FLOATING WIND JOINT INDUSTRY PROGRAMME

Power Curve Validation for Floating Offshore Wind Turbines

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Contents

Authors:

Arturo Andersen Chinbuah
Senior Associate, the Carbon Trust
Arturo.andersen@carbontrust.com

Nikolas Angelou
Senior Researcher, DTU

Mathieu Nicolas
Development Engineer, DTU

Luisa Amorim
Manager, the Carbon Trust
luisa.amorim@carbontrust.com

Alan Wai Hou Lio
Associate Professor, DTU

Paula Gómez
Head of Section, DTU

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Introduction

The power performance assessment of a wind turbine generator is performed following the standards published by the International Electrotechnical Commission (IEC). The standards describe the methodology that should be followed, the atmospheric parameters that should be measured, and the corresponding instruments that should be used in the context of power curve verification and validation (PCV).

Key industry stakeholders, including original equipment manufacturers (OEMs), wind energy project developers, wind Light Detection and Ranging (LiDAR) manufacturers, floater designers, and technical advisors, recognize the existence of these standards. However, since this methodology has been developed with a focus on fixed-bottom wind turbines, current standards do not address the challenges encountered when performing a PCV of a floating offshore wind turbine (FOWT). Therefore, there is a need for floating wind specific methodology that will lead to a new standardised practice on how to perform PCV for floating wind turbines.

The Power Curve Validation for Floating Offshore Wind Turbines project was delivered by the Technical University of Denmark (DTU) on behalf of the Floating Wind Joint Industry Programme (Floating Wind JIP). The aim of this project is to enhance the understanding of the processes that have an impact on the power curve validation for FOWT and to identify the methods that can be used as a basis for power curve validation in floating wind turbines.

DTU Technical University of Denmark

Project objectives

1. Determine the key parameters which need to be considered for power curve validation of FOWTs.
2. Propose a wind speed measurement uncertainty assessment for power curve validation.
3. Understand which parameters and wind reconstruction methods should be used as a basis for power curve validation on floating wind turbines.

Methodology

To understand current power curve measurement and validation methods and determine the uncertainties faced by floating offshore wind turbines, as well as model wind measurement scenarios in these assets, the following activities were undertaken.

Literature review and stakeholder engagement

A literature review focused on identifying the state-of-the-art related to power curve validation of FOWTs was conducted. It aimed to determine the key challenges connected to floating wind turbine power curve validation and identify the most suitable technology for inflow wind measurements.

Key stakeholders were engaged to gather feedback on the development methodology needed to achieve power curve validation of FOWTs.

Technology assessment and key assumptions

An uncertainty estimation for nacelle-mounted Light Detection and Ranging (LiDAR) wind speed measurements on an FOWT was performed to provide recommendations on which inflow characteristics and wind turbine motion parameters have the largest impact on the accuracy of wind LiDAR observations. This investigation was performed by modelling the operation of nacelle-mounted wind lidars that were subject to both ideal motions as well as using motion data from the operating Hywind Scotland floating wind farm.

Furthermore, a nacelle LiDAR hub height wind speed estimation for FOWT power curves was conducted using OpenFAST software. This investigation initially focused on the study of the motion of reference FOWT models under various environmental conditions. Subsequently, the nacelle-mounted wind lidar uncertainty model was applied to several test cases, corresponding to different FOWT models and wind lidar types, as well as the range of environmental conditions.

The estimation of the hub-height wind speed of a nacelle-mounted wind LiDAR installed on a FOWT was compared to the one derived by a wind lidar installed on a fixed-bottom wind turbine used as a reference. Deviations between the two are considered a bias, i.e. a systematic error in the estimated hub-height wind speed.

The biases and uncertainties of hub-height wind speed estimations were investigated based on a nacelle-mounted wind LiDAR, assuming:

- A technology-agnostic wind LiDAR that can acquire at least four measurements at two different heights, with two measurements being below the hub height and two above. This setup enables deriving the hub-height wind speed and direction, as well as the shear and veer of the inflow wind.
- That the wind LiDAR can provide observations at an upwind distance equal to 2.5 times rotor diameters.

An assessment of the impact of the motion of a FOWT on the measurements acquired by a nacelle-mounted wind LiDAR was undertaken, with a sensitivity analysis considering three rotational degrees-of-freedom (yaw, pitch, and roll) and using the three translational degrees-of-freedom (heave, sway, and surge) to verify the impact motions.

Aeroelastic model simulation of two wind turbine reference models, NREL 5 MW and IEA 15 MW, using OpenFAST was performed. The response of the two wind turbine reference models on two types of floaters, a spar and semi-submersible was investigated through over 6000 simulations. The variations in these simulations included:

- five different wind turbine and floater configurations, including two turbine types (NREL 5 MW and IEA 15 MW) and three substructures (spar, semi- submersible, in addition to a bottom-fixed structure);
- two wind LiDAR configurations, encompassing pulsed (constant-size probe volume, and continuous wave), and variable probe volume configurations. These were performed to assess and compare different LiDAR setups and their impact on power curve estimation;
- twelve wind and wave conditions covering a spectrum of different offshore conditions, including varying hub-height wind speeds and wave heights;
- six stochastic realisations introducing randomness in atmospheric turbulence and wave dynamics to ensure robust statistical representation of uncertainty;
- three levels of turbulence intensity to investigate the impact of varying turbulence levels or power output fluctuations and floater dynamics;
- three wind shear profiles in order to examine the effects of different vertical wind speed gradients on power output fluctuations.

Key findings

1 Nacelle-mounted wind LiDARs are currently the most suitable wind sensor for the power curve validation of a floating offshore wind turbine.

- Nacelle-mounted wind LiDARs are identified among the commercially available instruments developed to acquire offshore wind measurements as the most suitable option to provide the necessary inflow wind characteristics for a PCV. The line-of-sight measurements captured using this technology can be used to derive multiple metrics, including hub-height wind speed, wind direction, as well as wind shear and veer.
- The suitability of this solution is based on existing:
  - Measurement configuration (at least four lines-of-sight to measure wind speed and direction at varying heights);
  - Operation robustness;
  - Cost in relation to other alternatives.
- The current standard for PCV does not address the key challenges associated with FOWTs:
  - The requirement to acquire measurements at 2.5 rotor diameters in front of wind turbines;
  - The six degrees of freedom (DOFs) motion of the floater, which can greatly affect the accuracy of nacelle-mounted wind LiDAR measurements.
- A new methodology that includes inputs of the motion of a FOWT over six degrees of freedom (three translational: heave, sway, surge, and three rotational motions: roll pitch, and yaw) is required in the wind LiDAR data processing algorithm.
- A wind field reconstruction algorithm is necessary for an accurate estimation of the hub-height wind speed. The wind field reconstruction algorithm should be based on a parametrisation of the wind shear and veer, and consider the motion of the FOWT (pitch, yaw and roll).

2 The pitch motion of a floating wind turbine contributes the most in the bias of the hub height wind speed estimation.

- Among the three rotational motions of an FOWT, the pitch motion induces the largest bias, with its effect being amplified with increasing wind shear. The yaw misalignment could introduce significant biases when large values are observed and should be minimised or revised when performing motion correction. The roll motion contributes to hub-height wind speed bias, particularly when a wind veer is present, but the overall impact remains small.
- Deviations of the hub-height wind speed between a nacelle-mounted wind lidar installed on a FOWT and the one installed on a fixed-bottom wind turbine range from -3.0% to +1.0%. The biases exhibit a wind-speed dependent trend, with the largest underestimation occurring above the rated wind speed range.

- In general, in the case of a nacelle-mounted wind LiDAR installed on the NREL 5 MW wind turbine, similar biases are observed between continuous-wave and pulsed wind LiDARs for all types of wind turbine configurations and environmental conditions. However, in the case of the IEA 15 MW turbine, larger biases for the case of a continuous-wave wind LiDAR were encountered. This is attributed to the long probe lengths that characterise the measurements of continuous wave wind LiDARs, especially in the case where observations at 600 m in front of wind turbines are required.
- Overall, the environmental conditions do not have a significant impact on the biases, except for the IEA 15 MW, where both the shear exponent and the turbulence intensity increase the biases at the above-rated wind speed range.

3 **The motion of a floating wind turbine enhances the uncertainty of the hub-height wind speed estimation using a nacelle-mounted wind LiDAR.**

- Nacelle LiDAR wind speed uncertainties are higher for floating than fixed bottom cases due to the greater number of parameters used to estimate the wind speed. This is amplified by the increase in the magnitude of certain sensitivity coefficients in the uncertainty budget, which identifies key contributors to measurement errors, when motion is present.
- These uncertainties increase as the wind speed at the hub height increases. Pitch motion also increases uncertainty estimates, mostly due to the impact on the sensitivity coefficients.
- The estimated uncertainties of the hub-height wind speed are in general larger for both wind LiDAR configurations examined in the case of FOWT in comparison with a fixed-bottom wind turbine. The main contributor to these uncertainties is the motion of a FOWT. This finding is consistent for all the examined wind conditions, except for when the wind speed ranges around the rated speed. At these wind speeds, the magnitude of the shear exponent and turbulent intensity plays a role in the computed uncertainties, with its effect being more evident in the case of a FOWT with a spar floater.
- Power curve sensitivity to wind speed is higher in the region just below and approaching the rated wind speed, which does not typically coincide with the region of highest LiDAR wind speed uncertainty (closer to rated wind speed).

Industry needs/innovations

1 **Developing motion correction methods is key for nacelle-mounted wind LiDARs.**

- The findings of this project show that there is a need for a motion correction method to be incorporated into a future standardised power curve validation method for FOWT using nacelle-mounted wind LiDARs.
- A motion correction method should include at least the correction of the measurement position and the magnitude of line-of-sight speed of the wind LiDAR using the information on the yaw, pitch and roll angles, as well as a parametrisation of the wind shear.

- This requires a wind LiDAR capable of measuring at a minimum of two heights and motion sensors for collecting yaw, pitch and roll rotations data.
- It is recommended that the measurement of the motion of the nacelle is conducted as close as possible to the nacelle-mounted wind LiDAR to minimize any data collection error.
- Motion sensor performance under various rotations and accelerations should be examined, as sensor measurement uncertainty may vary under different environmental conditions.

2 **Enhanced modelling of floater motion is needed for reliable wind resource estimation.**

- The conclusion and recommendations regarding the hub-height wind speed uncertainty of a wind LiDAR's estimation are influenced by the floater type used, and its motion, as well as by the selected case study - the Hywind Scotland project.
- The research studies that have been performed so far consider a sinusoidal motion around six degrees of freedom. However, this consideration does not necessarily describe realistically the motion of the FOWT. More complex motions need to be implemented in future simulation studies.
- In the simulation study conducted for this project, the focus was on two floater types - semi-submersible and spar. However, given the variability reported in the literature regarding the response of different floater models, a consistent sensitivity analysis study across more floater types is needed.

3 **Additional field campaigns with nacelle-mounted wind LiDARs on FOWT are essential to improve LiDAR performance validation.**

- The magnitude of the bias and the uncertainty of the hub-height wind speed using a nacelle-mounted wind LiDAR are dependent on both the measuring scanning geometry and the amplitude and frequency of the nacelle motion.
- Different floaters exhibit different motions. However, due to the limited published research studies on this field, there is still a need to assess the impact that different floater types have on the measurements of a nacelle-mounted wind LiDAR.
- A measurement campaign is recommended to further verify the accuracy of the simulation code used in this project. This would enable a deeper understanding of how floating wind turbines respond to real-world conditions.

ABOUT THE FLOATING WIND JIP

The Floating Wind Joint Industry Programme (Floating Wind JIP) is a collaborative research and development (R&D) initiative between the Carbon Trust and 17 leading international offshore wind developers: bp, EDF Renouvables, EnBW, Equinor, Kyuden Mirai Energy, Ørsted, Ocean Winds, Parkwind, RWE Renewables, ScottishPower Renewables, Shell, Skyborn Renewables, SSE Renewables, TEPCO, Tohoku Electric Power Company, Total Energies and Vattenfall.

The primary objective of the Floating Wind JIP is to overcome technical challenges and advance opportunities for commercial scale floating wind. Since its formation in 2016, the programme scope has evolved from feasibility studies to specific challenges focusing on:

- Large scale deployment
- De-risking technology challenges
- Identifying innovative solutions
- Cost reduction

Stage 3 of the Floating Wind JIP commenced in 2022 and projects are expected to run until early 2027. With several commercial scale floating offshore wind farm projects in design phase and having the ambition to be commissioned by 2030, the industry needs to address several challenges. The 17 Floating Wind JIP partners agreed on six research areas where further understanding and advancement is required to reach full commercialisation of floating offshore wind projects.

Electrical systems	Mooring systems	Logistics	Windfarm optimisation	Foundations	Asset Integrity and monitoring

This Power Curve Validation for Floating Offshore Wind Turbines project addresses the ambitions of the windfarm optimisation research area:

Windfarm optimisation

1	Assess technology developments such as ballast, sizing and cost to support, with both floater and tower developments.
2	Understand floating specific windfarm layout and turbine specific developments to maximise yield.
3	Define floating specific controllers and modifications required in context to floating specific turbines.

The Stage 2 summary reports can be found here: Phase I, Phase II, Phase III, Phase IV and Phase V.

ABOUT THE CARBON TRUST

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Our mission is to accelerate the move to a decarbonised future. We are your expert guide to turn your climate ambition into impact.

We have been climate pioneers for more than 20 years, partnering with leading businesses, governments and financial institutions to drive positive climate action. To date, our 400 experts globally have helped set 200+ science-based targets and guided 3,000+ organisations and cities across five continents on their route to Net Zero.

carbontrust.com

+44 (0) 20 7170 7000

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