C2Wind

Wind farm turbulence at FINO1met mast

Park Siting tool Validation and capabilities overview

REPORT

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Document information and change log.

Revision	Date	Status / Reason for Issue	Author	Checker
0	2024-10-10	Issued for internal review	DIB/RGA	JOG
1	2024-10-28	First revision, including validation at FINO1	RGA	CBM

Section	Summary of Changes (latest revision only)

Changes made in the most recent revision, are marked with yellow highlighting. For figures and tables, this means that the first part of the caption, i.e. the word "Figure" or "Table", has been highlighted.

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Table of Contents

1. Introduction

This document provides an overview of **C2Wind Park Siting Tool,** C2Wind's wind farm turbulence calculation tool, and its validation against the FINO1 met mast data [FINO1] at the Alpha Ventus offshore wind farm in the German Bight.

The tool has been developed by C2Wind and has been validated using in-situ measurements at several locations already: see the Horns Rev 2 and Burbo Bank 1 cases in [CBMEWEA]. In the present document, additional validation cases are provided using the FINO1 met mast at the Alpha Ventus wind farm.

Figure 1-1: picture of the FINO1 met mast and the nearby The Alpha Ventus wind farm (© Fraunhofer IWES)

1.1 Understanding Turbulence Dynamics

As wind flows through the turbines, each rotor extracts energy from the wind, creating regions of lower wind speed and increased turbulence behind the turbines. This phenomenon, known as wake turbulence, not only affects downstream turbines but can also lead to increased mechanical stress, reduced turbine lifespan, and overall lower energy yields.

Turbulence generated within wind farms can propagate for several kilometres downwind, significantly influencing wind resource availability. The intensity and spatial distribution of these wake effects are influenced by several factors, including turbine layout, wind direction, and atmospheric conditions. In densely packed wind farms, the accumulated turbulence can reduce the effectiveness of downstream turbines significantly and impact the support structure design and WTG Rotor Nacelle Assemble durability.

Incorporating correct turbulences into the design phase of a wind farm is essential for optimizing turbine placement and improving long-term performance. The **C2Wind Park Siting Tool** overcomes this challenge and provides accurate wind farm turbulence and has been deployed for detailed design analysis for tens of projects worldwide.

1.2 C2Wind Park Siting Tool

The **C2Wind Park Siting Tool** (PST) is a software developed by C2Wind ApS and has been certified by DNV. The tool uses the wake turbulence theoretical and empirical framework from S. Frandsen [R1188], with adaptations leading to more accurate and lower turbulence values than otherwise derived through the methodology outlined in Annex E of the current IEC 61400-1 standard [IEC614]. The tool is fully documented in [PST].

The **C2Wind Park Siting Tool** is a software designed to optimize wind farm layout and performance, leveraging C2Wind's extensive experience in wind energy. Whether for offshore or onshore projects, the tool enables developers and engineers to maximize energy output while minimizing costs due to turbulence-induced loads. By offering a comprehensive analysis of wind conditions, turbine interactions, and site-specific factors, the **C2Wind Park Siting Tool** streamlines the design process and supports the development of high-performance, cost-efficient wind farms.

The tool provides:

- **Optimized Wind Farm Layouts for Maximum Energy Yield**
  *The **C2Wind Park Siting Tool** uses advanced algorithms to design wind farm layouts that minimize wake losses and turbulence impacts, ensuring optimal turbine placement for maximized energy production and efficiency.*

- **Customizable Site-Specific Analysis**
  Tailored to the unique characteristics of each wind farm and neighbouring site, the tool integrates wind data, turbine characteristics and environmental conditions, allowing for fully customized analysis that reflect the local conditions and constraints.

- **Seamless Integration of Turbine Models**
  *Easy application of various wind turbine models, the **C2Wind Park Siting Tool** ensures accurate simulation of turbine performance, including interaction effects between turbines, to refine placement decisions.*

- **Comprehensive Turbulence and Wake Studies**
  In-depth turbulence and wake effect analysis helps identify areas of potential load effect issues and fatigue damage, enabling informed design choices that improve the operational lifespan of the wind farm.

- **Cost-Effective Design Solutions**
  By balancing energy yield with operational costs, the tool supports developers in finding economically efficient solutions. It helps reduce CAPEX by providing optimized layouts that minimize cabling and foundation costs.

- **Time-Saving and User-Friendly Interface**
  Designed for efficiency, the intuitive user interface allows developers and engineers to quickly input data, run simulations, and export results. This reduces the time and complexity involved in wind farm planning.

- **Proven Performance in Offshore and Onshore Projects**
  Backed by C2Wind's deep expertise in wind farm design, the ***C2Wind Park Siting Tool*** *has been successfully used in an impressive list of both offshore and onshore wind projects, demonstrating its versatility and reliability in various conditions.*

- **Future-Proof Design with Continuous Updates**
  C2Wind ensures that the tool is updated with the latest industry standards, turbine models, and technological advancements, providing a future-proof solution that evolves alongside the market.

2. Validation at FINO1

A validation of PST's wind turbine wake turbulence intensity model results against in-situ measurements at the FINO1 met mast are provided in this Section. Data from the time period 2015-02-01 to 2018-06-01 have been considered, this corresponds to the period where only the nearby Alpha Ventus wind farm was operating.

2.1 Alpha Ventus Offshore Wind Farm – Overview

The Alpha Ventus offshore wind farm, located approximately 45 km north of the island of Borkum in the German North Sea, is the country's first offshore wind farm and a critical milestone in offshore wind development. It comprises 12 wind turbines, split equally between two models: the REpower 5M and the Multibrid M5000. These turbines are mounted on jacket foundations, where water depths reach approximately 30 meters. Together, these turbines contribute to Alpha Ventus' total capacity of 60 MW.

- The REpower 5M turbines have a rated capacity of 5 MW each and are characterized by their three-bladed, upwind rotor design with a rotor diameter of 126 meters. The hub height is 92 mMSL.

- Similarly, the Multibrid M5000 turbines, also rated at 5 MW, feature a compact, gearless design. The turbine has a rotor diameter of 116 meter. The hub height is 90 mMSL.

The FINO1 met mast is located in the German North Sea, next to the Alpha Ventus offshore wind farm and in the Borkum wind farm cluster; see Figure 2-1.

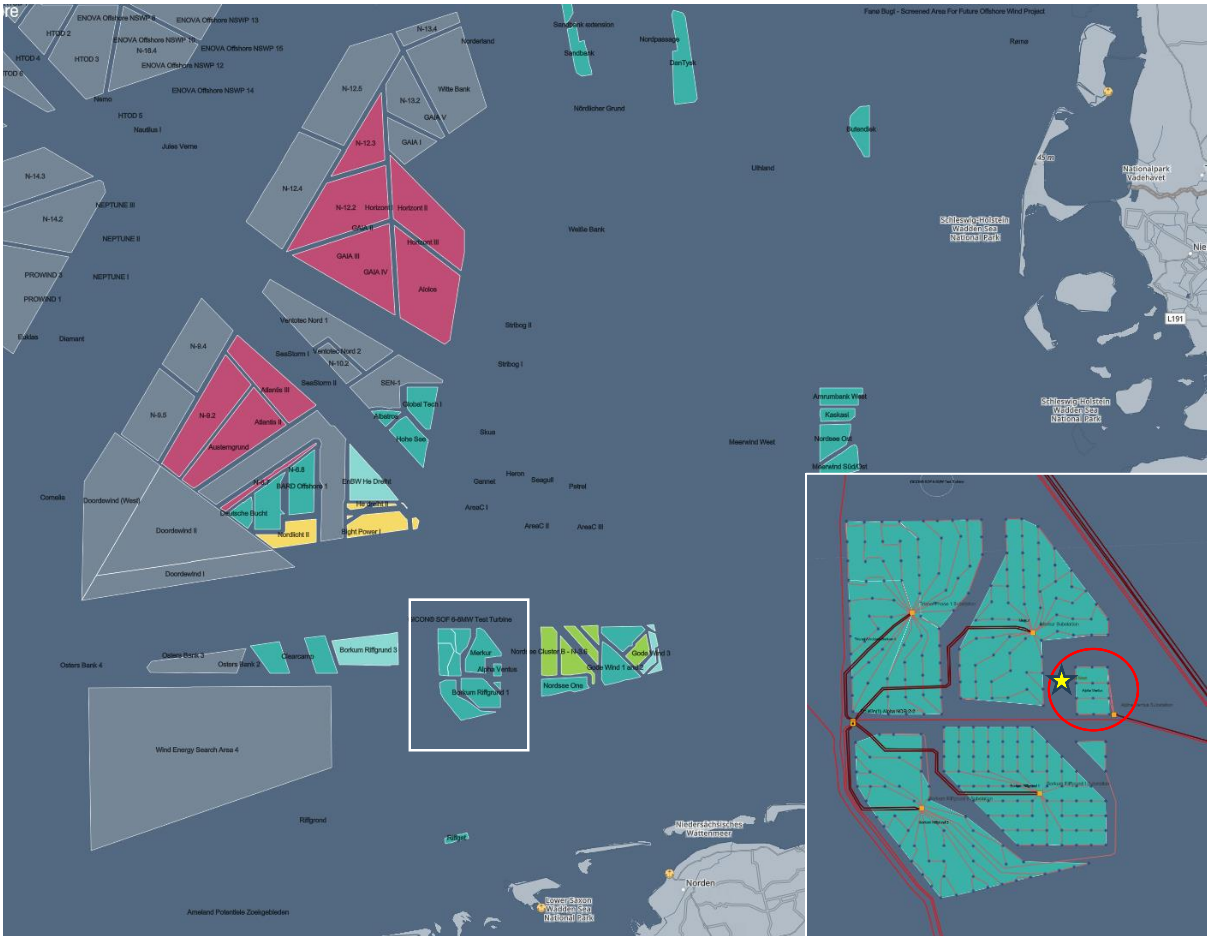

Figure 2-1: Location on the FINO1 met mast (yellow star) in the Borkum cluster in the German North Sea. The Alpha Ventus is marked with a red circle.

The Alpha Ventus (AV)- and Merkur turbines are located in close vicinity of the FINO1 mast. In this study, only the period 2015-02-01 to 2018-06-01, where AV is operating, have been considered. The Merkur wind farm was operational during summer 2019. Hence only the wake of AV is considered in the following.

For the period analysed the FINO1 mast is located in the close vicinity to operational AV wind farm and provides turbulence wake situations in the range of 3.3 to 14.6 rotor diameters, see Figure 2-2.

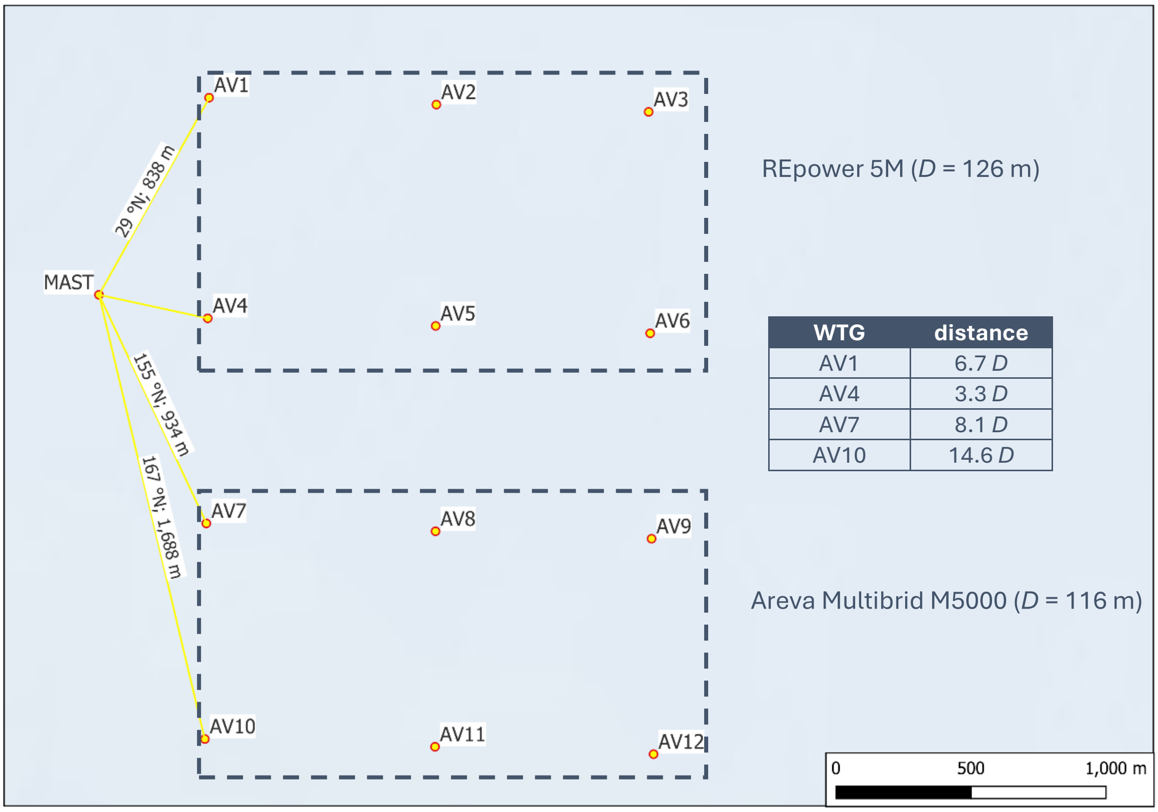

Figure 2-2: Locations of the nearest wind turbines to the met mast, with headings and distances from FINO1 to the turbines.

Thrust curves for the AV turbines have been obtained from the WindPRO software wind turbine catalogue.

2.2 FINO1 - Turbulence Intensity Validation

Beside regular data processing sanity checks, to make sure that situations where the AV turbines are out of operation are filtered out, the following criterion has been applied:

$$WS_{102\text{mMSL}}(t) < 1.05 \cdot WS_{41\text{mMSL}}(t) \quad \text{Eq. 2-1}$$

With:

$WS_{102\text{mMSL}}$ The wind speed measured at the top of the FINO1 mast.
$WS_{41\text{mMSL}}$ The wind speed measured at 41 mMSL.

For determining the freestream wind speed, an ERA5 100 mMSL time series interpolated at the mast location has been used. This is considered acceptable for the purpose of the analysis (obtaining three wind speed intervals), given the known accuracy of this model time series at this location (see [SPANGEHL23]).

Free stream turbulence intensity (mean and standard deviation, for each wind speed bin) has been derived for every 12 wind directional bins using the top sensor measurements using the time period prior to the start of operation of AV. A filtering of the FINO1 data has been undertaken and records having operational upstream turbines is considered.

Results are provided in Figure 2-3, Figure 2-4 and Figure 2-5 for three different wind speed bins. The figures show the measured mean and median turbulence intensity as a function of wind direction and for the wind sensor the closest to hub height at the FINO1 mast, as well as the modelled turbulence intensity (constant with elevation). Because the modelled turbulence intensity depends on the thrust coefficient, which itself depends on the wind speed, both the minimum and maximum modelled values are provided.

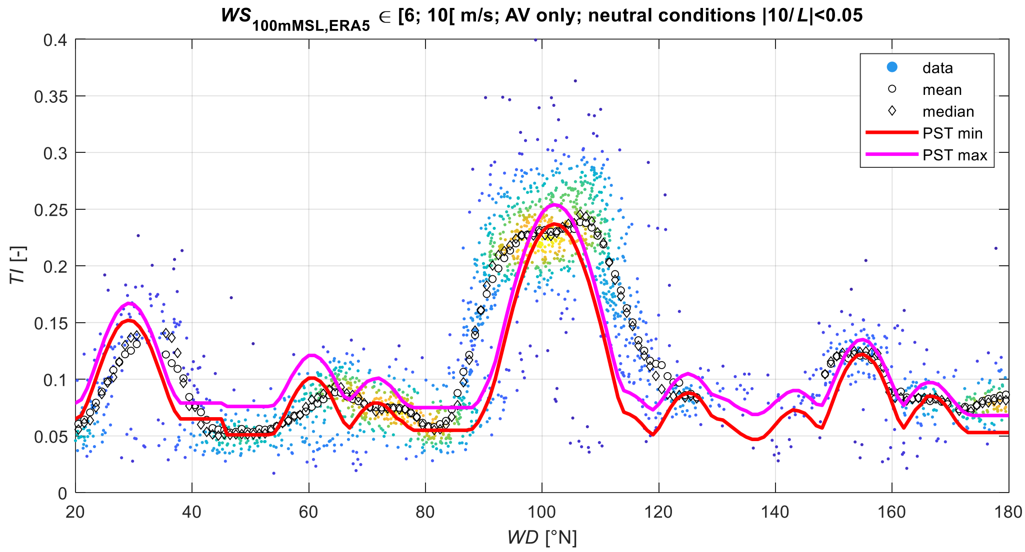

Figure 2-3: Comparison between measured- and modelled turbulence intensities at AV, for the near hub height wind speed bin [6; 10[m/s.

These results show a very good match between the modelled and measured data for the wind sensor the closest to hub height (102 mMSL), for the first wind speed bin. For larger wind speeds, the **C2Wind Park Siting Tool** provides slightly conservative results - however the distance to the FINO1 mast is 3.3 rotor diameters, where near wake situation is present.

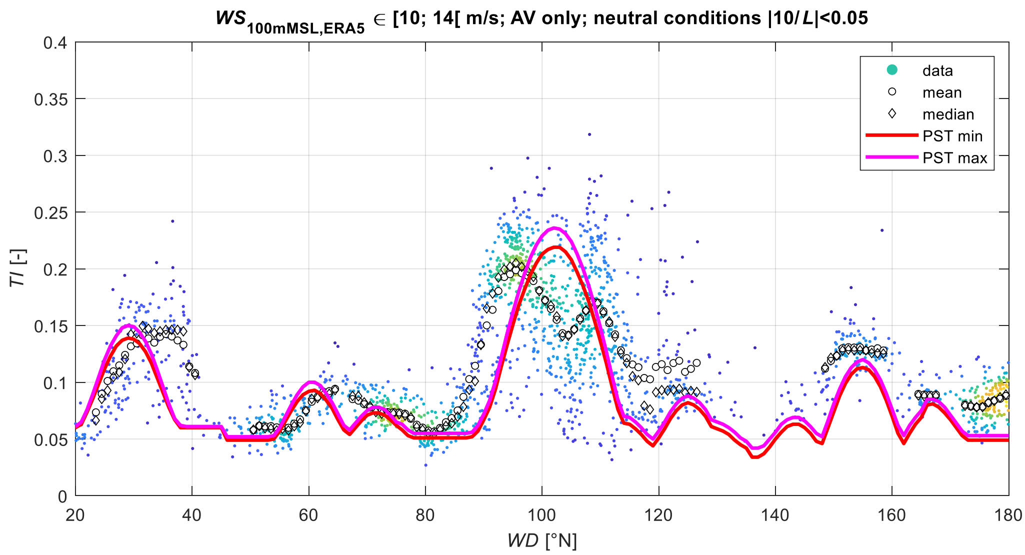

Figure 2-4: Comparison between measured- and modelled turbulence intensities at AV, for the near hub height wind speed bin [10; 14[m/s.

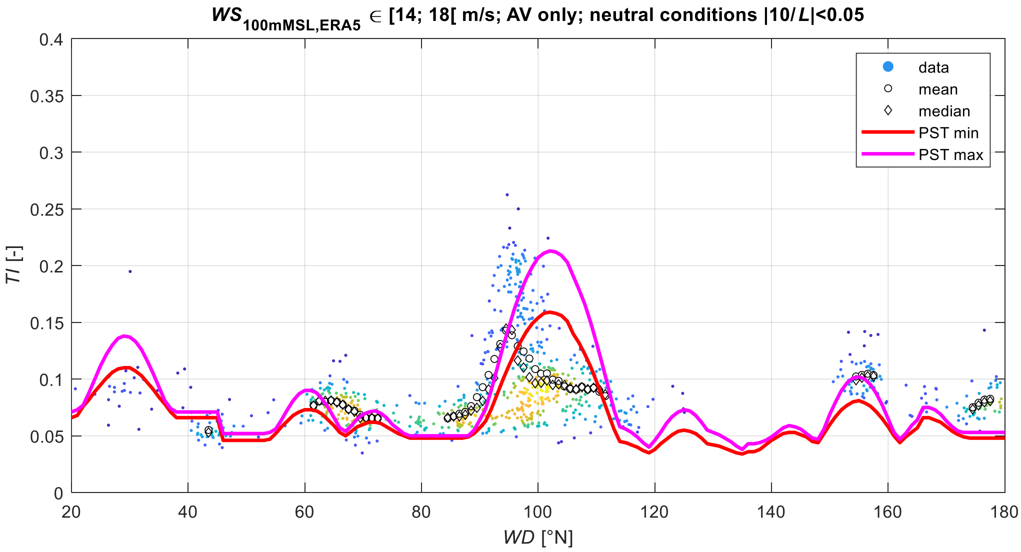

Figure 2-5: Comparison between measured- and modelled turbulence intensities at AV, for the near hub height wind speed bin [14; 18[m/s.

3. References

[CBMEWEA] **Mørch C.B.**
Turbulence Workshop, EWEA Offshore 11th March 2015.
(2015-03-11).

[FINO1] **BSH.**
FINO – Database information – Research platforms in the North Sea and Baltic Sea.
Link to database:
https://www.bsh.de/EN/TOPICS/Monitoring_systems/MARNET_monitoring_network/FINO/fino_node.html
Link to FINO1 metadata:
https://www.bsh.de/DE/THEMEN/Beobachtungssysteme/MessnetzMARNET/FINO/_Anlagen/Downloads/FINO1_metadata.pdf?__blob=publicationFile&v=3
Link to FINO3 metadata:
https://www.bsh.de/DE/THEMEN/Beobachtungssysteme/MessnetzMARNET/FINO/_Anlagen/Downloads/FINO3_metadata.pdf?__blob=publicationFile&v=3

[IEC614] **IEC.**
IEC-61400-1: Wind energy generation systems – Part 1: Design Requirements. Ed. 4.0. International Electrotechnical Commission. (2019).

[PST] **C2Wind.**
C2Wind Park Siting Tool. Methods and application manual. Doc. no. 17004-2-6. (2020-08-18).

[R1188] **Frandsen S.T.**
Turbulence and turbulence-generated structural loading in wind turbine clusters. Risø-R-1188(EN) (2003-06).
Link: https://backend.orbit.dtu.dk/ws/portalfiles/portal/12674798/ris_r_1188.pdf

[SPANGEHL23] **Spangehl, T., Borsche, M., Niermann, D., Kaspar, F., Schimanke, S., Brienen, S., Möller, T., and Brast, M**
Intercomparing the quality of recent reanalyses for offshore wind farm planning in Germany's exclusive economic zone of the North Sea, Adv. Sci. Res., 20, 109–128, https://doi.org/10.5194/asr-20-109-2023 2023.