REPORT

Energinet Eltransmission A/S

Thor Offshore Wind Farm

Description of measurement datasets

19009-3

Revision	Date	Description	Author	QC
0	2020-08-29	Issued for internal QA	RGA	ASM
1	2020-12-26	Issued for Client	RGA	ASM

Summary of Changes

Revision	Section	Changes
1	All	Issued for Client

Table of Contents

1. Introduction

This document has been produced by C2Wind for Energinet Eltransmission A/S (Energinet), the Danish national transmission system operator for electricity and natural gas. This report provides a high-level description of three wind measurements datasets available to participants (the bidders) to the Thor Offshore Wind Farm (Thor) tender[1].

The names and locations of the three datasets are provided in Figure 1-1 and Table 1-1. The present report focuses, for each dataset, on the documenting the following:

- Location and context of the campaign.
- Instrumentation setup.
- Data files and contents of the dataset.
- Data quality and -validity.

This report does so mainly through references to the relevant documentation, provided to the bidders together with the datasets.

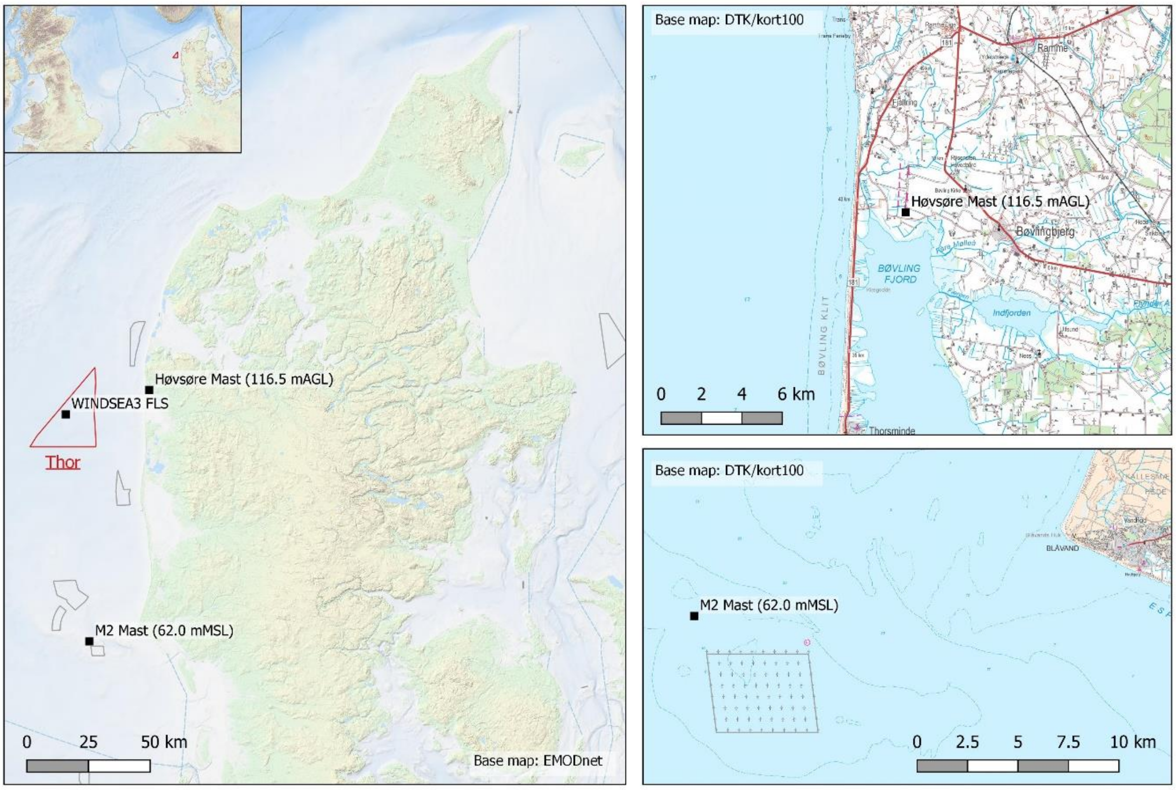

Figure 1-1: This map shows the locations of the three measurement datasets described in this report.

[1] See www.ens.dk/thor.

Dataset	Location (lat., lon.) {°N; °E} WGS84	Provider (Producer)	Time period
M2 met mast	{55.520; 7.787}	Energinet (Vattenfall)	1999-05-14 to 2007-15-13
Høvsøre met mast	{56.441; 8.151}	Energinet (DTU Wind Energy)	2004-05-31 to 2019-05-31
WINDSEA3 Floating LiDAR System	{56.347; 7.605}	Energinet (AKROCEAN)	From 2020-05-19 (on-going campaign)

Table 1-1: Source: Section 1.1 of [TW1], page 1 of [DTU1], page 15 of [AK1]. Regarding the latter, please note that page 15 of [AK1] erroneously lists the location as {56°20'800''N; 7°36'300''E} instead of the correct {56°20.800'; 7°36.300'} stated in earlier revisions of [TW1] and which corresponds much better with the GPS contents of [DATA] pertaining to the Floating LiDAR System's deployment at the site.

Regarding data quality and validity: it is beyond the scope of this document to carry out an extensive analysis[2], and this topic is dealt with only with two sub-items:

- "*Quality*" refers to the measurement sensor functioning according to its specifications or not. For instance, the subset of the cup anemometer signal at the bottom row of Figure 3-2 is of poor quality.
- "*Validity*" refers to the applicability of the signal for a given use of the data. Typically, validity is assessed by referring to international standards- and/or good practices documents.

At the same time, this report aims at providing the data users with most (if not all) of the information- and references needed to carry out such extensive analyses by themselves, and eventually quantify the uncertainty of the measurements. It can then be considered as a starting point and an introduction to further, more advanced, studies.

[2] Typically carried out by accessing a dataset's "Data Quality Dimensions": see for instance the Data Management Association (DAMA) International Guide to Data Management Body of Knowledge (DAMA DMBOK), https://www.dama.org/cpages/body-of-knowledge.

2. References

[AK1]	**AKROCEAN.** ENERGINET_021_Data Delivery Notice. Floating LiDAR Measurements - Thor Offshore Wind Farm. Version 3 (2020-09-15).
[COURTNEY14]	**Courtney M., Nygaard N. G.** The long term stability of lidar calibrations**.** DTU Wind Energy E-0033 (2014-01). Link: https://orbit.dtu.dk/en/publications/the-long-term-stability-of-lidar-calibrations.
[DATA]	**Energinet.** As part of the "Preliminary investigations" deliverables listed on the Danish Energy Agency (Energistyrelsen, ENS) website at https://ens.dk/thor, a number of datasets have been/will be provided to the bidders. The datasets are available on an FTP server, see details at the link above. When relevant, the present document makes references to specific subfolders and documents located on this FTP. Please note that, at the time of writing, the exact locations (paths) of these subfolders- and files are not known at the time of writing the present document; yet, these should be easily locatable as they all lie in three, main folders: "Mast_M2", "Mast_Høvsøre" and "FLS_WINDSEA3".
[DE1]	**DONG Energy**. Possible errors in wind data from Meteorological Masts M2 and M8 on Horns Rev. DONG Energy, Doc. no. 1963025A (2014-08-21).
[DE2]	**DONG Energy**. Resolution of M2 and M8 dataset calibration issues. DONG Energy, Doc. no. 1984701A (2014-09-15).
[DHIMO]	**DHI.** Thor Offshore Wind Farm – Metocean Hindcast Data and Validation Report. Project number 11824164. The newest revision should be used (at the time of writing, the current revision is: Final 2.0 (2020-11-19)).
[DNVGL]	**DNV GL – Energy.** Verification of the WINDSEA 3 Floating LiDAR at the LEG offshore platform. AKROCEAN. Document no. L2C197506-UKBR-R-01-C (2020-10-05).
[DTU1]	**DTU Wind Energy.** Report concerning delivering of wind resource data from Høvsøre. Ref: Quotation Doc. nr. 19/1034560. Submit to: Energinet Eltransmission A/S (2019-11-19).
[DTU2]	**DTU Wind Energy.** Calibration of ground-based lidar instrument: WLS866-26. Østerild Test Site. Doc no. DTU Wind Energy LC I-167 (EN) (2020-03).
[ED]	**ED Service-Center.** ED Service-Center has provided a log of the calibration certificates- and serial numbers of the top anemometer, in the file "*Coefficient tabel M2.xlsx*", located in the folder \Mast_M2\Meta_data\Calibration_certificates of the data package [DATA].
[IEC611]	**IEC.** IEC 61400-1: Wind energy generation systems – Part 1: Design Requirements. Edition 4.0. International Electrotechnical Commission (2019-02).
[IEC6112]	**IEC.** IEC 61400-12-1: Wind energy generation systems – Part 12-1: Power performance measurements of electricity producing wind turbines. Edition 2.0 (2017-03-03).
[KSH01]	**Hansen K. S.** Horns Rev – site documentation. Database on Wind Characteristics - Site and measurement description for Horns Rev measurements (2001-05-30). Source: http://130.226.56.150/extra/web_docs/hornsrev/description.pdf

[MDR]	**ENS.** Master data register for wind turbines at end of June 2020. Link: https://ens.dk/en/our-services/statistics-data-key-figures-and-energy-maps/overview-energy-sector
[OWARMv2]	**Carbon Trust.** Carbon Trust Offshore Wind Accelerator Roadmap for the Commercial Acceptance of floating LiDAR Technology. Version 2.0 (2018-10). Link: https://www.carbontrust.com/resources/roadmap-for-commercial-acceptance-of-floating-lidar
[PEÑA16]	**Peña A. D., Floors R. R., Sathe A., Gryning S.-E., Wagner R., Courtney M., Larsén X. G., Hahmann A. N.; Hasager C. B.** Ten Years of Boundary-Layer and Wind-Power Meteorology at Høvsøre, Denmark. Boundary-Layer Meteorology (2016) Link: https://orbit.dtu.dk/en/publications/ten-years-of-boundary-layer-and-wind-power-meteorology-at-h%C3%B8vs%C3%B8re
[POLLAK]	**Pollak D. A.** Characterization of Ambient Offshore Turbulence Intensity from Analysis of Nine Offshore Meteorological Masts in Northern Europe. DTU Wind Energy Master Thesis M-0056. EWEM/DTU/UO (2014-08-03).
[R1506]	**Hasager C. B.; Peña A., Mikkelsen T. K., Courtney M., Antoniou I., Gryning S.-E., Hansen P., Sørensen P. B.** 12MW Horns Rev experiment. Risø-R-1506(EN) (2007-10). Link: https://orbit.dtu.dk/en/publications/12mw-horns-rev-experiment
[SN00]	**Neckelmann S., Petersen[3] (sic) J.** Evaluation of the Stand-alone wind and wave measurement systems for the Horns Rev 150 MW offshore wind farm in Denmark. European seminar on Offshore wind energy in Mediterranean and other European seas, Syracuse (2000-04). Link: http://130.226.56.150/extra/web_docs/hornsrev/n227sne.pdf For additional information, see: http://www.gbv.de/dms/tib-ub-hannover/373121040.pdf
[TW1]	**Tech-Wise.** Wind Resources at Horns Rev. Report no. D-160949. Project no.: 11746.01.06 (2002-12). Link: https://www.yumpu.com/en/document/read/4469663/wind-resources-at-horns-rev
[TW2]	**Tech-Wise.** Eltra PSO 2001/no. 3192 – Measurements at the Horns Rev Offshore Wind Farm – Establishment of Meteorology Measuring Stations in the Horns Rev Wind Farm. Report. no. 02-839 (2002-05-30).

[3] This is likely a typo, and should probably read “Pedersen”.

3. Description of the datasets

3.1 M2 met mast

3.1.1 Location and context

The M2 met mast started its meteorological measurements in mid-May 1999 (see page 2 of [SN00]), as part of the project Eltra PSO-2001 no. 3192 (see [TW2]). The mast location is provided in Table 1-1. Since the 29th of July 2002, the Horns Rev 1 Offshore Wind Farm has been operating to the South-East of the mast, see Figure 3-1. Coordinates for the wind turbines, and their commissioning dates, can be found in [MDR].

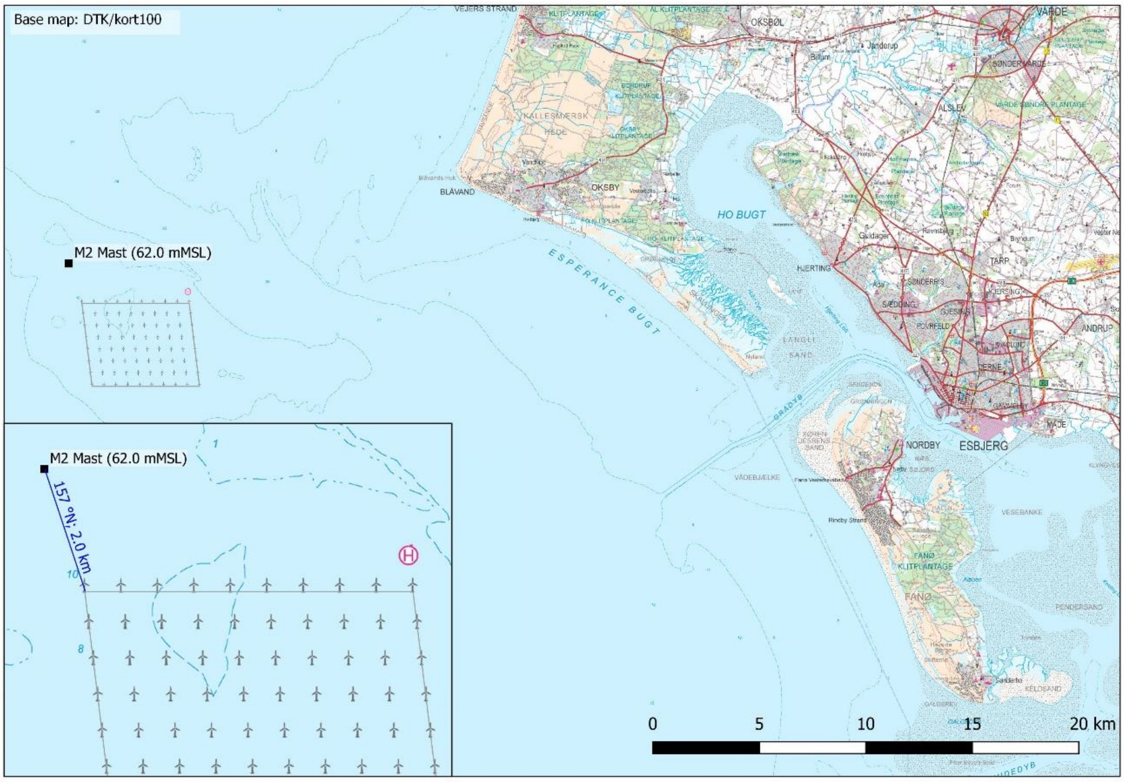

Figure 3-1: This map shows the location of the M2 met mast, off the city of Esbjerg in Denmark. The Horns Rev 1 Offshore Wind Farm, located approximately 2 km to the South-East of the mast, has been in operation since 2002-07-29 (first power, according to [MDR]).

3.1.2 Instrumentation setup

The instrument setup is described in the following documents: [NS00], [KSH01], and [TW1]. A list of the cup anemometers serial numbers, and their calibration certificates, can be found in [ED].

3.1.3 Data files and contents of the dataset

The data are provided in the binary MATLAB file “M2Corrected.mat” provided in the folder Mast_M2\ Data_file\ of [DATA]. This file consists of:

- M2dataCo: a data array with 406112 rows and 92 columns:
  - The 406112 correspond to the number of recorded 10-minute timestamps.
  - The 92 columns correspond to the 92 signal types.
- M2header: a cell which provides the name of the 92 signals:

- DT2 is the timestamp (in numerical format[4]).
- See a description of the headers in the file "Coefficient tabel M2.xlsx" of [ED]. The signals are named following the Kraftwerk-Kennzeichensystem[5] (KKS). For each signal, the subscript of the headers {A01; A02; A03; A04; A05} correspond to {Quality Code; Mean; Maximum; Minimum; Standard Deviation; 5-s Gust[6]}. The Quality Codes are given in Table 1.1 of [TW1].

Please note that the uncorrected data are also provided, in a csv-file zipped into a file called "M2.zip"; this file was kindly supplied by Vattenfall Vindkraft A/S, and was the file which C2Wind used – together with [DE1] and [DE2] – to produce the file "M2Corrected.mat". Thus, one may see exactly what has been changed by C2Wind in "M2Corrected.mat" through comparing its contents with those of "M2.zip".

3.1.4 Data quality and validity

The M2 dataset is generally of good quality, in the sense that the sensors have functioned well during the vast majority of the recorded timestamps. Yet, as illustrated in Figure 3-2, and as it is often the case with cup anemometry datasets, a careful and thorough analysis of the data need to be carried out by the user in order to remove faulty measurements.

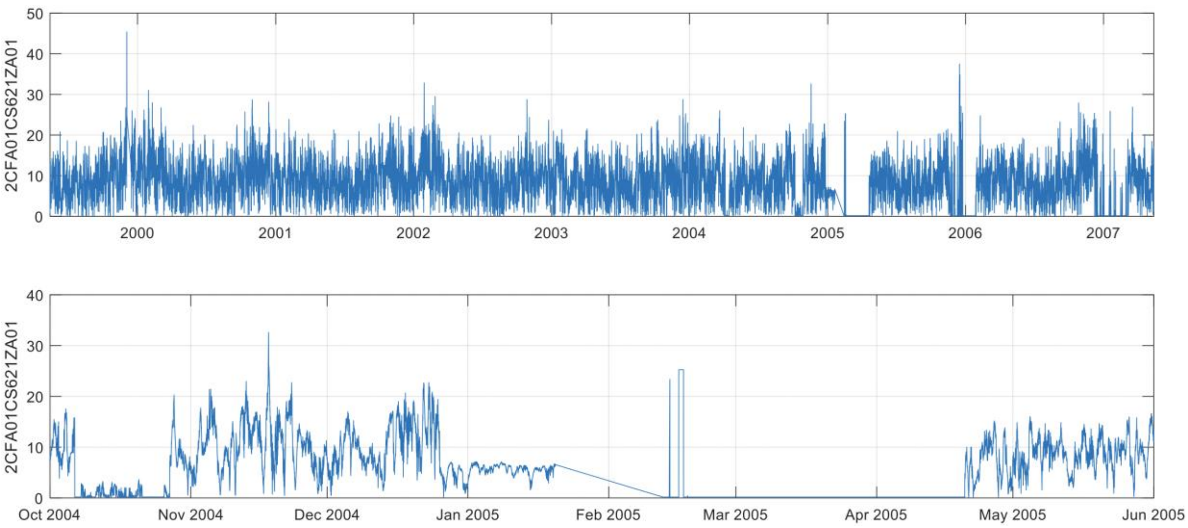

Figure 3-2: This figure displays, in the top row, the entire timeseries of the signal 2CFA01CS621ZA01, which is the mean wind speed of the cup anemometer mounted at 62 mMSL. A subset of the same timeseries is shown on the second row. As it is often the case with cup anemometry datasets, a careful and thorough analysis of the data need be carried out by the data user.

The influence of the neighbouring wind farm (see Section 3.1.1) and of the mast structure on the cup anemometer measurements needs to be assessed and accounted for; see the above-mentioned documentation, as well as Section 2.2.1 of [R1506].

In the summer of 2014, it was discovered that the masts M2 (at Horns Rev 1) and M8 (at Horns Rev 2 and not discussed in this report), exhibited remarkably different turbulence

[4] See a description of the numerical date format here: https://se.mathworks.com/help/matlab/ref/datenum.html.

[5] See https://de.wikipedia.org/wiki/Kraftwerk-Kennzeichensystem.

[6] Please note that [TW1] and [SN00] state 5-s gusts, while Section 5.2 of [TW2] states 3-s gusts; C2Wind could not establish what is correct.

intensity measurements compared with those of seven other offshore masts across Northern Europe; see e.g. Figures 4.5, 4.16 and 4.17 of [POLLAK][7]. This spurred an investigation at DONG Energy, which concluded that the cause of the misleading measurements was wrongly applied calibration constants (mostly for the met mast M8), and an error in the method used in calculating wind speed standard deviation. These discoveries are documented in [DE1], and their resolution is documented in [DE2]. As noted in Section 3.1.3, these resolutions have been implemented by C2Wind in the M2 dataset provided in the file M2Corrected.mat of [DATA], while the file M2.zip has not been corrected.

[7] Note: this work is currently not publicly available. Yet, please see Slide 21 of the following presentation for a summary of the findings on mean turbulence intensity conditions: http://www.pcwg.org/proceedings/2014-10-06/06-Turbulence-Intensity-measmnts-offshore-4-PC-verification-wind-res-assmt-R-RiveraLamatA-D-Pollack-Dong.pptx.

3.2 Høvsøre met mast measurements

3.2.1 Location and context

The Høvsøre met mast has been operational since 2004, and is installed to the South of the Southernmost wind turbine test stand at the DTU Wind Energy Test Centre Høvsøre. The mast is located close to the Northern shore of the Bøvling Fjord, see Figure 3-3. It has been operated and maintained since then by DTU Wind Energy, and its measurements have served as input to consultancy- and research works, see [PEÑA16]. Since 2012, the mast instrumentation has formed part of an accredited procedure for validating ground-based- and nacelle LiDARs; see [COURTNEY14].

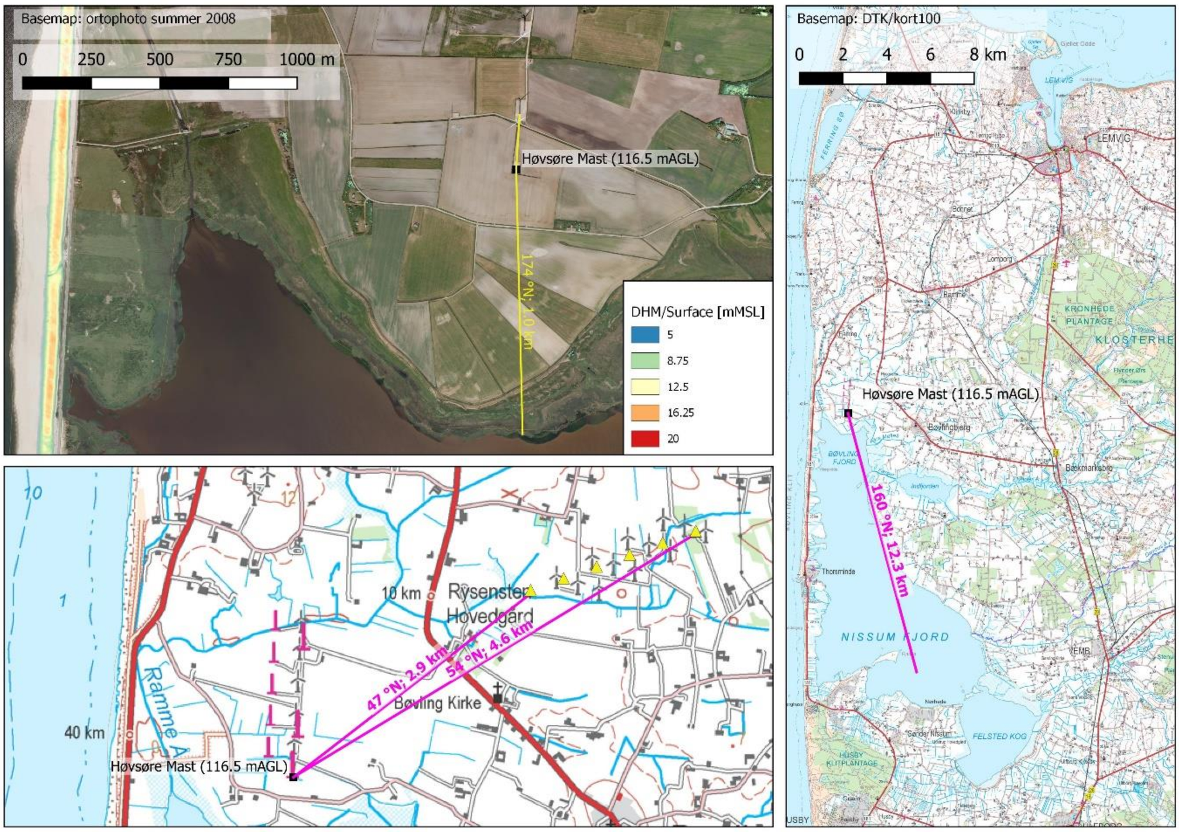

Figure 3-3: Location of the Høvsøre met mast, approximately 1.8 km from the North Sea (to the West) and 1.0 km from the Bøvling Fjord (to the South). Source of the basemaps: https://kortforsyningen.dk/. The magenta- and yellow lines show distances and headings (in °N) from the mast location to nearby landscape features mentioned in the text.

3.2.2 Instrumentation setup

The Høvsøre met mast instrumentation is described in detail in the documentation provided in the folder Mast_Høvsøre\Meta_data of [DATA]; this includes the folders with the self-explanatory names:

- \Metmast_structure_and_instrumentation.
- \IEC_Compliance.
- \Calibration_certificates.
- \Pictures.

Besides the mast data, a LiDAR dataset measured using a Leosphere WindCube, covering the period spanning 2016-02-17 to 2016-06-25, is provided to support any mast disturbance- and other, relevant studies.

3.2.3 Data files and contents of the dataset

Data files in ASCII format are provided in the following sub-folders of \Mast_Høvsøre:

- \Data_files_mast;
- \Data_file_LiDAR.

The mast data are provided in several batches (eight in total), identified by a letter subscript (A to H). The LiDAR data are provided in a single file. The mast signal headers are self-explanatory. The LiDAR signals are described in the file "\Meta_data\Fields description in Lidar data file.pdf"

3.2.4 Data quality and validity

The quality of the measurement timeseries is very good: see, for instance, the remarkably long and continuous timeseries at 116.5 mAGL (metres Above Ground Level) in Figure 3-4. Detailed information about the instruments' mounting arrangements is provided in the \IEC_Compliance folder mentioned in Section 3.2.2 above; it can for example be used for assessing the compliance of the mast instrumentation with the requirements stated in the international standard [IEC6112].

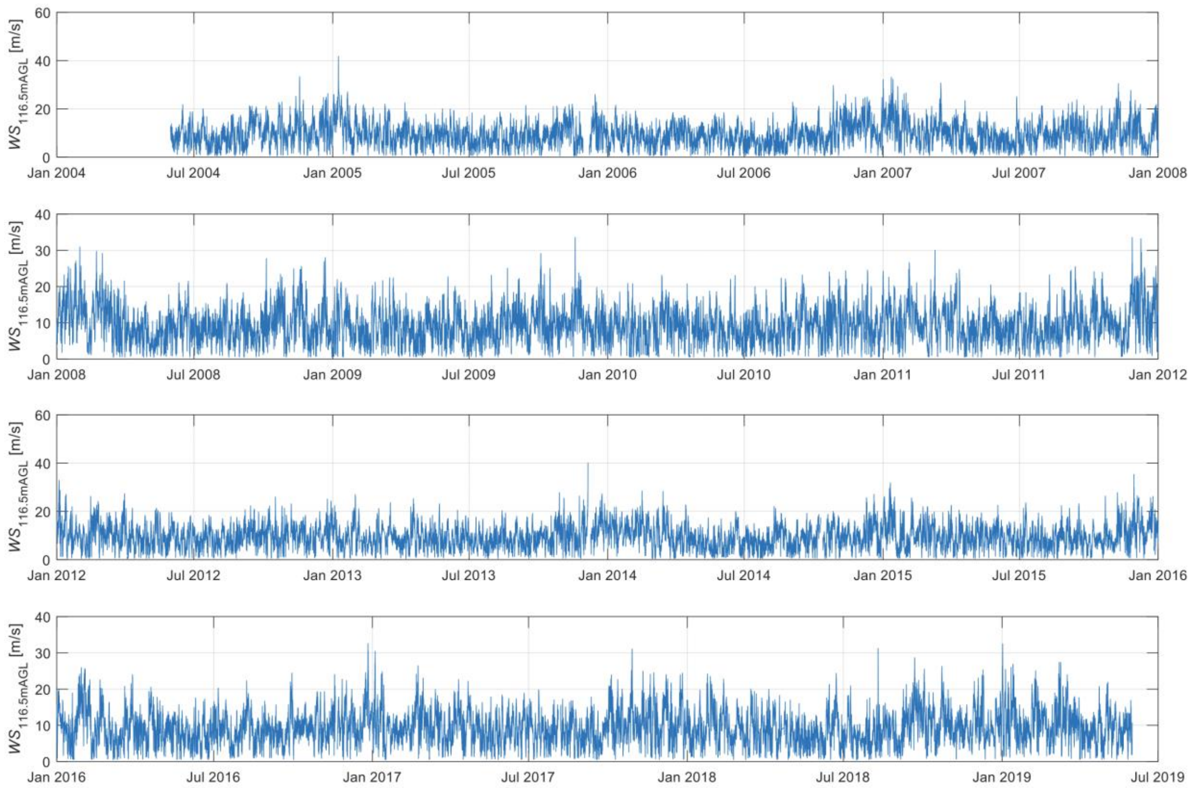

Figure 3-4: Timeseries of 10-minute mean wind speed from the Høvsøre met mast at 116.5 mAGL at the Høvsøre met mast.

Please note, as pictured in Figure 3-3, that a handful of nearby terrain features noticeably affect the wind conditions measured at the mast; in particular:

- The wind turbines test stands: the closest one is located approximately 200 m to the North of the mast.

- After 2014-12-15, the six Vestas V117-3.3 turbines at the Volder Mark wind farm (replacing[8] twelve V42/600 turbines), located between 2.9 and 3.6 km at 50°N heading from the mast.
- The Nissum Fjord, to the South.

Figure 3-5 shows the directional Turbulence Intensity (*TI*) values measured at 116.5 mAGL, the black lines show moving-average median values (full lines), as well as 10- and 90 percent quantiles (dashed lines). The data are split into four subsets: before- and after the start of operation of the repowered Volder Mark wind farm (top and bottom rows), and atmospheric stability (crudely[9] assessed using the differential temperature sensor, left and right columns). Besides the two above-mentioned features that are clearly visible in this figure, one can identify the wind directional bin for which the top anemometer measurements are likely representative of near-coastal offshore wind conditions, i.e. approximately [200; 320] °N.

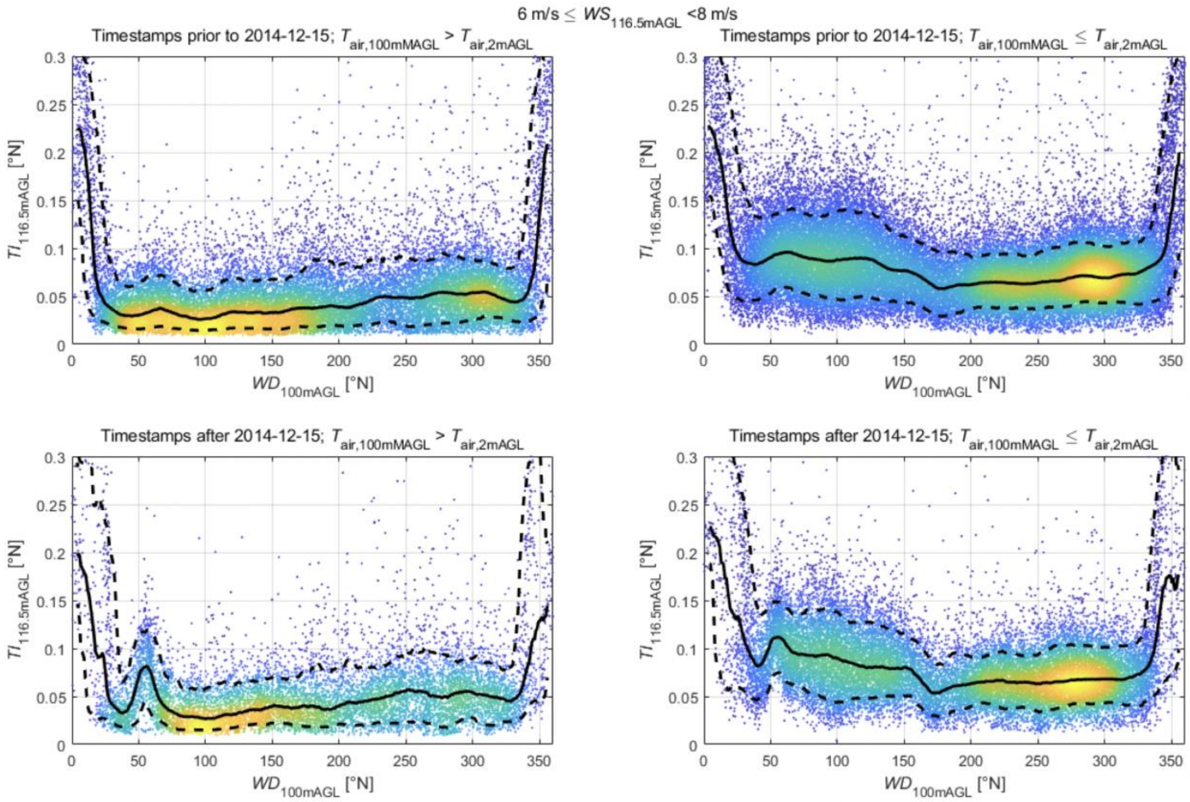

Figure 3-5: This figure shows scatter plots of *TI* (10-minute samples) measured at 116.5 mAGL against the wind direction measured at 100 mAGL, at the Høvsøre mast. The dataset is split into four subsets: the column to the left shows the timestamps for which the air temperature at 100 mAGL is larger than at 2 mAGL while the opposite is true for the column to the right (this is a crude measure of the atmospheric stability for onshore wind directions); the top- and bottom rows show timestamps before and the after the start of operation of the new Volder Mark wind farm (see Figure 3-3, and text).

[8] See https://planenergi.dk/wp-content/uploads/2018/05/Til_web_Volder_Mark_VVM.pdf.
[9] In effect, for offshore wind directional bins, a better proxy would be the difference between air- and water temperatures.

3.3 WINDSEA3 floating LiDAR system

3.3.1 Location and context

A Floating LiDAR System (FLS) has been deployed since 2020-05-18 within the Thor project area, see Figure 1-1 and Figure 3-6. The campaign is carried out by AKROCEAN, using a WINDSEA floating LiDAR (unit serial no. 3, labelled WINDSEA3). The GPS coordinates displayed in the bottom-right part of ibid. show that the FLS stayed within 200m of the location reported in Table 1-1. This measurement campaign has been commissioned by Energinet specifically for the Thor project, following requests expressed by stakeholders during the Thor Market dialogues[10]. The primary purposes of this measurement campaign are Wind Resource- and Energy Yield Assessments.

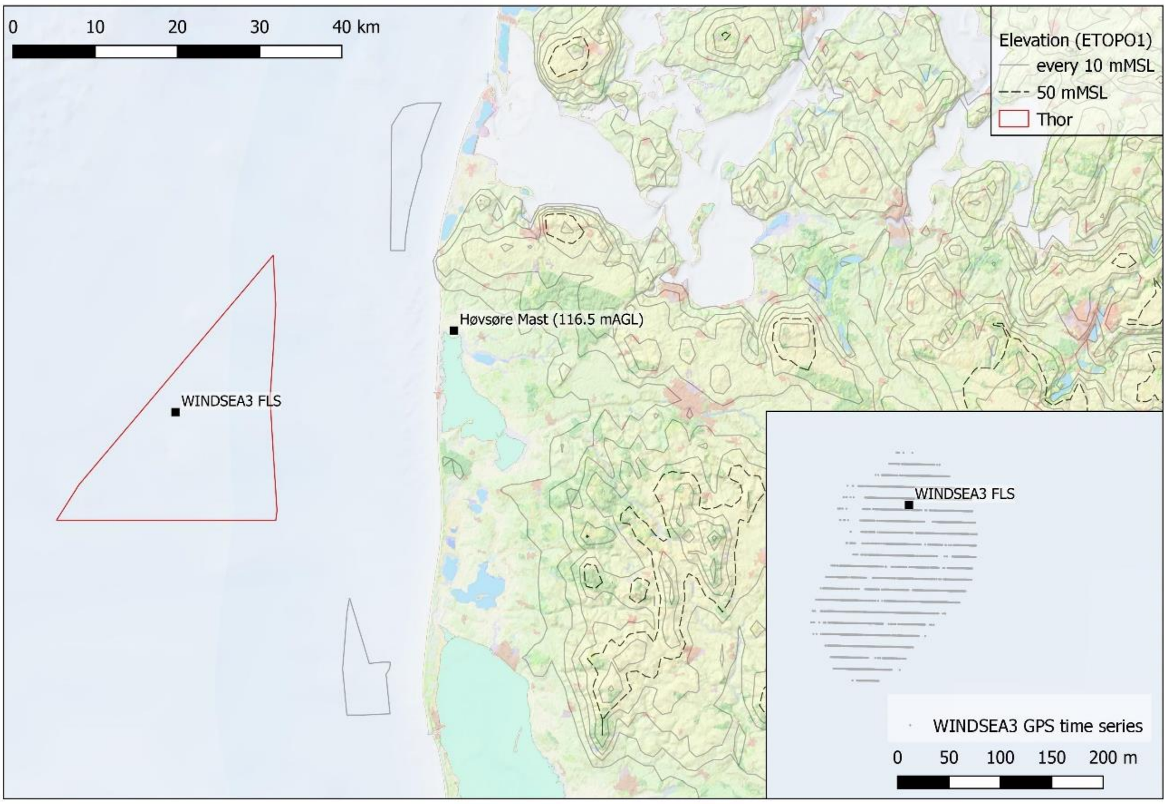

Figure 3-6: Locations of the WINDSEA3 FLS and the Høvsøre met mast. The map to the bottom-right shows, to the precision of its GPS data, the location of the FLS for each 10-minute timestamp between 2020-05-19 and 2020-08-17. The map shows orography contour lines as well as land-use classes (CORINE landcover 2012): green are forested areas, red are cities, and pale yellow are arable lands areas.

[10] In particular, after the 2019-05-13 Technical dialogue on site-investigations, see https://ens.dk/sites/ens.dk/files/Vindenergi/thor_site_investigations_-_q_and_a_from_workshop_20190513_final.pdf.

3.3.2 Instrumentation setup

The WINDSEA3 FLS floating LiDAR system is described in [AK1] and [DNVGL]. It includes:

- A Leosphere WindCube WLS 866 v2 LiDAR (serial no. WLS866-26).
- A Gill Instruments GMX500 weather station.
- An Aanderaa MOTUS Wave Sensor 5729.
- An Aanderaa Stand-Alone Current Sensor DCPS 5400.
- An AIRMAR EchoRange SS510 Depth Sensor.

The LiDAR has been configured to measure at the following elevations[11] above mean sea level: {43; 46; 57; 65; 75; 86; 100; 114; 132; 151; 174; 200} mMSL. These elevations are spaced almost equally in logarithmic scale, between the lowest possible measurement elevation (40 m above the LiDAR lens[12]) and 200 mMSL (an elevation for which the LiDAR availability remains reasonable large).

3.3.3 Data files and contents of the dataset

The data files are provided in [DATA], and contents of these data files described in [AK1]. As explained in Section 2.1.2 of [DNVGL], there are two LiDAR datasets available:

- *.stdsta files: non motion-compensated data.
- *.sta files: motion-compensated data. These are referred to as *dirsta* in ibid.

3.3.4 Data quality and validity

An overview of selected wind- and temperature measurement timeseries up to 2020-08-17 is provided in Figure 3-7. Only the wind direction signal from the motion-compensated STA files has been used. The wind direction signal from the non-motion-compensated STDSTA files should not be used. Both STA and STDSTA timeseries, as well as the air- and water temperature times series, are of good quality and compare well with the ERA5 timeseries interpolated at the location of the buoy.

[11] Please note that the second measurement elevation stated in Section III.1 of [AK1] is 49 mMSL, while the data inspected by C2Wind shows 46 mMSL. As the measurement elevations may change over time, the user of the data should check every data file and use the elevations stated therein.

[12] This implies that the actual elevations with respect to Mean Sea Level vary with time. For the Thor project area, one can get a sense of the Still Water Level variations' magnitude through the distance from the maximum Lowest Astronomical Tide to the Highest Astronomical tide (LAT to HAT) being approximately 1.2 m (see Table 5.4 of [DHIMO]), and the maximum 1-year High Still Water Level being approximately 1.6 mMSL (see Tables 0.1 to 0.3 of ibid.).

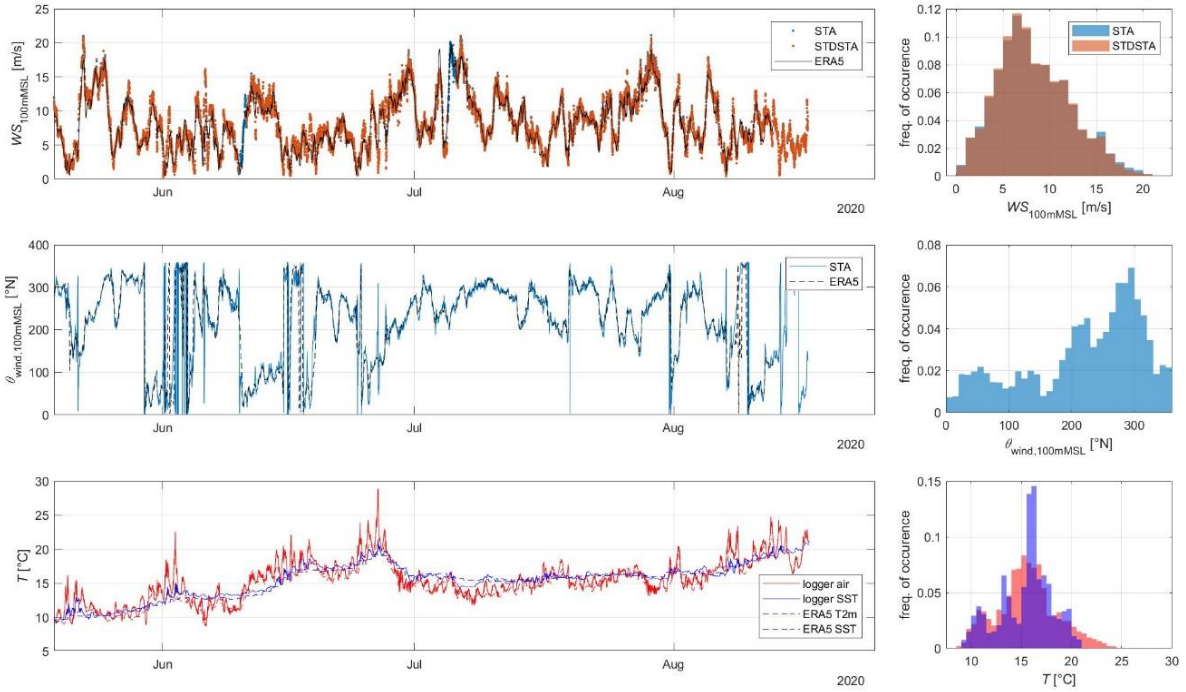

Figure 3-7: Left: Selected wind- and temperature measurement timeseries from the WINDSEA3 FLS, between 2020-05-19 and 2020-08-17, and simultaneous ERA5 timeseries. The histograms to the right show measured values only.

As stated in Section 10 of [DNVGL], the WINDSEA3 is a stage 2 (Pre-commercial) device according to the Carbon Trust Offshore Wind Accelerator Roadmap for the Commercial Acceptance of floating LiDAR Technology Version 2 [OWARMv2].