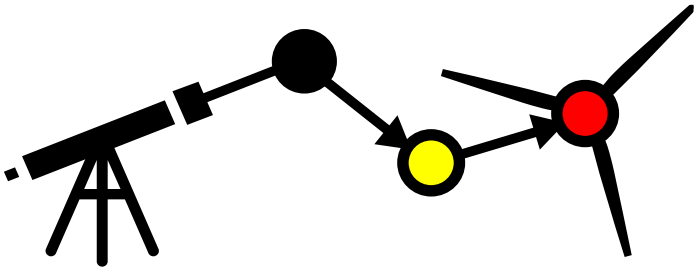
BeFORECAST



Deliverable: Analysis of heavy wind loading events through load fusion

Deliverable No.: D2.2

economie
FOD Economie, K.M.O., Middenstand en Energie

This project has received funding from the Energy Transition Fund of the Belgian Federal Public Service for Economy, SMEs, and Energy (FOD Economie, KMO, Middenstand en Energie)

DOCUMENT CONTROL SHEET

DOCUMENT INFORMATION	
Document title	Analysis of heavy wind loading events through load fusion
Author(s), (organization)	Pieter-Jan Daems, Timothy Verstraeten, Jakob Gebel, Jan Helsen (Vrije Universiteit Brussel)
Deliverable No.	D2.2
Work Package No.	WP2
Dissemination level	Public
Date of issue	

DOCUMENT SUMMARY

During their lifetime turbines are exposed to a substantial variability in environmental loading. Typically, standardized load cases are used as inputs for the turbine design simulations. An overview of such cases is given in IEC 61400-3-1.

However, the occurrence of the different cases is site-specific. Therefore, the availability of detailed field measurements and particularly wind conditions in the farm allows to gain insights in the occurrence of different wind loading events. This document has the following goals:

1. Showcasing a framework to identify different dynamic wind events to which wind turbines are exposed.
2. Assessing the loading at the level of different components during identified wind events by means of simulation

Table of Contents

1 Introduction

During their lifetime, turbines are exposed to a substantial variability in environmental loading. Typically, standardized load cases are used as inputs for the turbine design simulations. An overview of such cases is given in IEC 61400-3-1.

However, the occurrence of the different cases are site-specific. Furthermore, this listing might not be exhaustive. Therefore, the availability of detailed field measurements and particularly wind conditions in the farm allows to gain insights in the occurrence of different wind loading events to make simulations more representative of real operating conditions. This document has the following goals:

1. Describing a methodology to detect wind events using the following data sources:
    a. **Scada**: This data is available for all wind turbines within the farm without requiring dedicated instrumentation. This data source only contains measurements of the wind speed and wind direction at hub heights.
    b. **LiDAR**: In the scope of T1.2, LiDAR measurement campaigns have been performed at different wind turbines within the Belgian offshore zone. This device performs line-of-sight measurements at different distances and heights from the machine, allowing to gain insights into the veer/shear across the rotor.
    c. **Scanning LiDAR**: Within cSBO Cloud4Wake, a measurement campaign is performed with a scanning LiDAR. This device is capable of measuring line-of-sight wind speeds up to 10km, and can therefore be used to gain insights into the turbines wakes and the evolution of events throughout the wind farm.

2. Analysis of the turbine loading during different wind conditions by means of simulation using openFAST

1.1 Structure

To meet the above mentioned goals, Section 2 discusses the detection of wind conditions using the data sources available in the Beforecast project, with main focus on scada and nacelle LiDAR data captured in WP1. Afterwards, these insights are used in Section 3 to perform load simulations with representative wind conditions. Finally, conclusions are given in Section 4.

2 Detection of meteorological events of interest

The goal of this section is to give insights into the detection of different wind events using the available measurement devices. Only a brief summary is given in this section, for a full description of the applied methods, references are given to published articles listed in Section 5.

2.1 Detection of fast wind speed and wind direction changes using scada data

The detection of wind speed and wind direction changes has been performed in SBO Rainbow and is described in [1]. The methodology for detecting these events is based on using Gaussian wavelets. These allow to readily extract time windows with high variance in the time series. The advantage of this method is its low computational cost. Using thresholding on the wavelet coefficients, sudden wind speed and wind direction changes are identified. The timing of these events are registered, and compared between different turbines within the farm. In case sufficient turbines raise this alarm, a farm-wide flag is raised

that an potential event of interest is taking place, which is saved for further analysis. Examples of identified events are shown in Figure 1.

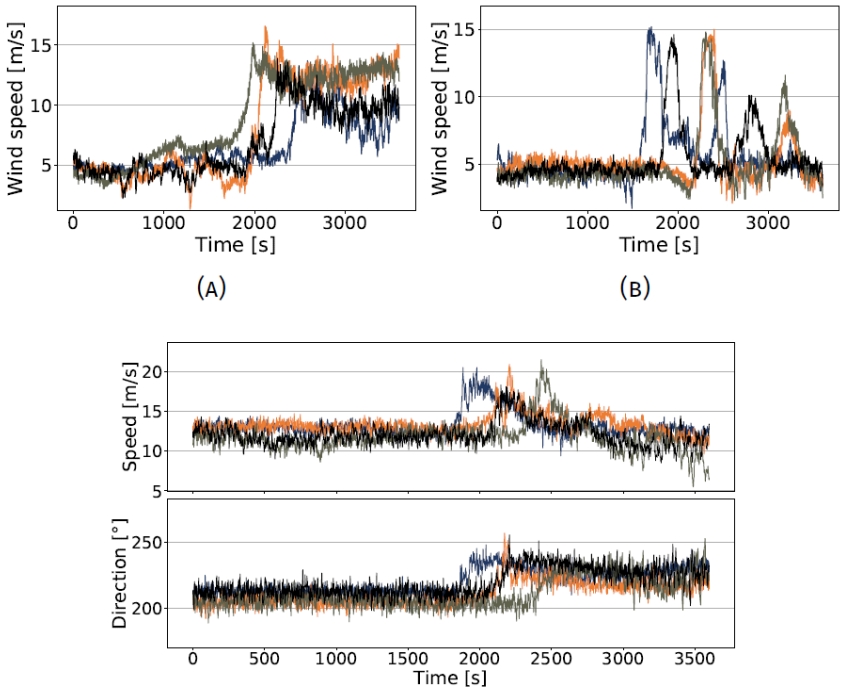


Figure 1 Examples of environmental events detected using the implemented methodology for four different wind turbines in a wind farm. (a) Example of a wind speed increase. (b) Example of a wind gust. (c) Example of a simultaneous wind direction and speed change

2.2 Detection of high shear/veer events using nacelle LiDAR data

The reconstruction of LiDAR data and the resulting detection of profiles of interest for further load analysis is described in [2, 3]. In short, the available LiDAR measures line-of-sight speeds in circular patterns at different distances from the rotor plane. To translate these line-of-sight measurements into a local wind field U, reconstruction is needed, solving the so-called cyclops dilemma. This reconstruction is done at different volumes across the rotor plane. In each of these volumes, the wind field is assumed to be homogeneous. Furthermore, it is assumed that the vertical wind speed component is negligible. In a given volume, the line-of-sight measurements are related to the wind field by means of a projection vector, dependent on the cone angle of the LiDAR. An optimization problem is solved to minimize the error between the observations and the fitted wind field. This yields the horizontal and vertical wind speed across the rotor plane. This profile is then further processed to:

(1) Gain insights into the average shear at different wind speeds
(2) Gain insights into the occurrence of profiles not complying with the power law (e.g. low level jets)

An example of profiles not complying with the power law can be seen in Figure 2. These are further processed in Section 3.

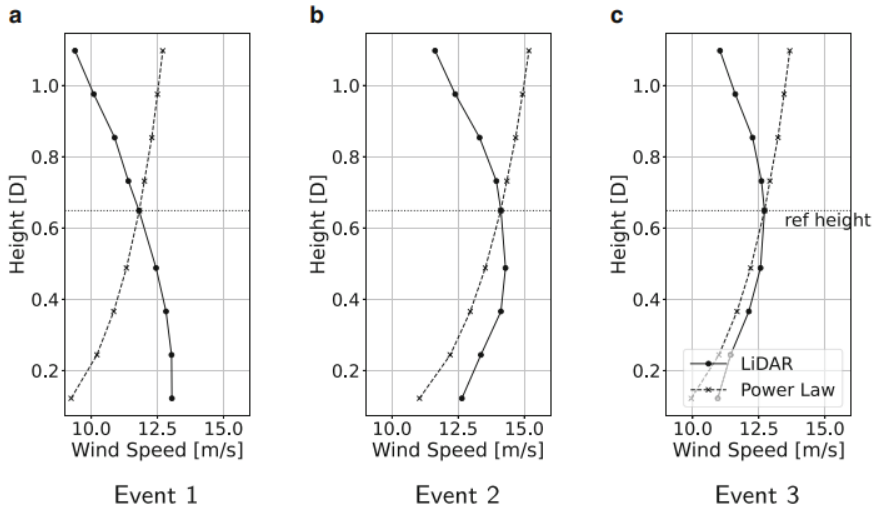


Figure 2 Examples of environmental events detected using the implemented methodology for four different wind turbines in a wind farm. (a) Example of negative shear. (b-c) Example of profiles similar to low level jets (LLJs)

2.3 Detection of farm-wide interactions and events using scanning LiDAR data

A scanning LiDAR campaign has been organized in the scope of cSBO Cloud4Wake. This device can capture line-of-sight wind speeds for distances up to 10km. This means that farm interactions and farm-wide events can be captured using this device, which is not the case with the nacelle LiDAR, which has a range of around 700m (Section 2.2). As this data source is outside the initial scope of this project, we limit the discussion in this document to highlighting its advantages over the nacelle LiDAR:

(a) Better capability to capture the interaction (e.g. wake behaviour) between wind turbines. This is the main scope for the scanning LiDAR campaign in cSBO Cloud4Wake.
(b) Better capability to capture the time evolution of farm-wide events such as wind direction changes (e.g. wind direction change, as indicated in Figure 3).

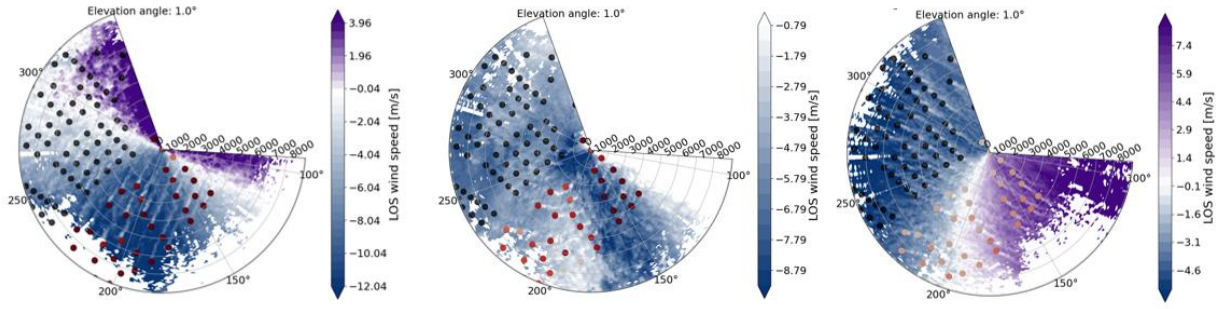


Figure 3 Examples of a wind direction change of 180° captured by the scanning LiDAR data.

3 Load analysis

For the load analysis, an openFAST model is used based on a scaled reference model using available design data of the target turbine [4]. The scaled model is then calibrated based on identified modal behavior and observed operational performance using drivetrain vibration measurements and SCADA data. Herein, the systems eigenfrequencies are obtained using operational modal analysis and stiffnesses and masses within the simulation model are adjusted to tune the model accordingly. A detailed description of the modelling and validation process is found in [4]. The model is a global turbine model with a simplified drivetrain modelled as a two-mass system with a torsional spring and damper. The model uses the ROSCO controller which was tuned based on power, pitch and RPM curves from the SCADA data to ensure similar control behavior. A schematic overview of the simulation model is given in Figure 4 defining inputs and outputs.

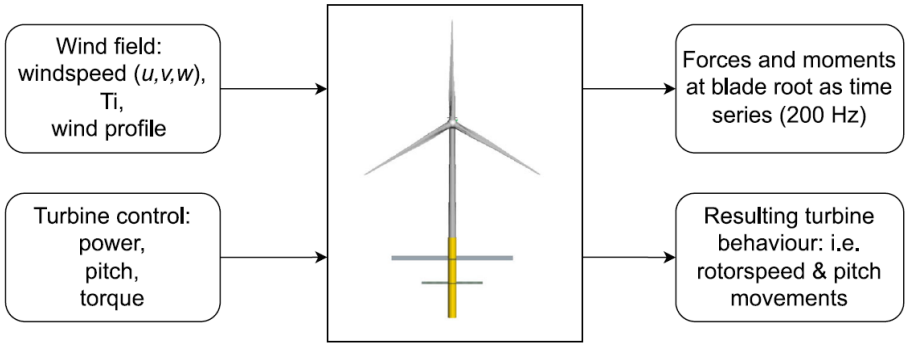


Figure 4: Schematic overview of the inputs and outputs of the wind turbine simulation

3.1 Wind field generation

For simulations in openFAST, the submodule aerodyn is to be provided with a description of the inflow conditions. The wind speed is to be defined in as the wind field (u,*v*,*w*) providing the wind speed in 3 directions for discrete points of a section in front of the turbine as a time series. Such wind fields are generated using TurbSim based on given input values, such as Ti, hub height wind speed, and the shear profile. Within the standards, the turbulence and vertical wind shear profile are defined based on statistical models. The following wind fields are generated:

(a) Profiles complying with the power law, with an imposed hub height wind speed, power law exponent, and turbulence intensity
(b) Profiles not complying with the power law, where LiDAR measurements are directly used to impose the profile across the rotor

3.2 Load assessment

To compare the loading of different inflow and operational conditions, the damage equivalent loads (DEL) is assessed across different datasets. The DEL condenses the complex load histories into a single equivalent load that causes the same amount of fatigue damage as the actual variable loads. To understand the DEL, one has to understand the damage calculation for fatigue damage. This procedure is described for blade root and bearing fatigue damage in [2]. In the following sections, a sensitivity study is

done at these levels depending on the inflow wind field and the (static) control setpoint. The latter will be further investigated during dynamic conditions in D5.5.

3.2.1 Effect of inflow conditions

This section discusses the effect of inflow conditions on blade and pitch bearing loading. First, it is opted to investigate this by assuming inflow conform to the power law. Afterwards, profiles from the LiDAR measurements are applied to investigate the added value of these measurement requiring dedicated equipment.

3.2.1.1 Loading under power law profiles

Figure 5 shows the damage equivalent load at the level of the blade root for different shear exponents (left) and turbulence intensities (right). It can be seen that a maximum is reached around the rated wind speed of the wind turbine (10.5m/s). The shear exponent has little influence on the DEL. At low turbulence levels, a maximum is obtained at the rated wind speeds. For higher TI levels, this becomes more smeared, as there is less time operated at rated wind speed, which is associated with the largest loads.

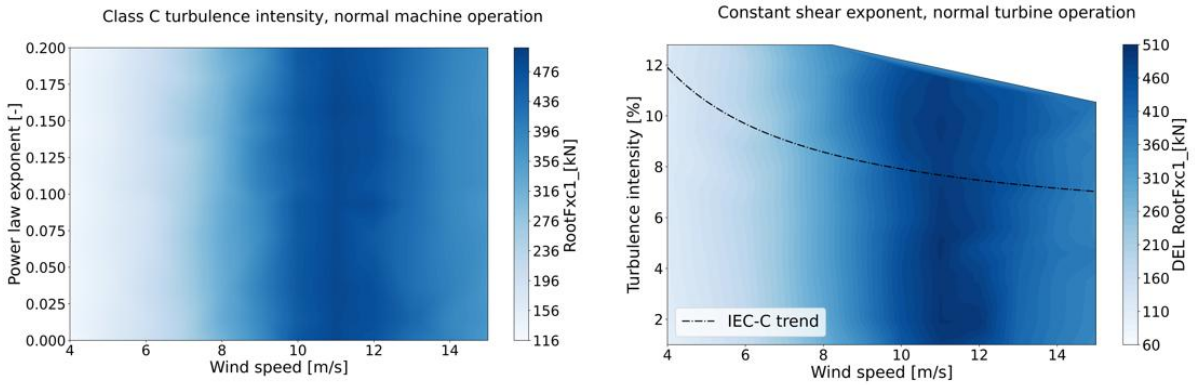


Figure 5: DEL at the level of the blade root for different inflow conditions

3.2.1.2 Loading under profiles not complying to power law (e.g. negative shear, low level jets)

In the previous section, all profiles are simulated according to the power law. In Section 2.2, different profiles have been identified that do not comply with the power law (e.g. negative shear [event a], low-level jets [events b and c]). These profiles are compared with the ones that would be simulated without the availability of LiDAR measurements (hub height wind speed, IEC power law exponent). This is shown in Table 1. It can be seen that for the investigated cases, the difference in DEL is larger at the level of the pitch bearing, showing that this component might be more sensitive at the proper definition of the inflow profile. The difference is nevertheless limited for the negative shear event (event A: +0.65%), which is within the variability of the simulations by applying other seeding for the wind field generation.

Larger differences are nevertheless obtained in case profiles similar to low-level jets are applied, reaching values up to 10%, which is well above the variability of the used seeding.

Event	Difference in blade root DEL	Difference in pitch bearing DEL
a	+0.22%	+0.65%
b	+3.18%	+9.96%
c	+2.74%	+5.78%

Table 1: Difference in DEL between the power profile measured by the LiDAR and a power profile

3.2.2 Effect of control actions

Within Section 3.2.2, no external control is applied. This section investigates the effect of performing deration at the level of the wind turbine. Deration is a control action where the maximum power output of a wind turbine is reduced in order to reduce mechanical loading on its components awaiting inspection and/or maintenance. The effect of this setpoint change can be seen in Figure 6. It can be noted that no change is observed at low wind speeds, as no change in control takes place. It can also be noted that the wind speed at which the highest DEL occurs, decreases as a function of the deration setpoint. This is logical, as this is the wind speed at which the turbine starts pitching, which indeed decreases at lower setpoints. Above this wind speed, it can nevertheless be seen that the deration action is able to reduce the mechanical loading.

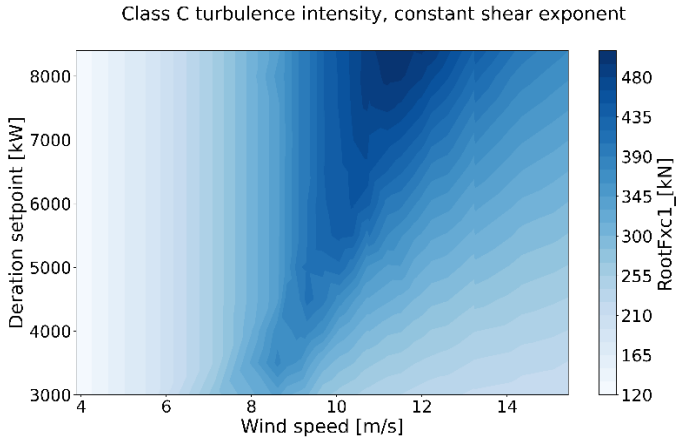


Figure 6: DEL at the level of the blade root for different control setpoints

4 Conclusions

This document has discussed the analysis of wind events and their effect on wind turbine loading at the level of different components (pitch bearing, blade root). This has been done in two steps:

a. Detection of events of interest for assessing turbine loading
b. Simulation of representative events based on the detection performed in step (a)

This document mainly focuses on discussing the key results. For more extensive discussions on the used methodology, supporting publications can be found in Section 5.

5 References and dissemination

Publications

[1] Daems Pieter-Jan, 2024. Automated assessment of wind turbine loading and dynamics using SCADA and vibration data, Vrije Universiteit Brussel

[2] Gebel, Jakob, et al. "Wind turbine blade root and blade bearing fatigue damage estimation based on field data." *Forschung im Ingenieurwesen* 89.1 (2025): 16.

[3] Marini, Rebeca, et al. "Assessing the impact of wind profiles at offshore wind farm sites for field data-enabled design." *Wind Energy Science Discussions* 2025 (2025): 1-32.

[4] Gebel, Jakob, et al. "System identification of offshore wind turbines for model updating and validation using field measurements." *Wind Energy Science Discussions* 2025 (2025): 1-25.

Conferences

Gebel, Jakob "Wind turbine blade root and blade bearing fatigue damage estimation based on field data." *Conference for Wind Turbine Drivetrains (March 11th – 12th 2025), Aachen, Germany*

Gebel, Jakob "Impact of Grid Services on Fatigue Life of Offshore Wind Turbine Components." *Wind Energy Science Conference (June 24th – 27th 2025), Nantes, France*