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Statistical analysis of wind energy characteristics in Santiago island, Cape Verde

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A B S T R A C T

As a volcanic archipelago, the Republic of Cape Verde relies dominantly on diesel to power its electricity supply. Recognizing the financial and environmental burden of diesel generation and risk of energy security, the government of Cape Verde has launched an ambitious goal of 50% electricity from renewables by 2020, since the country is endowed with high potential of renewable energy resources such as wind and solar. Although the annual average penetration rate of wind power has reached 24% of total electricity production generated in Cape Verde, raising the wind energy penetration level in future will pose numerous challenges for the operation and control of the power system because of wind's inherent intermittency and unpredictability. In this study, a statistical analysis of the wind characteristics in Santiago island, is presented by using historical wind speed and power data of the Santiago wind farm in 2014. A two-parameter Weibull distribution is first applied to model the wind speeds on various timescales and to determine wind energy potential in Santiago island, Cape Verde. The annual average wind speed was 8.57 m/s with a standard deviation close to 3.29 m/s. The monthly Weibull scale parameters varied from 5.64 m/s to 13.7 m/s, while the monthly Weibull shape parameters varied from 1.97 to 9.13. Although the monthly mean power density of the rainy season from August to September was low, the annual mean power density shows that Santiago has good wind potential. Then, an approach to modeling the equivalent power curve based on available wind speed and power output data from the wind farm is proposed. By utilizing the estimated power curve, the uncertainty set of wind power generation, resulted from the uncertainty of wind speed forecast, can be obtained to quantify the power system reserve requirements. A statistical analysis of wind power ramp is also given for estimating the power capacity requirement of the energy storage system that can be considered as a reasonable way to mitigate the wind intermittency and minimize curtailment of wind. Results of this study contribute to assess the wind energy potential of Cape Verde for investors, and can be used to quantify the uncertainties of wind power generation for the power system operator.

1. Introduction

In recent years, electricity generation by photovoltaic or wind power has captured considerable attention worldwide. In particular, from the point of view of security of power supply, for a country like the Republic of Cape Verde, which does not have known fossil fuel resources or reserves, renewable energy sources play an essential role in reinforcing levels of energy security, improving energy sustainability and mitigating risks from a fluctuant international energy market. The Republic of Cape Verde is an archipelago consisting of 10 islands and 13 islets approximately 400 km off the coast of Senegal in the Atlantic Ocean. The country has a total land area of 4033 square kilometers and a total population of 542,000 inhabitants [1]. It has limited natural resources and poor rainfall. In past, Cape Verde's energy was characterized by a high dependency on imported oil products [2]. Although 10 islands had been electrified, electricity supply was based on diesel and gasoline generators. Furthermore, since Cape Verde is not on a major shipping route and has to transport fuel to its islands, diesel is quite expensive. Therefore, a National Energy Plan 2003–2012 was published in 2003 laying out a pathway for the consolidation of the Energy Sector and a guarantee of national energy security [3]. Consequently, renewable energy has been rapidly invested in Cape Verde. The Cape Verde Wind Power project with the 32 turbines installed on four onshore wind farms on four islands (Santiago, Sao

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Vicente, Sal, and Boa Vista), was also awarded the 'Best Renewable Project in Africa' prize at the Africa Energy Awards 2011 in Johannesburg. Currently, more than 25% of the electricity produced in Cape Verde is based on the use of renewable energy resources. According to annual report 2014 of Cabeólica, a private-public company, the four wind farms together, produced a total of 80.9 GWh (Santiago 42%, Sao Vicente 27%, Sal 21%, and Boa Vista 10%) [4], as shown is Table 1. The annual average penetration rate of the four wind farms was 24% compared to total production generated in the country in 2014.

Recently, Cape Verde has set an ambitious goal of meeting 50% of its energy needs through renewable energy by 2020. The country has also planned to have at least one of ten islands 100% energy self-sufficient through renewable means by 2020. Since Cape Verde has excellent conditions for wind and solar power generation, renewable resources integration holds an important position in relieving dependence on foreign oil products, cutting operating cost and reducing the emission of pollutants. Although the goal is lofty and the corresponding government incentives have been established, Cape Verde will facing with a great deal of challenging issues. One of the most important issues in renewable integration is intermittency, which creates difficulties in meeting load demand. The power system in Cape Verde is a hybrid plant which is an integration of diesel generators with renewable energy resources, such as solar and wind. The hybrid plant must continuously manage the fluctuations of the load and power output of the renewable resources to maintain the nominal frequency of the power system, which is required for the satisfactory operation of the power system. That the diesel generator in the hybrid plant must operate above a minimum loading constraint will further exacerbate the operation and management of the power grid. Moreover, the wind farms in Cape Verde with low geographic diversity exhibit frequent occurrences of extremely high and low power outputs. Wind ramps caused by surge of wind speed will lead to higher ancillary service requirements, or curtailing or limiting the ramp rate of wind generation, to maintain the power system balance. Therefore, in 2014, the total wind power wasted on the four islands in Cape Verde approached 25% of total available wind energy. Most wind impact studies have been restricted to penetrations below 20%. As penetrations increase above 20% their impacts on power system operations including frequency control and transient stability, become more severe. To mitigate the wind intermittency and minimize curtailment of wind, the energy storage system (ESS) can be considered as a reasonable way to cater to such high wind penetrations in future. Recently, there are a number of innovations in technological development and a huge leap in business mode about the ESS. The ESS can decrease the total diesel consumption, carbon emissions, and fuel costs while increasing the value of renewable energy investment and improving the renewable generation output controllability. However, since there are always some errors of wind speed and wind power forecast, the relationship between the sizing power capacity of the ESS and the uncertainties of wind speed and power forecast, should be investigated thoroughly.

Table 1
Wind energy in Cape Verde [4].

Island	Installed capacity (MW)	Energy produced (MWh)	Wind speed (m/s)	Availability (%)
Santiago	9.35	33,898	8.6	99.5
S. Vicente	5.95	22,211	10.0	99.0
Sal	7.65	16,640	8.9	98.7
Boa Vista	2.55	8130	8.9	99.1
Total	25.50	80,878	9.1	99.1

The main objective of this paper is to gain insight into the wind resource of Cape Verde by analyzing the historical wind data obtained in Santiago island in 2014. Statistical analysis of wind resource data is critical to have an idea of how the future power system will operate with a higher wind penetration. Simple statistics extracted from the data can answer questions, such as, which month has the largest mean wind speed? What are the distributions of the monthly wind speeds? What is the diurnal variation of the wind speed? What is the relationship between the wind speeds and the active power outputs? How should ramps be defined especially in light of increasing penetration? Do severe ramps occur rarely or are they relatively frequent? For the planning of a wind farm or the preparation of expanding the capacity of a wind farm, one can assess the potential of the wind energy by using the historical wind speed and wind power data. The historical data can always be a promising source to find the uncertainties of wind speeds for any specific regions installing wind turbines. Moreover, the most suitable capacity of an ESS smoothing the wind farm power output, can be effectively determined by analyzing the historical wind data and considering the uncertainties of wind speed and power forecasting. Of course, long-term data sets of wind speed and responding active power measurements should be desirable to evaluate the impact of integrating wind energy into the isolated hybrid electrical network. As pointed out in Ref. [5], one year of records of wind speed and power behavior is sufficient to predict the long-term wind characteristics within an accuracy of 10% and a confidence level of 90%.

There are relatively few studies published for statistical analysis of wind characteristic, wind energy potential and economic evaluation of investments of wind energy for Cape Verde. In the pioneering work published in 2000 [2], Alves et al. had studied the renewable energy technologies and the corresponding social, economic and environmental benefits for Cape Verde. They alleged that renewable energy can compete with conventional energies for island and remote regions, such as Cape Verde. Therefore, their appeal that energy and environment policies should maximize the use of alternative sources of energy by introducing appropriated technologies, is insightful. In Ref. [6], five scenarios of development of electricity production for Santiago Island were presented to analyze the potential influence of clean development mechanism, as well as the influence of declining prices of renewable energy technologies. Due to the fact the technology prices of wind in 2002 were very high, the study in Ref. [6] concluded that wind was not economically viable on the island of Santiago. Nørgård and Fonseca simulated the power systems at three of the Cape Verdean islands with varying expected demand developments and varying wind power capacities by using the IPSYS time series simulation tool [7]. Freire et al. used the computer simulation program HOMER to evaluate the economic feasibility of adding a large wing turbine to an existing electric system in Cape Verde [8]. The simulation result is encouraging that the implementation of the turbines is viable for Cape Verde. Segurado et al. analyzed the way to increase the penetration of renewable sources by using pumped hydro storage in S. Vicente Island, Cape Verde [9]. However, their study was based on existing load data and meteorological data. Teixeira et al. analyzed the stability of power systems in Santiago Island with wind farm by using MATLAB/Simulink [10]. In Ref. [11], Ranaboldo et al. analyzed the designs of off-grid electrification projects based on hybrid wind-PV energies in 3 rural communities in Cape Verde. They assessed the wind resource by using the numerical wind atlas. Recently, a policy analysis tool was proposed to quantify the benefits and costs of implementing a grid-connected onshore wind project and applied to the appraisal of a wind farm in Santiago Island [12].

Other studies focusing on statistical analysis of wind energy characteristics around the world besides Cape Verde can also be