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Integrating large scale wind power into the electricity grid in the Northeast of Brazil

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ABSTRACT

Wind power in the NE (Northeast) region of Brazil is currently undergoing rapid development and installed capacity is expected to exceed 16,000 MW by 2020. This study examines the feasibility of integrating large scale wind power into an electricity grid (the Brazilian NE subsystem) which has a high proportion of existing hydroelectricity. By extrapolating existing wind power generation data, the maximum achievable wind power penetration (without *exports* to other Brazilian regions) and corresponding surplus energy is determined for the NE subsystem. The viable maximum penetration of wind energy generation in the NE subsystem was estimated to be 65% of the average annual electricity demand assuming that existing hydroelectric and gas generators have 100% scheduling flexibility. These results are compared to the actual gross penetration of wind power forecast to reach 55% in the NE subsystem by 2020. The overall LCOE (levelised cost of electricity) is calculated for various scenarios where wind power replaces all fossil fuel generators in NE subsystem. It was concluded that by 2020, wind power could feasibly reduce the overall LCOE by approximately 46–52% and reduce CO_{2eq} emissions by 34 million tonnes per year compared to a power system with no new renewable generation.

1. Introduction

The proportion of renewable energy (such as wind and solar power) is likely to play an increasing role in energy production in the coming decades. Wind power at good locations in Brazil is already more competitive than coal-fired power generation [1]. The penetration of wind power will grow significantly in the Northeast region of Brazil, and particularly in the state of Bahia, Ceará and Rio Grande do Norte during the coming decades. According to the Wind Atlas of Bahia the state's total wind power potential at a height of 80 m above ground is estimated to be 39,000 MW [2] which would be more than sufficient to supply the total electricity demand of the Brazilian Northeast region. However, as solar and wind power technologies are both variable technologies (that is, the amount of energy production cannot be regulated to match demand) the main difficulty is not with the amount of wind and solar resources available, but rather the smooth integration of these power sources into the electricity grid. The solution to integrate the intermittent generation from these power sources is likely to involve the development of various techniques including smart grids, weather forecasting, controlling hydroelectric plants on a sub-hourly basis to enable gap filling, interstate balancing and energy storage systems.

Wind power penetration, in terms of meeting electricity demand, is greater than 20% in a number regions and countries in the world including South Australia, Denmark, Portugal, Nicaragua and Spain where wind power met 40%, 39.1%, 27%, 21% and 20.4% of electricity demand in 2014, respectively [3,4]. Therefore, wind power has the capability to provide a large proportion of supply, however, more research needs to be conducted on the practical challenges of large scale integration and storage for wind and solar power. This paper examines the advantages and challengers of integrating wind energy into electricity grids with high proportions of hydroelectricity and uses the Northeast region of Brazil as a case study.

1.1. Objectives

The main objective of this study is to evaluate the technical, economic and environmental advantages and disadvantages of

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integrating variable renewable energy technologies, such as wind power, into the Brazilian Northeast electricity grid and still reliably meet electricity demand. The theoretical maximum feasible penetration of wind energy in the states of Bahia, Ceará, Rio Grande do Norte and the entire Northeast subsystem will be estimated assuming that wind power will be combined with existing hydroelectric and gas plants and that curtailed energy should be kept to a minimum. Additionally, the percentage of electricity spilled for different penetrations of wind power in Brazil's Northeast subsystem will be calculated. Spilled or surplus energy is defined as the curtailed energy (such as excess wind or solar energy) that cannot be used to balance demand.[1] A small percentage of curtailed energy is tolerable for variable renewable sources and allows for higher penetrations. For example, when wind energy with surplus generation still proves to be cheaper than an alternative fossil fuel energy source. However, very large proportions of spilled renewable energy effectively mean that renewable generators are operating at a lower capacity factor which has the consequence of a loss in revenue.

The technical, economic and environmental ramifications of the total wind energy penetration projected for each state in the Brazilian Northeast subsystem by 2020 will also be examined. Finally the LCOE (levelised cost of electricity) for the Northeast subsystem generation matrix is compared under various conditions, including scenarios where wind power replaces all fossil fuel generators.

The impact that large scale solar and wind energy have on the frequency and voltage stability and quality of a power system, for example during fault conditions, are discussed in detail by Shafiullah et al. [5], Hossain et al. [6] and Vilchez et al. [7] and are beyond the scope of this study.

1.2. Justification

This study differs from many previous studies because it examines the integration of large scale wind power into a power system with a high proportion of existing hydroelectric generation. As wind power deployment in the Brazilian Northeast is predicted to increase substantially in the coming years, the power system will need to be adapted accordingly in order to optimally balance the different generation technologies available. Therefore, this study is very important in a regional context, as it will help power system planners assess the impact of large scale wind penetration and identify where and how the power system needs to be upgraded.

The electricity supply matrix for Brazil in terms of installed capacity consists of 62% hydroelectricity and about 5.6% imported energy which is mostly hydroelectricity from Paraguay [8]. However hydroelectric potential near populated and industrialized areas is almost entirely saturated in most regions of the country. There are proposals for new large hydroelectric reservoirs in the remote Amazon and Cerrado river basins, but such developments will have high environmental, investment and transmission line costs [9] and cause significant greenhouse gas emissions from decaying rainforest flooded by the reservoirs [10].

The NE (Northeast) region of Brazil receives only a fraction of the annual total national rainfall [11,12] and the NE's hydroelectric reservoirs, which are located in the São Francisco basin (one of the driest regions in the country), are already over exploited. As a result of a drought which began in 2012 in the NE of Brazil, in 2013 hydroelectricity only contributed 41.9% of the total electricity demand in the NE subsystem (as shown in Table 1). The shortfall was supplemented by thermal power generation and *imported* electricity from other Brazilian regions contributing 28.8% and 25.7%, respectively, while wind energy contributed only 3.6% [13]. This is a marked difference to the situation in 2011 where hydroelectric generation contributed more than 70% of the total electricity demand in the NE [13]. Nevertheless, even in a drought year, the large proportion of hydroelectricity in the grid allows for substantial system balancing flexibility. The operational flexibility of a power system is its technical ability to quickly modulate electricity generation supplying the grid and outflows on the demand-side to effectively achieve a power balance within a specific grid area [14].

Table 1
Electricity generation sources supplying Brazil's NE subsystem from 2011 to 2014. "*Imported*" electricity consists mostly of hydro from Brazil's Southeast and North subsystems. Source ONS [13].

	2011	2012	2013	2014
Hydroeletric	70.6%	67.5%	41.9%	39.1%
Wind	1.8%	3.0%	3.6%	6.4%
Thermal	8.0%	14.1%	28.8%	40.1%
Imported	19.6%	15.4%	25.7%	14.4%

Climate change mitigation will increase the demand for emissions free electricity generation such as the use of more hydropower [15]. However another affect of climate change is that the hydroelectric potential in the São Francisco basin will be reduced due to more frequent and intense climate induced droughts [16,17]. Therefore energy storage provided by hydro reservoirs will be ideal for integrating intermittent wind power resources which can replace the lost hydroelectric energy [15]. Significant increases in wind power penetration would enable more water to be stored in the São Francisco basin. In November 2014 water levels in the São Francisco basin fell to their lowest levels in 13 years with only 13% of the total capacity remaining in terms of stored energy [13].

In 2014 6.4% of the Brazilian Northeast's electricity was generated from wind power, however, as a result of the continuing drought, more than 40% of the NE's electricity was generated from thermal power sources [13]. Furthermore, approximately 6000 MW of new thermal power plants are planned for construction or already under construction [8]. According to de Jong et al. [12], there is a huge potential to substantially increase the penetration of wind and solar power in the NE region because average wind speeds and solar radiation levels are the highest in the country. This would offset the need for unsustainable fossil fuel power generation and *imported* electricity from other regions of Brazil. Currently only 15 MW of PV (photovoltaic) is connected to the national grid [8], however, as a result of the national energy auctions, an additional 2180 MW of PV capacity have been contracted for construction [8,18]. A total of 5740 MW of wind power capacity was finally contracted in the NE during the 2013 and 2014 energy auctions [18]. Together with those wind farms already planned for installation, if all newly contracted wind farms programmed for installation by 2019 are commissioned by 2020,[2] this will see the total installed capacity of wind power in the NE region grow to

[1] In actual fact, there are always small amounts of spilled energy in a large electricity grid. These may be due to transmission line congestion, power system faults or load and weather forecasting uncertainty which result in differences between the actual load and hourly generator scheduling. For this reason the generation matrix has a specified spinning reserve to account for these small imbalances. However, these amounts of spilled energy are beyond the scope of this study.

[2] In the past, the completion of a number of wind farms (and other power generation projects) in Brazil has been delayed, in some cases several months behind schedule. Therefore, in this study it is assumed that the commissioning of wind farms and their respective transmission lines could be delayed up to 12 months, Hence, it is assumed that all wind farms currently contracted to commence operation in 2015–2019, will be generating power for the NE subsystem by 2020.