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Impact of forested fetch on energy yield and maintenance of wind turbines

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ABSTRACT

In a wind farm whose turbines have either a forested or unforested fetch, measurements of the wind speed, wind direction and turbulence intensity are made with a 3D scanning LiDAR, and measurements of the tower head aeroelastic deflections are simultaneously made with an opto-mechanical measurement system. It is seen that in the forested fetch there is up to 2.5 times larger turbulence intensity than in the unforested fetch. Aeroelastic deflections of the tower during normal operation are up to 2.8 times larger for a turbine in forested fetch compared to a turbine in an unforested fetch. It is observed that the turbine with forested fetch has 17% lower annual energy yield compared to a turbine in an unforested fetch. The deficits in the direction-wise energy yields are shown to be primarily a function of the upstream streamwise extent of the forest. Furthermore, an analysis of the maintenance logs of the turbines shows that there are 2.2 times more fault durations per year and 20% shorter time intervals between unscheduled and scheduled maintenances for a turbine in a forested fetch; thus more frequent scheduled maintenances are recommended for turbines with a forested fetch.

1. Introduction

In 2014, there was a 44% growth of installed wind capacity compared to the previous year with 51.5 GW of new installed capacity, 97% of which was installed onshore [1]. Efficient use of available land is required in order to keep up with the rapid development of onshore wind energy. Given the regulatory restrictions on siting of wind farms in urban areas [2], onshore wind farms are mostly installed in rural areas. As the rapid growth of the onshore wind sector continues, it is increasingly the case that wind farms will be in close proximity to forested areas. Nevertheless, the impact of forest-elevated turbulence levels on wind turbine operation is not completely understood. Since elevated turbulence levels can increase fatigue loads on the turbines by up to 80% [3], an improved understanding of the impact of a forested fetch on the power generation and maintenance cost of wind turbines is required. In spite of the commercial sensitivity, there are reports of up to 15 tower collapses and 30 structural failures of blades per year [4]. Hence an improved knowledge of the impact of a forested fetch on the wind flow field and the operation and maintenance of turbines can contribute towards improving the reliability of wind turbines that are sited close to forested areas.

Computational fluid dynamic simulations [5–8] have been used to investigate turbulence generation above and downstream of forests. Large eddy simulations [6] show the presence of a complex vortical structure above the canopy that is initiated from $9H_{forest}$ downstream of the forest edge. Reynolds-averaged Navier-Stokes simulations of the flow over forests were performed in Ref. [7], where TKE as high as twice the upstream TKE was predicted downstream of the forest. Modelling of the forest as a porous media was suggested in Ref. [8]. In addition to computational fluid dynamic simulations, sub-scale models [9,10] and full-scale experiments have also investigated the turbulence generation above and downstream of forests. Full-scale measurements have mainly been made with meteorological masts [11–14]. Field measurements show that the effect of forests extends above the forest canopy up to a height of 5 times the height of the forest, as well as downstream of the forest [11]. Measurements above the forest canopy show there is a negligible difference in turbulence anisotropy upstream and downstream of forest edges [12,13]. Shear generation above the forest canopy is suggested to be the principal source of turbulence generation above and below the forest canopy, as TKE in the sub-canopy layer is observed to be one-tenth of TKE above the canopy [14]. Since meteorological masts yield only point measurements,

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Nomenclature

a_{ij}	components of turbulence stress tensor
D_i	fault duration
H_{forest}	height of forest
u', v', w'	wind speed fluctuations in principal, lateral and vertical wind direction
L	streamwise extent of forest
t	fault date
u_{ref}	hub height wind speed
W	lateral distance from forest edge
θ	laser beam elevation angle
ΔP	power deficit
$\overline{\Delta t}$	average interval between scheduled and unscheduled maintenance
σ_u	standard deviation of wind speed in principal wind direction
$\sigma_{u,\ los}$	standard deviation of line-of-sight component of wind speed

Abbreviations

AEY	annual energy yield
AGL	above ground level
CFD	computational fluid dynamics
DA	degree of anisotropy
IEC	International Electrotechnical Commission
LAI	leaf area index
LiDAR	light detection and ranging
LOS	line-of-sight
PSD	power spectral density
SCADA	supervisory control and data acquisition system
TI	turbulence intensity
TKE	turbulent kinetic energy
VAD	velocity azimuth display

limited information about the spatial distribution of flow field around forests are obtained. However due to abrupt geometric changes at forest edges, flow around forests are expected to have considerable spatial gradients. Remote sensing devices such as LiDAR provide wind flow field measurements over the spatial extents of an area or a volume [15,16]. used a continuous-wave laser LiDAR in a vertical VAD profiler mode for measurements of wind speed and flow tilt angle at forest edge [17,18]. Used 3D scanning LiDAR system for flow field measurement at forest edge.

Although several studies have addressed the impact of forests on the wind flow above and downstream of forests, only a few studies have assessed the impact of elevated turbulence levels on wind turbine's operation and power generation. The impact of elevated turbulence on turbine performance has been investigated in Ref. [10] using a sub-scale wind tunnel model. However, as turbulence generation is dependent on Reynolds number, there is a concern with wind tunnel experiments since the full-scale Reynolds numbers are three to four orders of magnitude larger than in the wind tunnel. In addition to a Reynolds number mismatch, the use of stiff forest tree models in wind tunnels is a concern since, the top of the forest canopy may oscillate due to the flexibility of trees; the attendant vorticity generation mechanisms are absent in sub-scale experiments [19]. Used meteorological mast measurements to assess the impact of turbulence at the forest edge on wind turbine loads. Measurements showed that turbulence dissipation rate is 9 times higher over forest, compared to undisturbed flow and turbulence anisotropy is the same in forested and unforested terrain.

The present work is conducted in a utility-scale wind farm that is adjacent to a forested area. The impacts of a forested fetch compared to an unforested fetch on the wind flow field, turbine performance and turbine maintenance are compared. To the authors' knowledge the present work is the first to combine the capabilities of a mobile 3D scanning LiDAR for measurements at a forest and an assessment of the impact of flow field on wind turbine's performance. Since long-range 3D scanning LiDAR systems are usually not portable, field measurements with 3D scanning LiDARs are mostly limited to measurements at one location. The mobile-based LiDAR measurement approach that is used in the present work is a cost-effective solution to perform LiDAR measurements from multiple locations during a single measurement campaign. This paper is organised as follows: first, the experimental methodology is described. Then the wind flow field, turbines' power generation, aeroelastic deflections of towers and mechanical faults of turbines in unforested and forested fetches are compared. The paper concludes with the key observations.

2. Experimental methodology

2.1. LiDAR measurement system

The LOS component of wind speed is made using a scanning LiDAR system that is installed in a mobile laboratory. A more complete description of this mobile LiDAR system can be found in Ref. [20], but a few salient features are presented here for completeness. The LiDAR is a long range inland Galion model. The LiDAR's measurement principle is based on the Doppler shift of laser light that is backscattered from aerosols in the atmosphere. Based on our comparative measurement to measurements on a meteorological mast and SODAR the LiDAR's accuracy in measurement of the LOS wind speed component is ± 0.25 m/s [20]. The LiDAR has a moveable head that allows for 3D scanning measurements over azimuth angles in the range 0°–360° and elevation angles of -17 to 90°. Using an electronic spirit level, we have verified the angular position accuracy to be 0.1°.

2.2. Opto-mechanical measurement system

The aeroelastic deflections of the wind turbine towers are measured using an opto-mechanical measurement system that is described in detail in Ref. [21]. The primary component of this system is an infrared laser that measures the distance to solid objects based on the time-of-flight principle. The laser has a beam divergence of 1.7 mrad and a wavelength of 905 nm. The accuracy in the measurement of distance is 1.9 cm. The measurement range is up to 300 m. The measurement data are acquired at a rate of 500 Hz. This system is well suited for measurements on multi-megawatt wind turbines that have tower heights in the range of 60–110 m and rotor rotational frequencies in the order of 0.25 Hz. The laser head is mounted on a platform with two rotational degrees of freedom, such that azimuthal and elevation scans of the laser beam can be made; the angular resolutions are 0.06°; at the maximum measurement range, the corresponding linear resolution is 30 cm.