Computers and Chemical Engineering 102 (2017) 52–63

Contents lists available at ScienceDirect

Computers and Chemical Engineering

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

A long-term multi-region load-dispatch model based on grid structures for the optimal planning of China's power sector

Zheng Guo [a], Linwei Ma [a], Pei Liu [a,*], Ian Jones [b], Zheng Li [a]

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

ARTICLE INFO

Article history:
Received 28 April 2016
Received in revised form 18 June 2016
Accepted 20 June 2016
Available online 25 June 2016

Keywords:
Power generation
Power transmission
Grid structures
Multi-region modelling
Load dispatch
Clean energy
Carbon dioxide mitigation
Least cost optimisation

ABSTRACT

China's power sector has experienced rapid development over the past decade. With the clean energy targets and carbon mitigation objectives proposed by the government as well as rapid development of power transmission infrastructure, future potential pathways for the expansion of China's power sector are worth assessing. In this paper, a mathematical model, named the Long-term Multi-region Load-dispatch Grid-structure-based (LoMLoG) has been developed and a "most-likely" scenario has been created that delivers insights into optimal regional power generation, transmission and emissions profiles. The results confirm the importance of clean energy targets in driving deployment of renewable energy and maximizing its contribution to carbon mitigation of China's power sector. In addition, the development of power transmission infrastructure will significantly influence regional power generation and transmission profiles. Last but not least, carbon mitigation approaches in the long term are discussed, and rational methods of allocating future carbon caps are presented.

1. Introduction

China's power sector has experienced rapid development over the past decade strongly correlated to its ever growing economy (IMF, 2016). Total installed capacity expanded sharply from 391 GW in 2003 to 1258 GW in 2013, whilst total power generation increased from 1903 billion kWh to 5420 billion kWh (NBSC, 2015). Notably, the share of installed fossil fuelled generating capacity decreased continuously from 76.7% in 2006 to 69.7% in 2012, at the expense of accelerating deployment of renewable energy and nuclear power (EIA, 2016). China announced ambitious clean energy development targets and carbon mitigation goals in 2014 (The State Council, 2014) and, more recently, the government has enacted even more aggressive clean energy targets and regulations for the better utilization of renewable energy by 2020 (The State Council, 2016). In addition to the requirement to install low-carbon and renewable generation, the State Grid company and the government plan a dozen new long-distance Ultra-High-Voltage (UHV) transmission projects to better utilize natural resources and help mitigate regional localized pollution issues (SGCC, 2016; The State Council, 2013a). With electricity demand expected to continue to increase (Hu et al., 2009), the development of China's power sector is a comprehensive and complex subject that includes sustainable, clean energy development and inter-regional power transmission issues as well as carbon mitigation requirements. Thus studies for the optimal planning of China's power sector, though challenging, can play an important role in helping it to make the right choices.

Studies that focus on the long-term planning of the power sector can be divided into two groups based on whether they treat China as a single entity or as a series of interconnected regions. Examples of studies that treat China as a single entity include the Stockholm Environment Institute's Long-range Energy Alternatives Planning System (LEAP) model that delivers scenarios under different policy considerations (Cai et al., 2007). Similarly, the Energy Research Institute's – a division of China's National Development and Reform Commission (NDRC) – Integrated Policy Assessment Model that assesses possible development pathways for China's power sector under three demand scenarios with carbon mitigation goals (Hu et al., 2009). In addition to these two "bottom-up" modelling approaches, portfolio theory has also been adopted to generate three likely scenarios for China's power sector (Zhu and Fan, 2010). Optimization models such as the power mix planning model by Chen et al. (2011) and the multi-period planning model by Zhang et al. (2012) have also been constructed to address planning issues. In Zhang et al.'s work, two scenarios are used to demonstrate

* Corresponding author.
E-mail address: liu_pei@tsinghua.edu.cn (P. Liu).

http://dx.doi.org/10.1016/j.compchemeng.2016.06.017
0098-1354/

the importance of deployment of Carbon Capture and Storage (CCS) technology and a cap-and-trade scheme to delivering future carbon mitigation. However, these studies do not consider regional differences and the role that inter-regional power transmission could play in delivering an optimal solution for China. Thus the scope of their application is limited to very high level, nationwide assessment.

In terms of studies that attempt to reflect regional characteristics and inter-regional power transmission, the possible integration of Shandong and Shanghai's electricity markets by inter-regional transmission as a mean of minimizing total costs is discussed in Gnansounou and Dong's work (Gnansounou and Dong, 2004). The multi-region model built by Cheng et al. considers the possibility of neighboring-region power transmission and impact that potential power transmission pathways and regional resource endowments could have on the development of regional installed capacities (Cheng et al., 2015). By investigating China's actual grid structures and planned transmission lines, Guo et al. developed a grid-structure based optimization model that includes available long-distance cross-regional power transmission pathways to better represent the current as well as future possibilities (Guo et al., 2016a). These studies indicate that, to be most relevant, a power planning model needs to reflect regional differences and inter-regional connectivity via power transmission lines to better reflect real-world situations, differing regional characteristics and inter-regional dynamics.

In addition to the spatial characteristics of China's power sector, some multi-region studies also consider temporal variations of power demand and the flexibility of power generation technologies. These are crucial considerations for integrating fluctuating and intermittent renewable generation into electricity grid systems (Varbanov and Klemeš, 2011) and thus it is also common to consider the temporal characteristics in both distributed energy systems (Zhou et al., 2013a,b) and district energy systems (Fazlollahi et al., 2014), even down to hourly resolution. However, in order to include these temporal characteristics of the power sector, both the Regional Energy Deployment System developed by the U.S. National Renewable Energy Laboratory (NREL) (Short et al., 2011) and the multi-region load dispatch model constructed by Guo et al. (2016b) divide a year into several time-blocks to capture the intricacies of varying power demand and the intermittence of renewables whilst keeping the overall system optimisation manageable. Their work suggests the necessity of including these temporal characteristic while dealing with realistic challenges in the power sector. Thus, an ideal optimization model for the planning of the power sector should consider both spatial and temporal characteristics of the system, as well as power transmission pathways that will have a significant influence on shaping both regional power installed capacity requirements and the optimal utilization of those assets.

In this paper, a long-term multi-region load-dispatch model that incorporates physical grid infrastructure and includes the above-mentioned features for the optimal planning of the power sector is developed. By creating a "most-likely" scenario for China's power sector, the work aims at delivering insights into optimal regional power generation and transmission developing trends, as well as optimal solutions to tackling carbon emission issues across the country.

2. Methodology

In this section we discuss the evolution of our power sector planning model from its original pioneering version through to the latest version, known as the Long-term Multi-region Load-dispatch Grid-structure-based (LoMLoG) model. We have been continually developing the model for more than five years and new functional modules and features have been periodically added in order to add complexity and more precisely reflect real world challenges in order to deliver insights into China's long-term power sector planning. The following contents aim to give a clear and concise overview of how we have designed these functional modules and demonstrate modelling approaches that illustrate the additionality that the new features bring. At the end of this section, the latest version of our model with its new features for coping with new challenges in the real world is presented.

2.1. The pioneering model

The origins of the model were established by Zhang et al. (2012). The model was constructed to investigate how a cap-and-trade carbon mitigation scheme could create a low-carbon pathway for China's power sector through to 2050. The model was capable of making and optimizing construction, retrofit and decommissioning investment decisions for power plants according to its objective function, which is to minimize total system costs of the power sector whilst meeting future electricity demand. Ten different types of technology, notably CCS for coal-fired plant, were considered in the work and were divided into three categories according to their various characteristics. The first category included six types of plants that the model can only decommission at the end of their expected operational lifetimes including Natural Gas Combined Cycle (NGCC), Nuclear (NU), Hydropower (HD), Wind (WD), Biomass (BM) and PV. The second category included PC (Pulverized Coal) and IGCC (Integrated Gasification Combined Cycle) plants which the model can decommission before their expected operational lifetimes or be retrofitted with CCS technologies. The third category included newly-built PC with CCS (PCC) and IGCC with CCS (IGCCC) or those that the model determines would be retrofitted from existing PC or IGCC plants.

2.1.1. Mathematical description

In Zhang et al.'s work, three sets, t, g and f, stand for time, power generation type and fuel type, respectively. Meanwhile, t and t′ (or t″) share the same set in formulations. For clarity, the physical meanings of parameters and variables in the model are shown in Appendix A. Formulations such as the objective function and constraint equations are listed below. These are used to illustrate the main features of the evolution of the model in this paper. Other formulations such as installed capacity for technologies and inequality constraints are shown in Appendix B.

2.1.1.1. Objective function. The objective function in Zhang et al.'s work is to minimize total system costs of the power sector including capital costs for construction, capital costs for retrofitting, operation and maintenance costs, fuel costs and carbon dioxide emissions costs. The function is expressed in Eq. (1).

$$atc = \sum_{t=2010}^{2050} \frac{ac_t}{(1+I)^{(t-2009)}} = \sum_{t=2010}^{2050} \frac{tinv_t^{nb} + tinv_t^{rf} + tom_t + tfc_t + cec_t}{(1+I)^{(t-2009)}} \quad (1)$$

2.1.1.2. Power balancing. The sum of electricity generated by different technologies in a given year must equal the total annual electricity demand. This constraint can be expressed in Eq. (2). An important issue to note here is that the operating hours for technologies in this work are parameters determined from historical