Applied Energy 195 (2017) 538–555

Contents lists available at ScienceDirect

Applied Energy

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

Forecasting high proportions of wind energy supplying the Brazilian Northeast electricity grid

Pieter de Jong [a,*], Roger Dargaville [b], Jeremy Silver [b], Steven Utembe [b], Asher Kiperstok [a], Ednildo Andrade Torres [a]

[a] Universidade Federal da Bahia, Escola Politécnica/PEI, Rua Aristides Novis, n° 2, Federação CEP 40.210-630, Salvador, BA, Brazil
[b] Earth Sciences, University of Melbourne, Victoria 3010, Australia

HIGHLIGHTS

- The WRF model accurately simulated hourly wind speeds at several wind farm locations.
- The particularities of the Brazilian Northeast (NE) will enable substantial wind energy penetration.
- The NE's coastal wind power generation correlates well to the hourly load curve.
- In semi-arid regions (such as the NE) hydroelectricity is susceptible to climate change.
- Wind energy in these regions could replace lost hydroelectric annual availability.

ARTICLE INFO

Article history:
Received 12 October 2016
Received in revised form 14 February 2017
Accepted 10 March 2017

Keywords:
Wind power
Hydroelectricity
Solar power
Renewable energy integration
Forecasting
WRF

ABSTRACT

This study examines the optimal integration of high proportions of wind energy into an electricity grid which traditionally depends on hydroelectricity. Wind power in the Brazilian Northeast (NE) is expected to generate 57% of the NE's electricity supply by 2020. As rainfall in the NE region is susceptible to climate change, it is anticipated that wind energy could substitute lost hydroelectric availability. The Weather Research and Forecasting (WRF) Model is used to simulate wind speeds for all of 2014 and calculate wind power across the entire NE region of Brazil. The NE region's aggregate hourly wind generation and net load curve are then estimated for increasing wind penetrations using the planned rollout of wind farms in the region as a baseline. The maximum wind energy penetration in the region is estimated to be approximately 50% before significant amounts of energy would need to be curtailed or exported to other Brazilian regions. It was found that wind energy generation from coastal wind farms in the region best correlates with the hourly and monthly variations of the NE subsystem's load curve. Conversely, inland wind farms on the NE's elevated plateaus typically generate more power late at night, but have higher capacity factors.

1. Introduction

The Paris Agreement to limit the global temperature rise below 2 degrees Celsius above pre-industrial levels officially entered into force in November 2016. One aspect of combating climate change will necessitate the use of larger proportions of emissions free electricity generation such as the use of more hydroelectricity, wind and solar power. In many developing countries, hydroelectricity is still the majority source of renewable energy, however, climate change may have a negative impact on the long term of hydroelectric availability as a result of more frequent and intense climate induced droughts [1]. It is anticipated that wind energy (and also other renewables such as solar PV) could replace lost hydroelectric potential, however, unlike dispatchable hydroelectricity, wind energy is somewhat stochastic.

Wind energy penetration in terms of percentage of electricity generation is already well above 20% in several countries and balancing regions around the world. In 2015 wind energy penetration was 42% in Denmark, 35% in South Australia, 31% in Iowa, 24% in Ireland and 23% in Portugal [2,3]. However, wind power is a variable generation technology (that is, the amount of energy production cannot be easily regulated to match demand, as it is dependent on fluctuating weather conditions). Therefore, considering the steadily increasing penetrations of wind energy expected in various countries and balancing areas, the main engineering

* Corresponding author.
E-mail address: pieterj@ufba.br (P. de Jong).

http://dx.doi.org/10.1016/j.apenergy.2017.03.058
0306-2619/

challenge will be the smooth integration of this power source into the electricity grid. One such balancing area is the Northeast (NE) region of Brazil, where wind energy is projected to produce more than half of the NE's electricity demand by 2020 [4]. Using the Brazilian NE region as a case study, the aim of this study is to forecast the detailed hourly, monthly and surplus wind power production using a numerical weather prediction tool and determine to what extent wind power correlates with demand and complements existing generation infrastructure. This paper takes a holistic approach to the challenges of integrating increasing penetrations of wind energy under different scenarios and also considers the impacts of global warming on various renewable energy sources. This type of study is very important for regions which expect to have substantial amounts of new wind energy, but rely heavily on hydroelectric generation (or biomass) that could be susceptible to climate change. Furthermore, a unique method is demonstrated to estimate the optimal installed wind power capacity at various wind farm locations in a balancing region that aggregately would generate electricity to best correlate with the electricity load curve.

As wind power generation is variable, system operators treat it as a negative load and hence the concept of load net wind or net load (defined as, the hourly electricity load minus hourly wind and solar power generation) is used [5–8]. For example, due to diurnal and seasonal wind variability in the NE region, it was estimated that if wind power penetration increased above 65%, then at certain times (such as, during hours of low load), hourly wind power would be greater than the NE subsystem's electricity demand [9]. Thus, at certain times the net load would become negative, which is an indication that there is surplus wind energy. This excess wind energy would need to be curtailed or if possible *exported* to other Brazilian regions [9]. At other times, when the output from wind power is low and demand is high, gap filling from dispatchable backup generators is required (for example from existing hydroelectric and gas generator capacity). Understanding the constraints and predicting the output of high proportions of wind energy is essential to ensure that grid reliability is maintained and also to prevent energy being wasted unnecessarily. For example in 2015, 15% of China's wind energy generation had to be curtailed due to transmission difficulties [2]. While this study focusses on integrating wind energy generation in the Brazilian NE power system, the methodology could be equally applied to other regions where similar challenges exist. Furthermore, the results of this study are compared to similar studies in other regions.

1.1. Objectives

The principal objective of this study is to simulate the aggregate hourly wind power and net load in the Brazilian NE subsystem based on the planned wind farm deployment until 2020. Firstly, the locations and capacities of all wind farms contracted in the NE region and projected to be operational by 2020 are determined. The Weather Research and Forecasting (WRF) Model is used to simulate hourly wind speeds at the various wind farm locations in the NE region (for all of 2014). Then the hourly wind power is calculated (where wind farms are or will be built) using a standard power curve for typical wind turbines used in the region.

This paper is a continuation of the work by de Jong et al. [9], which estimated the hourly and monthly aggregate wind power production in the Brazilian NE region by 2020, based on observed wind power generation data from 16 existing wind farms located in the states of Bahia, Rio Grande do Norte and Ceará. Rather than extrapolating observed wind power data, this paper simulates wind power generation using the WRF model, based on the planned installation of more than 600 wind farms across all 8 states in the NE subsystem. This novel method differs from previous studies that estimate wind energy production because many of them extrapolate future wind power data from a relatively small number of existing wind farms or poorly located weather stations.

In the baseline scenario, the aggregate hourly wind power and net load for the NE subsystem is calculated based on planned wind farm deployment until 2020 and beyond. Based on the hydroelectric minimum flow requirements of the NE's São Francisco River, it was assumed that existing hydroelectric and gas generators in the NE region of Brazil have 80% scheduling flexibility to quickly modulate electricity generation to effectively supply the net load and balance the power system. In a second and third scenario it is assumed that the installed wind power capacities at all wind farm locations are entirely flexible. For the second scenario wind power capacities are optimised in order to achieve the maximum wind energy penetration in the NE subsystem with least curtailment. Thus, the locations of wind farms that generate wind power, which best correlates to the NE load curve, can be determined. In the third scenario, the wind power capacities are optimised to achieve least cost of electricity generation. Thus, the locations of the most cost effective wind farms (those with the highest capacity factors), can be determined.

Forecasting the details of future wind power production is important in a regional context because transmission systems will need to be expanded and the power system will need to be adapted in order to effectively integrate new wind farms with existing hydroelectric generation. Furthermore, existing hydroelectric generation is susceptible to droughts in the short term and climate change in the long term (see Section 1.2), thus the viability of wind energy effectively replacing lost hydroelectric production needs to be investigated.

1.2. The Brazilian Northeast's electricity matrix and the impacts of climate change

In recent years, the Brazilian electricity generation matrix has been diversified and wind power has become the second cheapest generation technology (after hydroelectricity) in terms of levelised cost of electricity [10,11].[1] In the past, Brazil heavily relied upon large scale hydroelectric plants for electricity generation, however, the large majority of hydroelectric potential in the Northeast (NE) region of Brazil is already being exploited and there is no potential for new large scale plants [12]. As a result, wind power deployment in the NE region of Brazil has grown rapidly since 2010. Currently the NE region has approximately 8250 MW of wind power capacity connected to the grid and by 2020 an additional 7500 MW will be installed [4]. Therefore by 2020, almost 16000 MW of wind power capacity will be operational across more than 80 municipalities [4].

The interior of the NE region of Brazil is mostly semi-arid and suffers from frequent droughts, which can also affect the region's power supply. This is because the majority of the NE's electricity (typically 70%) is supplied from hydroelectric dams that are located in the lower-middle São Francisco River basin in the centre of the NE region (one of the driest areas in the country). Furthermore, low rainfall, river flows and extended drought in the Northeast region are also linked to the El Niño phenomenon [13].

From 2005 to 2007 hydro electricity was responsible for more than 87% of the NE's electricity supply [14]. However, as a result of a drought in the region that began in 2012, in 2013, 2014, 2015 and 2016 these hydroelectric plants only generated 42%, 39%, 31% and 25%, respectively, of the NE subsystem's total electricity demand. The effect on hydroelectricity generation is illustrated in Fig. 1. Until recently this shortfall was mostly

[1] As a result, total installed wind power capacity in Brazil already ranks amongst the top 10 countries in the world [2].