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Use of spatio-temporal calibrated wind shear model to improve accuracy of wind resource assessment

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HIGHLIGHTS

- Analyzed field wind data collected by a high accuracy LiDAR system at onshore and offshore sites.
- Identified seasonal and diurnal variations in wind resources and calibrated wind shear models considering such variations.
- Indicated that empirical wind shear model parameters commonly used underestimates the wind speed and energy potential.
- The analyses will help improve the accuracy of wind energy assessment and wind energy forecast.

ARTICLE INFO

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Wind energy
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Roughness length
LiDAR system
Time-varying analysis

ABSTRACT

Wind shear models are commonly used to predict the wind speed at wind turbine hub heights from the wind data collected at the elevation of the monitoring station. In many cases, the model parameters are based on empirical values recommended by design specifications that reflect the site conditions. This paper evaluates the benefits of incorporating site-specific wind data to calibrate the wind shear model parameters. Wind speed data collected by a ZephIR® Light Detection and Ranging (LiDAR) system over a 2-year (Oct. 2010–Sept. 2012) period are used for the analyses. The atmospheric stability is found to have appreciable effects on the wind shear parameters, i.e. wind shear coefficients (WSC) for the power law model and roughness lengths for the logarithmic law wind shear models. The calibrated wind shear model parameters by the monitored wind data during the first year are presented in the format of a contour map to demonstrate the spatio-temporal variations, which shows daily and seasonal variations. The calibrated wind shear models are then validated by the wind data collected during the second year, which demonstrates decent performance. The accuracy and performance of incorporating site-specific wind shear model calibration to predict the wind energy resource is evaluated, where six different methods are compared. The results show that the consideration of spatio-temporal variations of wind shear model parameters achieved improve performance over the application of the empirical or yearly-averaged wind shear model parameters in extrapolating the wind speed. It is also found that the performance of considering spatio-temporal wind shear parameters are even better at higher elevations. Furthermore, the analyses find that the use of empirical wind shear model parameters underestimates the wind energy output at the studied sites. Site-specific calibration of the wind shear models could further improve the accuracy of wind energy assessment by considering the site condition and the variability in the atmospheric stability.

1. Introduction

Energy productions from fossil fuels lead to massive amounts of carbon dioxide emissions that contribute to global warming [1]. The development of renewable energies is a strategy to mitigate the global climate change. Wind energy has been one of the world's fastest-growing renewable energy sources and is seeing surges in the United States and other nations [2,3]. Wind energy is renewable, sustainable, and locally available; furthermore, it is believed to feature a high return on investment compared to other renewable energy technologies. The average growth rate of installed wind power was approximately 28% during the last decade [4], and it is projected that the worldwide installation of wind energy will increase at an even faster pace in the next few decades [5,6].

Near-surface measurement of wind conditions helps to maximize the performance of wind farms, which includes determinations of wind

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farm sites, distributions of the wind turbines, and selections of wind turbine types [7–10]. The wind energy potential is evaluated based on the wind speed at wind turbine hub heights and the turbine's rated power curve. Elevations of the wind speed measurement depend on the measurement equipment [11], and it is often necessary to extrapolate wind speeds from the monitored heights to the hub height of the wind turbine [12]. Wind speeds are typically collected at 10 m or 30 m above the ground level by use of sensors installed on a met mast. Wind speeds are extrapolated to the wind speed at the proper height using the wind shear model (typically using the Power Law or the Logarithmic Law), taking into consideration the effects of the terrain type. Such procedures have been followed by a significant amount of studies [13,14] across many regions and countries. Kwon [15] evaluated the wind energy potential at Kwangyang Bay on the southern coast of the Korean Peninsula using the Power Law; the wind speed at 10 m was extrapolated to the hub height of the prototype wind turbine. Ohunakin et al. [16] studied the wind energy potential in seven selected locations in Nigeria measured at a 10 m height by cup anemometers; they used the Power Law with a wind shear coefficient of 1/7 to transform the wind speed to the wind speed at the target hub height. Durisic and Mikulovic [17] discussed the wind energy resource in the South Banat region of Serbia based on wind data collected at 10 m, 40 m, 50 m, and 60 m from an in-situ 60 m tube anemometer mast; they also used the Power Law to calculate vertical wind speed profiles. Roughness lengths and wind shear coefficients used in these studies, however, are mainly based on empirical values according to the local terrain, which inevitably leads to errors. For example, the 1/7 power law is only reasonable over smooth, grass-covered terrain under near-neutral climate conditions [18]. However, the WSC of 1/7 is commonly used at sites when no reference data is available. Additionally, the variation of the wind shear coefficient is typically considered as a small perturbation and is neglected in many studies. Consequently, the wind speed estimation from using wind shear models is often a major contributing factor to the uncertainty of the wind resource assessment, which leads to large errors in the estimation of wind energy productions. Furthermore, as the elevation increases, the accuracy of the wind speed derived from the empirical wind shear coefficients further deteriorates.

Wind shear model parameters are important for accurate assessments of the wind turbine power production. According to the research of Wan et al. [19], the energy output is sensitive to very small changes in wind shear coefficients. Structural design specifications, such as ASCE7-05 [20], provides wind shear model parameters associated with different topological conditions, which is a constant value for a particular site. In reality, various studies [21–23] have been conducted to investigate the variation of the wind shear parameters at different terrain types, and it has been demonstrated that the wind shear parameters could vary within a wide range depending upon the atmospheric stability. The variation of the wind shear parameter is due to the differences in vegetation, air pressure, humidity, bending of trees, waves on water surfaces, and magnitude of the wind speed [24]; the most significant parameter is the atmospheric stability [25]. Rehman and Al-Abbadi [26] used data collected over four years measured at 20 m, 30 m, and 40 m above the ground level from a met mast in Saudi Arabia to study the variation of the wind shear coefficient; they found that the WSC values are higher at night and smaller during the day while no evident seasonal trend was identified. Firtin et al. [27] investigated the effects of wind shear coefficients on energy production by analyzing one-year's data from a met mast in Turkey; they analyzed daily and seasonal variations of the wind shear coefficient and found that there are 49.6% differences in the estimation of energy production by using different wind shear coefficients. Durisic and Mikulovic [28] presented wind data recorded by met mast located at three different locations with different terrain types. The data was monitored at elevations of 10 m, 40 m, 50 m, and 60 m for a one-year period, and the WSC shows obvious daily variations. Kubik et al. [29] compared the energy output between the actual energy output from an active wind farm in North Rhins, Scotland and the extrapolated data with a fixed wind shear coefficient. They found that using a fixed wind shear coefficient for the whole year yields a good approximation for annual energy output, but that errors in any given hour could be significant. Gualtieri [30] studied the wind shear coefficients affected by the atmospheric stability based on a 3-year dataset at 10 m, 20 m, 40 m, and 80 m from the met mast. The author compared three different power law based approaches in assessing wind resources and found the Panofsky and Dutton (PD) model was the most accurate method. They also stated that the evaluation of the wind shear parameters through considering the daily and seasonal variation is important to improve the accuracy of wind energy assessment. These previous studies show great improvement in wind shear coefficients assessments. Most of the former studies focused on the power law since it is more accurate at lower atmosphere. However, the hub height of the modern wind turbine could reach as high as 120 m above the ground level [31]. Improving the reliability of wind shear models to estimate the expected wind speed and energy at a higher hub height of wind turbine is seen as a crucial factor for decisions by the wind energy investment sectors [32]. Furthermore, the logarithmic law should be discussed, as it is suitable for wind profile assessment at higher altitudes.

This research uses site-monitored wind data to obtain the 2-D temporal contour map of wind shear model parameters where the daily and seasonal variations are presented. The wind speed data was collected by a ZephIR® LiDAR system at different altitudes up to 150 m above the ground level. The studied site is located in an industrial area 4 miles inland of the Lake Erie shoreline in Northeast Cleveland, Ohio, USA. The data was monitored between October 2010 and September 2011 at elevations of 30 m, 70 m, and 100 m and between October 2011 and September 2012 at the elevations of 30 m, 100 m, and 150 m. The characteristics of the wind at different altitudes are analyzed, which includes the average wind speed, the wind rose, and the Weibull distribution parameters. The atmosphere stability effects are evaluated by using monitored data to calibrate the wind shear model parameters for both the power law and logarithmic law wind shear models. An algorithm is programmed in the commercial computer language MATLAB to analyze one year of wind data in a 10 min time interval. The Year 1 data is used to determine the wind shear parameters and presented as a 2-D wind shear model contour map, which shows the daily and seasonal variations. The Year 2 data is used for the validation and comparison. Six different procedures including both the power law model and the logarithmic law model are compared in terms of their performance in the extrapolation of wind speed and estimation of wind energy potentials.

2. Methodology and theoretical background

2.1. Theoretical wind power output

The wind power output of a turbine is described by the well-known equation [33]:

$$P = \frac{1}{2}C_p \rho A v^3 \tag{1}$$

where P is the power output; ρ is the density of air (typically 1.225 kg/m^3); C_p is the power coefficient; A is the rotor swept area, and v is the inflow wind speed. The equation shows clearly that for the same type of wind turbine at a certain air density condition, the power output is significantly affected by the inflow wind speed.

2.2. Weibull distribution

A statistical function is commonly used in the wind engineering to describe the characteristics of wind speed distributions [34]. The Weibull distribution has been widely used to describe the probability density function (PDF) of the wind speed [35], and it has been found to