Applied Energy 184 (2016) 987–994

Contents lists available at ScienceDirect

Applied Energy

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

Reducing curtailment of wind electricity in China by employing electric boilers for heat and pumped hydro for energy storage

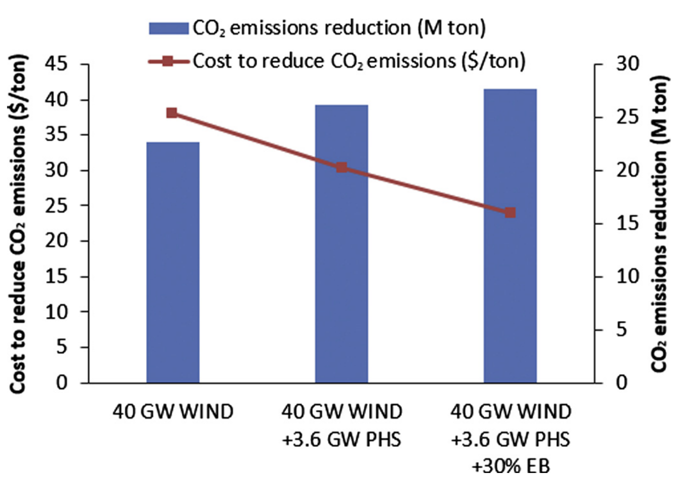
Ning Zhang [a,1], Xi Lu [b,c,*], Michael B. McElroy [c,d,2], Chris P. Nielsen [d,e,3], Xinyu Chen [c,4], Yu Deng [f,5], Chongqing Kang [a,6]

[a] Department of Electrical Engineering, Tsinghua University, China
[b] School of Environment, Tsinghua University, Beijing 100084, China
[c] School of Engineering and Applied Sciences, Harvard University, Cambridge, MA 02138, USA
[d] Department of Earth and Planetary Sciences, Harvard University, Cambridge, MA 02138, USA
[e] Harvard China Project, Harvard University, Cambridge, MA 02138, USA
[f] Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, Datun Road, Chaoyang District, Beijing 100101, China

HIGHLIGHTS

- Quantitative evaluation of benefits of PHS and EBs for reducing wind curtailment in China.
- Deployment optimization of wind power, PHS and EBs for a CHP-dominated, high-wind power system.
- Simulation of both the power and heating systems by an improved hourly chronological approach.
- Identification of EBs a cost-effective means to reduce wind curtailment in a CHP-dominated system.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 12 June 2015
Received in revised form 20 October 2015
Accepted 22 October 2015
Available online 1 December 2015

ABSTRACT

Accommodating variable wind power poses a critical challenge for electric power systems that are heavily dependent on combined-heat-and-power (CHP) plants, as is the case for north China. Pumped hydro storage (PHS) and electric boilers (EBs) are two of the strongest technological options under discussion in China to address this challenge, but rigorous quantitative analyses of their effectiveness rooted in actual system data are lacking. An improved unit-commitment based power system chronological simulation is applied to evaluate potential benefits from PHS and EBs in West Inner Mongolia (WIM), where CHP

* Corresponding author at: School of Environment, Tsinghua University, Beijing, 100084, China; RM 100B, Pierce Hall, 29 Oxford St., MA 02138, USA. Tel.: +1 617 496 9395.
E-mail addresses: ningzhang@tsinghua.edu.cn (N. Zhang), xilu2012.h@gmail.com (X. Lu), mbm@seas.harvard.edu (M.B. McElroy), nielsen2@fas.harvard.edu (C.P. Nielsen), xchen@seas.harvard.edu (X. Chen), dengy@igsnrr.ac.cn (Y. Deng), cqkang@tsinghua.edu.cn (C. Kang).
[1] Address: RM 3-206, West Main Building, Tsinghua University, Beijing 100084, China. Tel.: +86 10 62794361.
[2] Address: 100C Peirce Hall, 29 Oxford St., MA 02138, USA. Tel.: +1 (617) 495 4359.
[3] Address: RM G2F, China Project, 29 Oxford Street, Cambridge, MA 02138, USA. Tel.: +1 617 496 2378.
[4] Address: RM G2E, Pierce Hall, 29 Oxford St., MA 02138, USA.
[5] Tel./fax: +86 10 6488 9109.
[6] Address: RM 3-204, West Main Building, Tsinghua University, Beijing 100084, China. Tel.: +86 10 62788166.

http://dx.doi.org/10.1016/j.apenergy.2015.10.147
0306-2619/© 2015 The Authors. Published by Elsevier Ltd.

Keywords:
Wind power
Combined heat and power generation
Pumped hydro storage
Electric boiler
CO_2 emission

capacity is projected to increase to 33.8 GW by 2020. A business-as-usual (BAU) reference model assumes deployment of 20 GW of wind capacity. Compared to BAU, expanding wind capacity to 40 GW would allow for a reduction in CO_2 emissions of 33.9 million tons, but at a relatively high cost of US $25.3/ton, reflecting primarily high associated curtailment of wind electricity (20.4%). A number of scenarios adding PHS and/or EBs combined with higher levels of wind capacity are evaluated. The best case indicates that a combination of PHS (3.6 GW) and EBs (6.2 GW) together with 40 GW of wind capacity would reduce CO_2 emissions by 43.5 million tons compared to BAU and at a lower cost of US$16.0/ton. Achieving this outcome will require a price-incentive policy designed to ensure the profitability of both PHS and EB facilities.

1. Introduction

Development of wind energy has grown rapidly in China over the last decade. By the end of 2013, the total capacity of wind power in China had increased to 91.4 GW, exceeding that of the US by 30 GW [1]. Despite this, wind farms in China produced almost 20% less electricity than those in the US in the same year [1]. A primary factor in the low efficiency of wind farms in China results from significant curtailments of wind power in three northern regions of the country, where more than 86.4% of the national capacity for wind power is deployed. In these regions, coal-fired combined-heat-and-power (CHP) plants account for most of the electricity delivered to the power system. In winter, these plants must operate at nearly full capacity to meet the demand for building heat (delivered as hot water through district heating systems), and by design must produce electricity at the same time. Facing a potential oversupply of electricity, occasioned by the demand for heat from these CHP plants, wind farms are often idled in China at precisely the time when their output could be highest, as wind conditions are most favorable in winter. Close to 17.1% and 10.7% of the total wind power available from China's wind systems were curtailed in 2012 and 2013, respectively, resulting in estimated financial losses of 1.72 and 1.41 billion US dollars [2] (with an assumed electricity price of US 8.6¢/kWh for Chinese wind power).

This paper explores options to reduce the extent to which wind-generated power is curtailed in West Inner Mongolia (WIM), adopted as a representative example of the three northern regions where China's wind power potentials are greatest [3]. WIM has experienced a rapid expansion of capacities for both wind power and CHP over the past decade. The capacity of wind power in WIM increased from 0.04 GW in 2003 to 10.85 GW in 2013, corresponding to an annual growth rate of 74% [4]. CHP capacity in the region grew from 4.5 GW in 2003 to 26.1 GW in 2013, quintupling over the same time period [5]. In 2013, the generating capacity of the WIM power system totaled 48.8 GW, with 22.2% from wind and 53.6% from CHP units [6] with lower contribution from conventional coal units (20.4%), natural gas (2.1%) and hydro (1.7%). The fractions of wind power curtailed in 2012 and 2013 were 26.0% and 12.2%, respectively [2]. Electricity produced in the WIM system primarily serves local demand, with a small fraction exported to the larger North China Gird (approximately 16% of generation). Planning documents project that demand for electricity for WIM will increase from 155 TW h in 2012 to 351 TW h in 2020, based on assumed annual average growth rates of 10.2% from 2012 to 2015 and 9.3% from 2016 to 2020 [7]. The capacity of wind power in the WIM region is projected to increase from the 2013 level of 10.9 GW to 20 GW by 2015, reaching 40 GW by 2020 [7,8]. At the same time, investment in CHP plants is projected to continue to meet the increasing demand for both hot water and electricity (see the supporting information, SI). This trajectory clearly poses a serious challenge to integrating the increasing supply of wind power in the future WIM power system.

The present study takes the WIM power system as a case in point to explore the benefits that could be realized by incorporating pumped hydro storage facilities (PHS) and electric boilers (EB) in the overall power system. PHS could provide an opportunity to store electricity when supply exceeds demand and to generate electricity when there is a shortfall in supply, reducing wind curtailments [9]. Current PHS capacity in China amounts to 16.9 GW, and is projected to increase to 50 GW by 2020 [10]. Much of this additional capacity is planned for the eastern and southern regions of the country, with only 16 GW under consideration for the north. A 1.2 GW PHS system began operation in WIM in Jan 2015 [10]. EBs could utilize the wind power that may have been curtailed to produce heat, and at the same time cut back the heat demand of CHP generation to further increase its flexibility. A limited number of EBs have been deployed in China's three northern regions to explore the role these systems could play in reducing curtailment of wind power [11–13]. The objective of this study is to identify the combination of wind power, PHS, and EBs in the WIM region that could obtain the most cost-effective generation of electricity and the most cost-effective reduction in emissions of CO_2.

A number of studies have explored the benefits of PHS and EB in accommodating wind power in the regional power systems of China, US, and some European countries [14–20]. Zhang et al. [14] analyzed the investment and operational costs of introducing PHS at capacities varying from 2.1 GW to 6.9 GW in the Jiangsu provincial grid in 2020, with 10 GW of installed wind power capacity. Their results not surprisingly indicated that curtailments of wind power would decrease with the increasing capacity of PHS facilities. A study by Tuohy and O'Malley [15] found that introduction of 500 MW of PHS in the Irish power system would likewise reduce the curtailment of wind power. They concluded further that the capital costs of PHS facilities could be justified by savings in wind curtailment at wind penetration levels at or above 50% of total power generating capacity. Ummels et al. [16], using a central unit-commitment-and-economic-dispatch optimization model, explored a number of possible options to integrate 6–9 GW of wind power into the Dutch system by 2020. They found that installation of EBs at CHP facilities could increase the operational flexibility of these units, providing a cost-effective means to integrate large-scale wind power in the power system of Netherlands. The optimization analyses in these studies sought to minimize the overall costs of introducing these refinements. They did not however consider the costs of avoided emissions of CO_2.

Compared to current study, the contribution of the paper is threefold:

(1) An improved chronological approach was adopted to simulate the year-round operation for the power system as well as residential heating supply in a CHP-intensive power system, such as the WIM.