Applied Energy 137 (2015) 413–426

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

A multi-region optimization planning model for China's power sector

Rui Cheng [a], Zhaofeng Xu [a], Pei Liu [a], Zhe Wang [a,*], Zheng Li [a], Ian Jones [b]

[a] State Key Lab of Power Systems, Department of Thermal Engineering, Tsinghua-BP Clean Energy Center, Tsinghua University, Beijing 100084, China
[b] BP Group Technology, Sunbury, UK

HIGHLIGHTS

- A multi-region model is proposed to optimize the planning of China's power sector.
- Spatial distribution of resource, generation and demand is taken into account.
- Results of multi-region model and single-region model are compared and discussed.
- There is a saving of cost when using multi-region model.
- Regional generation mix and power transmission pathways are presented.

ARTICLE INFO

Article history:
Received 8 February 2014
Received in revised form 9 September 2014
Accepted 6 October 2014

Keywords:
Power sector
Multi-region model
Optimal planning
Power transmission
Cap-and-trade

ABSTRACT

Demand for electricity in China kept accelerating in recent years; moreover, there exist serious mismatches among the distribution of power demand, energy resources, and power generation infrastructure across different regions in China, both of which indicate a necessity of a holistic and integrated approach to the strategic planning and development of its power industry. Material benefits could be realized by ensuring that the long term development of the power system is optimized by taking into consideration the different regional dynamics and characteristics. This paper proposes a multi-region optimization model that can deliver insights into how planning of the long term development of China's power sector could minimize the total cost of China's power sector by considering regional variations in availabilities of resources and inter-region power transmission line capacity. A case study considered how investment decisions to expand and alter the existing generation mix could be optimized across a timeframe from 2011 to 2050. By comparing results between single and multi-region optimizations, it was possible to show the likely impact on how investment decisions would differ when regional differences were taken into account. The multi-region optimization arguably better reflects and considers conditions and challenges in the real world.

1. Introduction

Demand for electricity in China has accelerated in the recent years with national power generation increasing from 1347 TW h in 2000 to 4197 TW h in 2010 [1] and at an average annual growth rate of approximately 12%. Under a low-carbon scenario, electricity generation might be expected to grow to around 11,263 TW h by 2050 [2]. With CO_2 emissions increasingly being recognized as a major cause of climate change, the case for making global reductions is growing stronger. China currently contributes quite large portion of the world's total CO_2 emission [3], with the power sector representing the largest single contributor at around 40% [4]. Liu et al. demonstrated the difficulty in realizing the CO_2 emission intensity target in 2020 if the current state of thermal power continues [5]. As a major source of CO_2 (as well as SO_x and NO_x) emissions, the power sector will inevitably have a major role to play in helping to mitigate climate change through encouraging future investment in low and zero carbon emitting generation and carbon abatement technologies. However, optimizing investment in reducing carbon emissions is not the only consideration with regional variations in factors such as electricity demand, resources, and power generation; transmission infrastructure across China also needs to be factored in. Xie et al. [6] demonstrated that the generation form have a significant influence on future environmental efficiency performance, but the differences various greatly according to regional supply and demand situation. Their work suggested the power development plan should regard regional resources endowment, and the regional power and demand situation. By combining all of these variables and constraints

* Corresponding author. Tel.: +86 10 62795739; fax: +86 10 62795736.
E-mail address: zhewang@tsinghua.edu.cn (Z. Wang).

http://dx.doi.org/10.1016/j.apenergy.2014.10.023

within a single optimization, it has been possible to deliver insights into long term (to 2050) investment planning on a nationwide basis that would simultaneously deliver material reductions in carbon emissions whilst exploiting regional cost and transmission advantages to deliver a least cost solution to the total system.

Studies have previously concentrated on optimizing the development of China's power sector as a single entity. Cai et al. [7] utilized a Long-range Energy Alternatives Planning System (LEAP) model to analyze CO_2 reduction potential and simulate pathways of China's power sector under different policy scenarios. Zhu et al. [8] applied portfolio theory and Pareto optimal principles to analyze China's power sector planning under three different scenarios. Dai et al. [2] assessed the maximum potential of renewable energy in China's power sector plan under three power demand scenarios by using a sub-model of the Integrated Policy Assessment Model developed by the Energy Research Institute of National Development and Reform Commission (NDRC) of China. Zhang et al. [9] also developed a long-term optimization model to plan the development of China's power sector under different carbon emission policies, including a cap-and-trade scheme. In all of these studies, China's power sector was modeled as a single region, and little consideration was given to the fact that different regions in China have significant variations in terms of distribution of resources, economy, population, and industrial infrastructure.

Edgard et al. [10] considered inter-region power transmission and electricity market integration in their optimization process for Shanghai and Shandong Province. Hao et al. [11] divided China into coastal and inland areas because of these regions' difference in terms of foreign energy dependence. They also discussed the influence of environmental policies on the market penetration of clean coal technologies. Notably, these works either simplified China into two regions or simply studied two provinces. Increasing in the number of regions increases the complexity of the analysis and yields different results.

Multi-region models have been developed in other countries to optimize power grid development. Parikh et al. [12] developed a multi-area model and obtained optimal power transmission paths for India. Rajeev et al. [13] used a mixed-integer programming model based on Parikh et al.'s work to simulate the expansion of transmission paths. Using this model, Rajeev et al. analyzed the influence of operation planning (transmission expansion, fuel production, and supply rescheduling) on total cost and electricity shortages. These studies focused mainly on grid optimization, thus greatly simplifying the power generation technology options. However, optimization of investment in the power generation mix is becoming increasingly more complicated than presented in previous studies; particularly with wind and solar generation technologies increasingly closing in on grid parity and emerging technologies such as carbon capture and storage (CCS) offering the potential for material reduction carbon emission from fossil-fueled generation [14]. Furthermore, these studies did not consider potential environment policies such as those targeting future CO_2 emission reductions. Koltsaklis et al. [15] developed a mixed-integer linear programming (MILP) model to optimize the long-term planning of Greek power system. The model considered lignite-fired, natural gas-fired, wind, hydro, solar geothermal, biomass, and heavy fuel oil power generation, and determined the generation mix, international power imports, the domestic electric networks, and the transportation of primary energy resources. Koltsaklis et al.'s work specifically modeled the generation and transmission of electricity, the transportation of fuel, power system stability and security constraints, and a "cap and trade" principle, while this model ignored the possibility of retrofitting current coal power technologies for CCS and ignored the life cycle (including building, retiring, and retrofit) of individual plant. In addition, these multi-region models may have limited application in the context of China because its national grid infrastructure differs significantly.

The present work proposes a multi-region superstructure optimization model that would optimize the regional development of China's power sector under a carbon mitigation policy scenario. It features an Energy Systems Engineering approach proposed by Liu et al. [16], and the approach to modeling and optimization has been applied to the design of polygeneration energy systems [17], design of commercial buildings [18], and design of a pipelines network for CO_2 transport [19]. This work includes the energy redistribution planning through power transmission and fuel transportation, as well as a better spatial utilization of renewable resources regarding the variations of regional distributions, which is very important for China's power sector development planning.

Building on the long-term single-region model developed by Zhang et al. [9], we developed a multi-region linear optimization model for gaining insights into the long term regional development of China's power sector. Compared with the existing studies, the proposed model is able to reflect the utilization of inter-region power transmission connections in matching primary energy resources, generation, and demand.

2. Multi-region optimization model description

2.1. Model structure and assumptions

China is modeled as 10 regions reflecting the current physical structure of regional high voltage transmission networks. As shown in Fig. 1, the 10 regions are as follows: Northeast (Heilongjiang, Jilin, Liaoning, and East Inner Mongolia), North (Beijing, Tianjin, Hebei, Shanxi, and West Inner Mongolia), Shandong, East (Shanghai, Jiangsu, Zhejiang, and Anhui), Fujian, South (Guangdong, Yunnan, Guizhou, and Guangxi), Chuanyu (Sichuan and Chongqing), Central (Jiangxi, Hubei, Hunan, and Henan), Northwest (Shaanxi, Gansu, Ningxia, and Qinghai) and Xinjiang. Hainan, Tibet, Hong Kong, Macau and Taiwan were excluded as these regions have relatively independent grids and small regional power demands.

As with the previous version of the model [9], 10 types of power generation technologies were considered: pulverized coal (PC), PC with carbon capture and storage (CCS) (PCC), integrated gasification combined cycle (IGCC) (China's first 250 MW IGCC Demonstration Power Project was put into operation in Huaneng Tianjin Gasification Co., Ltd. in 2012), IGCC with carbon capture and

Fig. 1. Regional division of China.