Power generation

Seven types of power generation technologies with great developing potentials [17] are included in the model. They are Sub-critical and Super-critical Pulverized Coal (SPC) representing most of the existing coal-fired power plants in China, Ultra-Supercritical Pulverized Coal (UPC), Natural Gas Combined Cycle (NGCC), Nuclear (NU), Hydropower (HD), Wind Power (WD) and solar Photovoltaic (PV). In China, the electricity market is highly regulated and on-grid prices for different forms of power generation are fixed for each region. In line with the on-grid pricing mechanism, these technologies are divided into two groups. The first group includes SPC, UPC, NGCC and HD, whose on-grid prices are regulated at all times. The second category includes NU, WD and PV, whose on-grid prices are either a strike price or a feed-in tariff determined by the time when the plant is put into operation. Amongst these technologies, only SPC plants are allowed to retire earlier than its expected lifespan considering its relatively low efficiency compared to UPC. The other technologies are assumed to operate for their entire expected lifespan. In addition, the model considers the clean energy targets announced by the government [18] that installed capacity of nuclear, hydropower, wind and solar will reach 58 GW, 350 GW, 200 GW and 100 GW by 2020, respectively. Furthermore, it is assumed that no nuclear power plants will be deployed in the resource-rich areas stated before.

The model optimizes future investment trends mainly on an economic basis from the power generation sector only. Transmission costs are excluded from the total system costs since they are borne by the grid companies in China.