REPORT

Energinet Eltransmission A/S

Thor Offshore Wind Farm

Wind Conditions for a Light Site Conditions Assessment

19009-4

Revision	Date	Description	Author	QC
0	2020-09-18	Issued for internal QC	RGA	ASM
1	2021-01-06	Issued for Client	RGA	ASM
2	2021-01-29	Updated due to DNV-GL comments	ASM	RGA

Summary of Changes

Revision	Section	Changes
1	All	Issued for Client
2	3.1.3	Added a statement on the data basis used to assess the air density.
	3.3.2	Added a statement on the data basis used to assess the air density.
	5	Corrected typos in 2nd axis labels of Figure 5-6, and added clarification to caption.

Changes in the most recent revision, after Rev. 1, are marked with yellow highlighting.

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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. It provides a high-level characterisation of the wind conditions at the Thor Offshore Wind Farm (Thor) project area. This report will be provided to pre-qualified participants (the bidders) to the Thor tender, as agreed during the Thor Market Dialogue[1]. It is intended to be used for the following purposes:

- Preliminary site suitability analysis of the Wind Turbine Generator (WTG) Rotor Nacelle Assembly (RNA).
- Front-End Engineering Design (FEED) of offshore WTG support structures.

The purpose of this report is to document the main wind- and atmospheric parameters that can be used as input to preliminary Integrated Load Analysis (ILA) and FEED. The purpose is thus not to produce design values for a certified Site Conditions Assessment in the sense of Figure 3 of [IECRE502], but instead to make reasonable estimates of design parameters and provide an overview of the quality- and validity of the available datasets used to establish these estimates[2]. These definitions of the purpose are in accordance with Slide 10 of [MOI]. The resulting estimated design parameters are provided in Section 3, where they are listed in the same order as in Slides 11 and 12 of [MOI].

The analyses in this report make use of primarily three measurement datasets:

- The M2- and Høvsøre meteorological (met) mast datasets from [THORDATA], described in [MEAS] (see their locations in Figure 1-1 and Table 1-1).
- The IJmuiden met mast- and LiDAR datasets, described in Section 4.

The measurements from the Floating LiDAR System (FLS) deployed within the project area have not been used, since they span only a limited duration at the time of writing the present report.

Dataset	Location (lat., lon.) {°N; °E}	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 (FLS)	{56.347; 7.605}	Energinet (AKROCEAN)	From 2020-05-19 (on-going campaign)

Table 1-1: This table gives an overview of the measurement data sources whose measurement locations are shown in Figure 1-1. The table is a reproduction of Table 1-1 of [MEAS].

Furthermore, the following datasets have been used:

- The latest ECMWF reanalysis dataset [ERA5] (hourly time series products at single elevations).
- The New European Wind Atlas [NEWA].

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[1] In particular, after the 2019-05-13 Technical dialogue on site-investigations, see [MOI].

[2] This limitation of the purpose of the present document is the reason for the document name of “Light Site Conditions Assessment” in the sense of being a light (i.e. undetailed and preliminary) version of a Site Conditions Assessment.

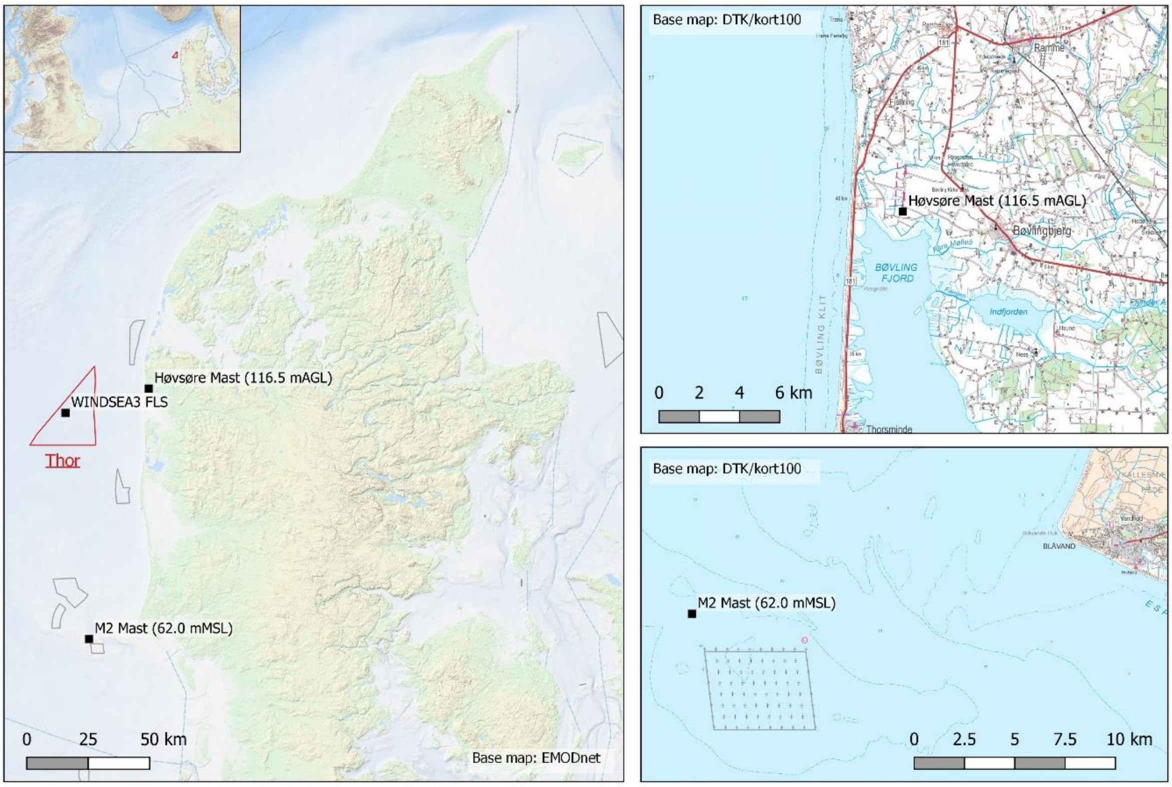

Figure 1-1: This map shows the locations that the three measurement datasets in Table 1-1 correspond to. The figure is a reproduction of Figure 1-1 of [MEAS].

The WTG hub height has been set to 140 mMSL. This value has been selected by using:

- A minimum distance of 20 meters between the Highest Astronomical Tide (HAT) and the lowest blade tip, as required by the Danish Maritime Authority[3].
- A HAT to MSL distance of 0.6 m (the largest of the values in Table 5.4 of [DHI]).
- A rotor diameter of 220 m.

These, combined, lead to a minimum hub height of 130.6 mMSL, but a larger value may be necessary, forced by the combination of maximum 50-year crest elevation, air gap, installation tolerances and local settlements, Local Water Level Changes, an external working platform height (i.e. vertical extent), and the minimum blade clearance between an external working platform top and the lowest blade tip. In C2Wind's experience, a likely range of hub heights for the Thor project is [135; 145] mMSL. Therefore, for the purpose of this report, the hub height has been set to 140 mMSL, and the design parameters listed in Section 3 are valid within, at least, the interval [135; 145] mMSL. In addition, the values may be applicable for smaller- as well as larger hub heights as well, but the user of this document needs to assess this on a case-by-case and parameter-by-parameter basis.

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[3] See https://www.dma.dk/SikkerhedTilSoes/Sejladssikkerhed/EntreprenoeropgaverSoes/Sider/HavvindmoellerEnergianlaeg.aspx (accessed 2020-09-01).

2. References

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[THORDATA]	**Energinet.** See the reference [DATA] of [MEAS].
[DHI]	**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)).
[DS472]	**Dansk Standard.** External conditions in Denmark for the design of wind turbines. DS 472 E. Dansk Standard (2007-06-28).
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[GRYNING15]	**Gryning S.-E., Floors R., Peña A., Batchvarova E., Brümmer B.** Weibull Wind-Speed Distribution Parameters Derived from a Combination of Wind-Lidar and Tall-Mast Measurements Over Land, Coastal and Marine Sites. Boundary-Layer Meteorology (2015-11-27). Link: https://link.springer.com/article/10.1007/s10546-015-0113-x
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[HANNESDÓTTIR19]	**Hannesdóttir Á., Kelly M., Dimitrov N.** Extreme wind fluctuations: joint statistics, extreme turbulence, and impact on wind turbine loads. Wind Energ. Sci., 4, 325–342 (2019). Link: https://doi.org/10.5194/wes-4-325-2019
[IEC611]	**IEC.** IEC 61400-1: Wind energy generation systems – Part 1: Design Requirements. Edition 4.0. International Electrotechnical Commission (2019-02).

[IEC613]	**IEC.** IEC 61400-3: Wind Turbines – Part 3: Design Requirements for Offshore Wind Turbines. Ed. 1.0. International Electrotechnical Commission (2009).
[IEC6131]	**IEC.** IEC 61400-3-1: Wind energy generation systems – Part 3-1: Design Requirements for Fixed Offshore Wind Turbines. Ed. 1.0. International Electrotechnical Commission (2019-04). Includes A11:2020 (2020-11).
[IECRE502]	**IECRE.** IECRE - Operational Document: IEC System for Certification to Standards relating to Equipment for use in Renewable Energy applications (IECRE System). Project Certification Scheme. IECRE OD-502. Edition 1.0 (2018-10-11).
[IJFLSvsMast]	**Ecofys.** Uncertainty Assessment Fugro OCEANOR SEAWATCH Wind LiDAR Buoy at RWE Meteomast IJmuiden 11.04.2014 – 27.10.2014. Rev. 3.0 (2016-09-02). Link: http://offshorewind.rvo.nl/file/view/45051462/uncertainty-assessment-ecofys.
[IJMast1]	**ECN.** Offshore Meteorological Mast IJmuiden – Abstract of Instrumentation Report. ECN-Wind Memo-12-010 Rev. 0.1 (2012-04-19). Link: https://www.windopzee.net/wp-content/uploads/2019/07/ecn-wind_memo-12-010_abstract_of_instrumentatierapport_meetmast_ijmuiden.pdf.
[IJMast2]	**ECN.** Wind Measurements at Meteorological Mast IJmuiden. Rev. 1.0. Doc. no. ECN-E--14-058 (2015-02). Link: https://publicaties.ecn.nl/PdfFetch.aspx?nr=ECN-E--14-058
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[KAIMAL72]	**Kaimal J. C., Wyngaard J. C., Izumi Y., Coté O. R.** Spectral characteristics of surface-layer turbulence. Quarterly Journal of the Royal Meteorological Society (1972-07). Link: https://apps.dtic.mil/dtic/tr/fulltext/u2/748543.pdf
[KANG16]	**Kang S-L., Won H.** Spectral structure of 5 year time series of horizontal wind speed at the Boulder Atmospheric Observatory. Journal of Geophysical Research – Atmospheres (2016-10-03). Link: https://agupubs.onlinelibrary.wiley.com/doi/full/10.1002/2016JD025289
[LARSÉN16]	**Larsén X. G., Larsen S. E., Petersen E. L.** Full-Scale Spectrum of Boundary-Layer Winds. Boundary-Layer Meteorology 159, Page 349-371 (2016-02-02). Link: https://orbit.dtu.dk/en/publications/full-scale-spectrum-of-boundary-layer-winds
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[MIKKELSEN17]	**Mikkelsen T, Larsen S. E., Jørgensen H. E., Astrup P., Larsén X. G.** Scaling of turbulence spectra measured in strong shear flow near the Earth's surface. Physica Scripta (2017-11-01). Link: https://orbit.dtu.dk/en/publications/scaling-of-turbulence-spectra-measured-in-strong-shear-flow-near-
[MOI]	**Energinet/C2Wind.** Technical Dialogue on Site Investigations – MetOcean. Doc. no. 19009-1. Revision 3 (2019-05-11). Link: https://ens.dk/sites/ens.dk/files/Vindenergi/3_metocean_input.pdf
[NEWA]	**NEWA.** New European Wind Atlas, a free, web-based application developed, owned and operated by the NEWA Consortium. For additional information see www.neweuropeanwindatlas.eu. The web interface is located at: https://map.neweuropeanwindatlas.eu/. Summary wind statistics from NEWA WRF mesoscale ensemble have been used as well, see https://zenodo.org/record/4002351#.X1CbWcj7QuU.
[NORSW]	**Peña Diaz A., Mikkelsen T., Gryning S.-E., Hasager C. B., Hahmann A. N., Badger M., Karagali I., Courtney M.** Offshore Vertical Wind Shear: Final report on NORSEWInD's work task 3.1. DTU Wind Energy-E-Report-0005(EN) (2012-08-29). Link: https://orbit.dtu.dk/en/publications/offshore-vertical-wind-shear-final-report-on-norsewinds-work-task.
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[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). Please note: this work is currently not publicly available, yet please see Slide 21 and 23 of the following presentation for a summary of the 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.
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[SATHE10]	**Sathe A.** Atmospheric stability and wind profile climatology over the North Sea - Case study at Egmond aan Zee (2010-06). Link: https://pdfs.semanticscholar.org/bfd5/16c6748b5e62217da6cf88e9c320279b0458.pdf
[UKHSE]	**UK HSE.** Offshore Technology Report, Environmental considerations. Doc 2001/010. Health & Safety Executive (2002). Link: http://www.hse.gov.uk/research/otopdf/2001/oto01010.pdf
[WOZ]	**ECN.** Wind op Zee measurement database. Link: https://www.windopzee.net/

3. Wind conditions

As stated in Section 1, the design parameters provided in this section are listed in the same order and format as in Slides 11 and 12 of [MOI]; see Table 3-1 below.

Normal conditions parameters. Given at h_{Hub} = 140 mMSL.		**Reference**
Mean wind speed	$WS_{\text{Hub,mean}}$ = 10.5 m/s.	Section 3.1.1
Omni-directional Weibull wind speed distribution parameters	k_{Hub} = 2.3, A_{Hub} = 11.85 m/s.	Section 3.1.1
Wind profile for wind speed extrapolation with elevation, at least in the interval [114; 164] mMSL.	$WS(z) = WS_{\text{Hub}} \cdot \left(\frac{z}{h_{\text{Hub}}}\right)^{0.06}$ Here, z and h_{Hub} are in mMSL.	Section 3.1.2
Wind profile for Integrated Load Analysis, Normal Wind Profile (NWP)	$WS(z) = WS_{\text{Hub}} \cdot \left(\frac{z}{h_{\text{Hub}}}\right)^{0.09}$ Here, z and h_{Hub} are in mSWL.	Section 3.1.2
Normal Turbulence Model (NTM)	Not summarized, see Table 3-3.	Section 3.1.2
Mean air density	$\rho_{\text{Hub,N}} = 1.23\ \frac{\text{kg}}{\text{m}^3}$.	Section 3.1.3
Mean air temperature	$T_{\text{Hub,mean}}$ = 8.5 °C.	Section 3.1.3
Extreme Turbulence model (ETM)	Not summarized, see Section 3.2 and Table 3-4.	Section 3.2
Extreme conditions parameters (Extreme Wind speed Model, EWM). Given at h_{Hub} = 140 mMSL.		**Reference**
Wind profile for extreme wind speed extrapolation with elevation	$WS(z) = WS_{\text{Hub}} \cdot \left(\frac{z}{z_{\text{Hub}}}\right)^{0.11}$ Here, z and z_{Hub} are in mMSL.	Section 3.3.1
Wind profile for Integrated Load Analysis	$WS(z) = WS_{\text{Hub}} \cdot \left(\frac{z}{z_{\text{Hub}}}\right)^{0.11}$ Here, z and z_{Hub} are in mSWL.	Section 3.3.1
Turbulence Intensity	TI_{EWM} = 0.11.	Section 3.3.1
Mean air density	$\rho_{\text{Hub,EWM}} = 1.21\ \frac{\text{kg}}{\text{m}^3}$.	Section 3.3.2
Maximum 10-minute mean wind speed for a 50-year EWM	$WS_{\text{Hub,50}}$ = 47.0 m/s.	Section 3.3.3.5
Items that are not delivered	**Note**	
Not delivered: Wake- and wind farm Turbulence Intensities	This is not delivered, since it depends on both WTG type (through its C_T-curve and rotor diameter) and the wind farm layout.	
Not delivered: Gust parameters	This is not delivered, since the gust parameters are determined by the standard to which the WTG type is type certified, and furthermore depend on the WTG type (through its C_T-curve and rotor diameter) and the wind farm layout. Finally, the way gusts are applied in ILA is determined by the standard to which the WTG type is type certified.	

Table 3-1: Summary of the wind conditions provided in this report, in accordance with Slides 11 and 12 of [MOI].

3.1 Normal Wind Conditions

This section provides preliminary design parameters related to Normal Wind Conditions[4] at the hub height stated in Section 1: mean wind speed, omni-directional wind speed Weibull distribution parameters (see Section 3.1.1), wind shear and free stream Turbulence Intensity (Section 3.1.2), as well as other parameters (Section 3.1.3).

For all of these parameters, missing data (i.e. data gaps) and non-integer number of years have been handled through the method of Mean-of-Monthly-Means (MoMM) explained in Section 6 to avoid seasonal bias.

3.1.1 Wind speed Weibull distributions

As specified on Slide 11 of [MOI], the present section provides a mean wind speed at hub height, together with omni-directional Weibull distribution parameters. For Wind Resource- and Energy Yield Assessment purposes, these parameters are not sufficient, and each user (e.g. each participant in the Thor tender) should therefore perform its own analysis; see Slide 7 of ibid.

The Thor project area is located between ca. 20 and 50 km from the Western coast of the peninsula of Jutland in the Kingdom of Denmark. Previous studies have shown that the wind resource in this area is one of the largest across Danish Waters, see examples in Figure 3-1 from [HAHMANN12] and [HAHMANN20].

For the purposes of the present report, the wind resource at the Thor project area has been assessed using, as primary sources:

- The Høvsøre- and Horns Rev M2 (M2) met mast measurements, see Sections 3.1 and 3.2 of [MEAS].
- ERA5 100 mASL (metres Above Surface Level) wind time series at the Høvsøre- and M2 met mast locations.
- Mean wind speeds from the New European Wind Atlas interface (NEWA), see [NEWA].

As a secondary source, the following document has been used:

- A presentation about the Wind Resource at the Danish Nearshore wind farm projects areas, [COWI1].

First, the top cup anemometer time series from the Høvsøre- and M2 met masts have been processed and filtered. Then, the time series have been long-term corrected using the Measure-Correlate-Predict (MCP) Variance Ratio method described and explicated in [RAMLI11], using twelve wind-directional bins. For each mast, an ERA5 100 mASL time series horizontally interpolated to the mast location has been used as long-term reference. Several combinations of time averages and durations of the MCP time series have been investigated.

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[4] Please note that the definition of “Normal conditions” in Section 6.3.1 of [IEC6131] is somewhat less specific than that of Section 6.3 of [IEC613]: The latter states that normal conditions occur “more frequently than once per year”, while the former states they occur “frequently during normal operation”. In the present report, the definition from [IEC613] has been used. This is also in accordance with the definition in Section 6.3.5 of [IEC6131], although that section pertains specifically to Other Environmental Conditions: Air temperature, -humidity, and -density, water density and -temperature, and a list of other topics (notably not including wind conditions, waves, water levels, and currents); see the full list in ibid.

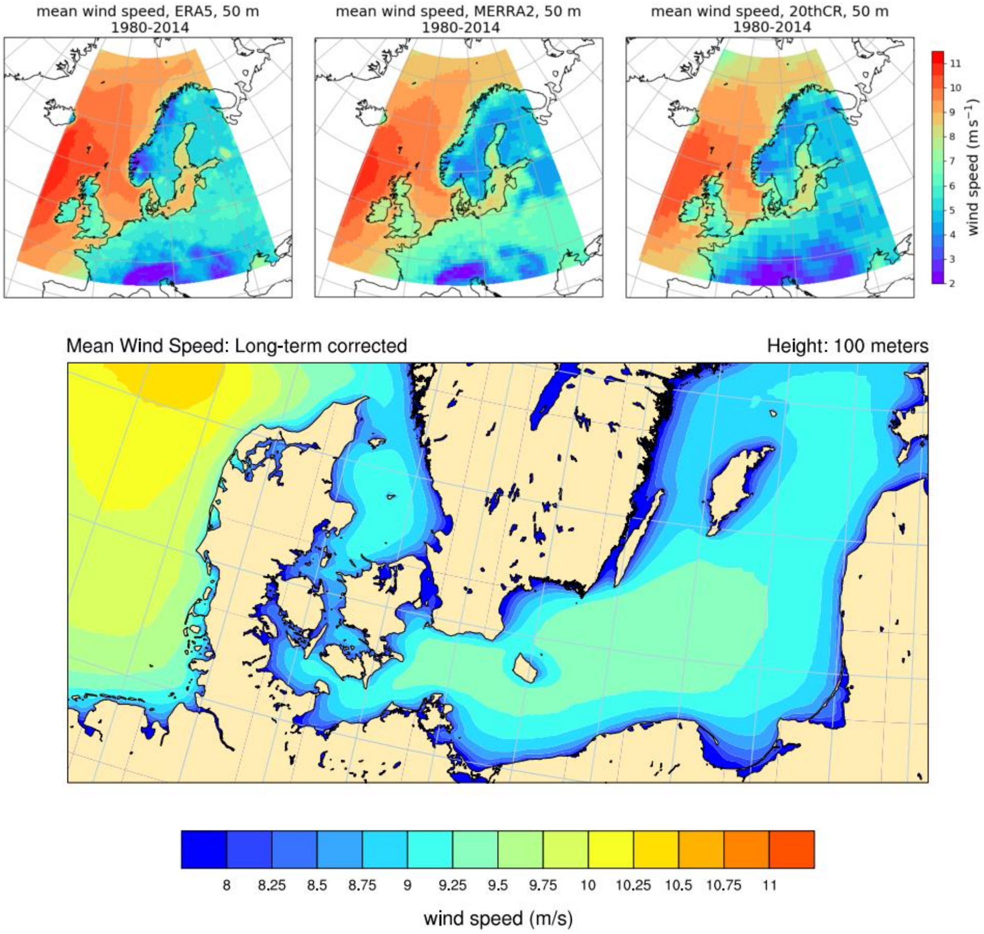

Figure 3-1: Top row: mean wind speed at 50 mASL derived from three different reanalysis datasets (ERA5, MERRA2, and 20CR) – reproduced from Slide 5 of [HAHMANN20]. Bottom: map of the long-term corrected mean wind speed at 100 mASL computed using WRF – reproduced from Figure 29 in [HAHMANN12].

Please note that the wind speeds values at Høvsøre, for the wind directional bin centred on 0 °N, are smaller than the free stream wind speeds, due to the wake of the nearby WTGs. This effect has been accounted for by comparing model- and measured wind speeds for each wind directional bin, and thereafter correcting the MCP time series in the waked wind directional bin. This results in an increase of 0.3% of the mean wind speed at the Høvsøre mast (the details of this correction are beyond the present document's scope).

The long-term mean wind speeds at the mast locations, at the top of the masts, are then chosen as: 9.50 m/s for Høvsøre (116.5 mASL) and 9.60 m/s for M2 (62 mMSL).

These mean wind speed values are then horizontally extrapolated to the westernmost (windiest) corner of the Thor area using mean wind speed values from the NEWA mesoscale runs; see Figure 3-2. The values of mean wind speeds displayed in blue in this figure have been used for that purpose. They correspond to the mean values at 100 mASL, computed over the period spanning the years [1989; 2018] (i.e. both endpoint years included). The (geographical) speed-up factors between the masts- and the westernmost corner of the Thor project area have been computed from these values, and they are provided in Table 3-2. The present report makes the reasonable assumption that these factors vary only little between the masts' top anemometer elevations and 100 mASL.

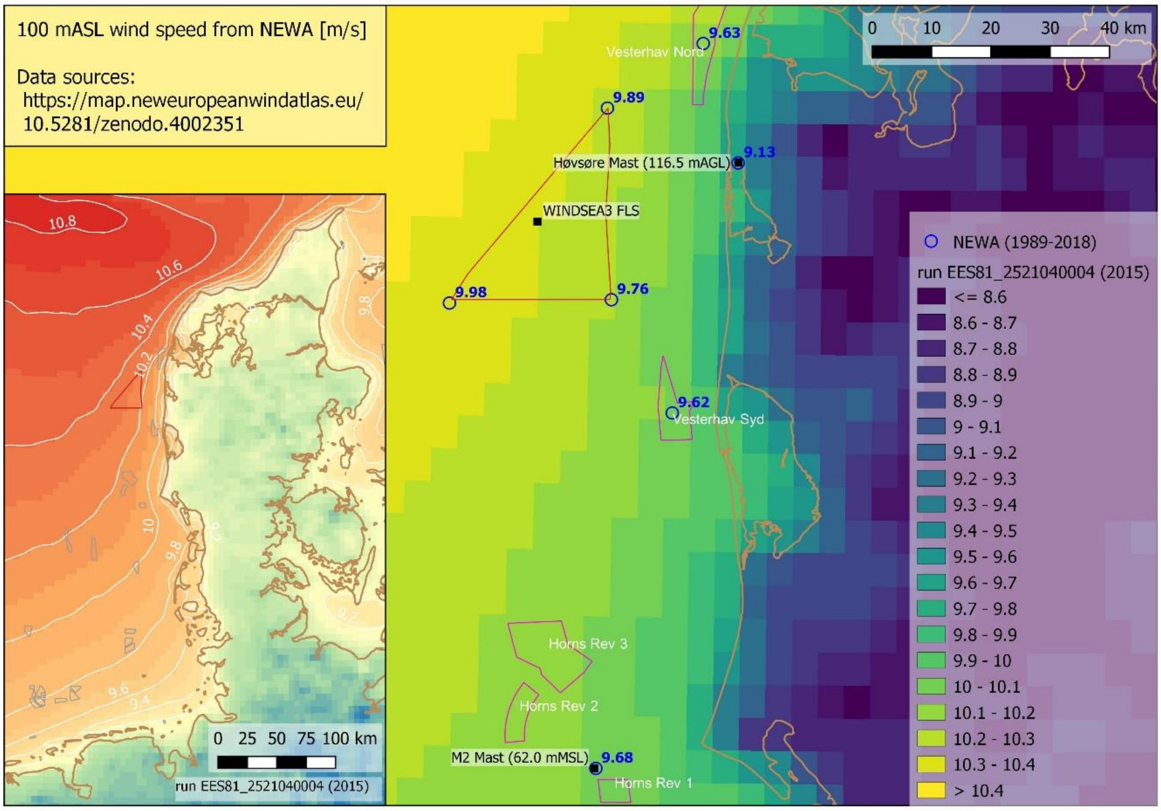

Figure 3-2: Mean wind speed maps (mesoscale dataset) from the New European Wind Atlas, [NEWA]. The figures displayed in bold blue have been read off from the NEWA web interface, and correspond to the mean wind speed values over the period spanning the years [1989; 2018]. The values on the raster maps, provided here for illustration purposes, come from the run EE81_2521040004 which covers only the year 2015, see ibid.

Lastly, the mean wind speeds values have been extrapolated upwards using two different power law shear values: 0.083 for Høvsøre, and 0.060 for M2. The values differ because the ranges of elevations over which the extrapolation is carried out differ; they have been derived based on C2Wind's experience with LiDAR measurements in the Southern- and Central North Sea (i.e. areas with similar atmospheric stability conditions). The end results are provided in Table 3-2.

	Høvsøre met mast	**M2 met mast**
Long term wind speed (mast top anemometer elevation)	9.50 m/s (116.5 mASL)	9.60 m/s (62 mMSL)
Horizontal speed-up factor to Thor	1.093	1.031
Wind speed at Thor at mast top anemometer elevation	10.38 m/s	9.90 m/s
Wind shear exponent	0.083	0.060
Wind speed at Thor at hub height	10.54 m/s (140 mMSL)	10.39 m/s (140 mMSL)

Table 3-2: Summary of the long-term mean wind speed estimate at the Thor project area, using two different met mast datasets.

The long-term mean wind speed at hub height at the Thor project area, for the purpose of the present document, is then taken at the mean of these two estimates:

$WS_{\mathrm{mean,140mMSL}}$ = 10.5 m/s.

As a secondary source of information, the high-level presentation for the Nearshore projects [COWI1] provides estimates of mean wind speeds at 100 mMSL for Vesterhav Nord (VHN) and Vesterhav Syd (VHS), see Slide 110 of ibid., where both sites have similar estimates: 9.8 m/s.

Using:

- The estimate above, of 10.5 m/s at 140 mMSL at the westernmost corner of the Thor project area,
- a power law shear exponent of 0.06, and
- the ratio of mean wind speeds between these nearshore sites and the westernmost corner of the Thor project area,

the long-term mean wind speeds at the centre of VHN and VHS is 9.9 m/s at 100 mMSL. While this difference of 0.1 m/s from the estimate from [COWI1] would be significant for the purpose of Energy Yield Assessments, this difference is acceptable for the purposes of the present document.

The corresponding Weibull parameters are then derived by setting the value of the shape parameter to *k* = 2.3, following Figure 9 of [GRYNING15], and using this value of *k* and the mean wind speed to find the Weibull shape parameter *A*. Therefore:

$k_{140mMSL}$ = 2.3.
$A_{140mMSL}$ = 11.85 m/s.

3.1.2 Wind shear and free stream turbulence

As argued in Section 4, the IJmuiden met mast and -LiDAR measurements have been used for the purpose of assessing turbulence- and shear conditions at the Thor project area. In this document, the wind shear will be modelled as:

$$WS(z) = WS(z_{\mathrm{Ref}})\left(\frac{z}{z_{\mathrm{Ref}}}\right)^{\alpha},$$

where

z_{Ref} is the reference elevation,
z is the elevation of the needed wind speed,
α is the wind shear exponent.

Using the IJmuiden LiDAR dataset, a shear analysis is performed for each timestamp, thereby assigning a shear exponent value for each timestamp in the dataset. The shear analysis is done by a least-squares linear fit of the natural logarithm of the 10-minute mean *WS* vs. the natural logarithm of the sensor elevations covering the rotor plane (for this purpose, a rotor diameter of 220 m has been assumed); thus, a power law shear profile is assumed.

Then, a hub height wind speed time series at 140.0 mMSL, WS_1400_Hub, is derived by extrapolating upward, for each timestamp, the mast-corrected wind speed time series at 91.1 mMSL as follows:

- The 10-minute mean wind speed is extrapolated using the power law shear for each timestamp derived above.
- The standard deviation is kept constant (as explained in Section 5, this approach yields conservatively large values in the averaged senses used for ILA).

A scatter plot of the wind shear exponent versus wind speed is shown in Figure 3-3. These values have been obtained by fitting a power law to each 10-minute timestamp, for all LiDAR measurement elevations up to 239.1 mMSL.

The shear exponent value that can be used for extrapolating the wind speed distribution (e.g. through the Weibull *A*-parameter) to other elevations than 140 mMSL has been taken as the mean shear exponent of the time series calculated from the measurements at all elevations between 114.1 and 164.1 mMSL, using MoMM:

$$\boldsymbol{WS(z) = WS_{\mathrm{Hub}} \left(\frac{z}{h_{\mathrm{Hub}}}\right)^{0.06}}.$$

Can be used for extrapolating the wind speed distribution with elevation, at least in the interval [114; 164] mMSL.

Here, z and h_{Hub} are measured in mMSL.

The shear exponent value which is to be used for ILA Design Load Cases (DLCs) requiring the Normal Wind Profile (NWP) has been taken as the mean of the binned absolute shear exponent values between 10 and 20 m/s, where the shear exponents and their statistics have been computed using MoMM in the same as manner as in Figure 3-3.

$$\boldsymbol{WS_{\mathrm{NWP}}(z) = WS_{\mathrm{NWP,Hub}} \left(\frac{z}{h_{\mathrm{Hub}}}\right)^{0.09}}.$$

To be used for ILA.

Here, z and h_{Hub} are measured in metres above Still Water Level (SWL), i.e. mSWL.

The time series of Turbulence Intensities (*TI*), computed at 140 mMSL at the IJmuiden mast location using the wind speed mean- and standard deviation 10-minute time series obtained as described above, has been subjected to a simple *TI*-detrending, and then used for producing the Normal Turbulence Model (NTM) results displayed in Figure 3-4 and Table 3-3. For each wind speed bin, the NTM values have been found:

- For all wind speed bins centred on values up to- and including 29 m/s: as the 90-percent quantile of the values of *TI*.
- For the wind speed bins centred on 30 m/s and larger values: conservatively, to the value recommended in Section 6.3.3.2 [IEC611], due to the small number of samples in those bins.

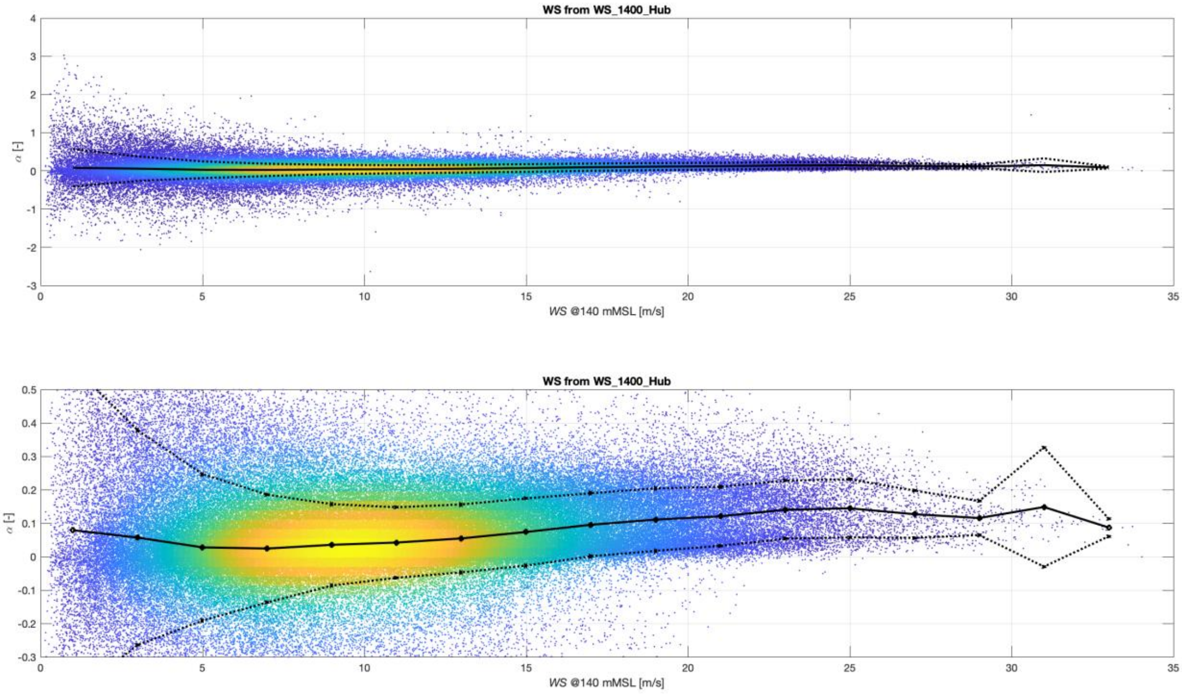

Figure 3-3: Scatter plots of wind shear exponents vs. Hub height wind speed. The plots show the points coloured according to density. The upper plot shows all data, whereas the lower plot shows details for the most widespread values. The black points, joined by the fully drawn black line, shows the Mean-of-Monthly-Means wind speed-binned mean values. The x-markers joined by dashed lines show the mean values described in the preceding sentence, plus and minus one Mean-of-Monthly-Means wind speed-binned standard deviation.

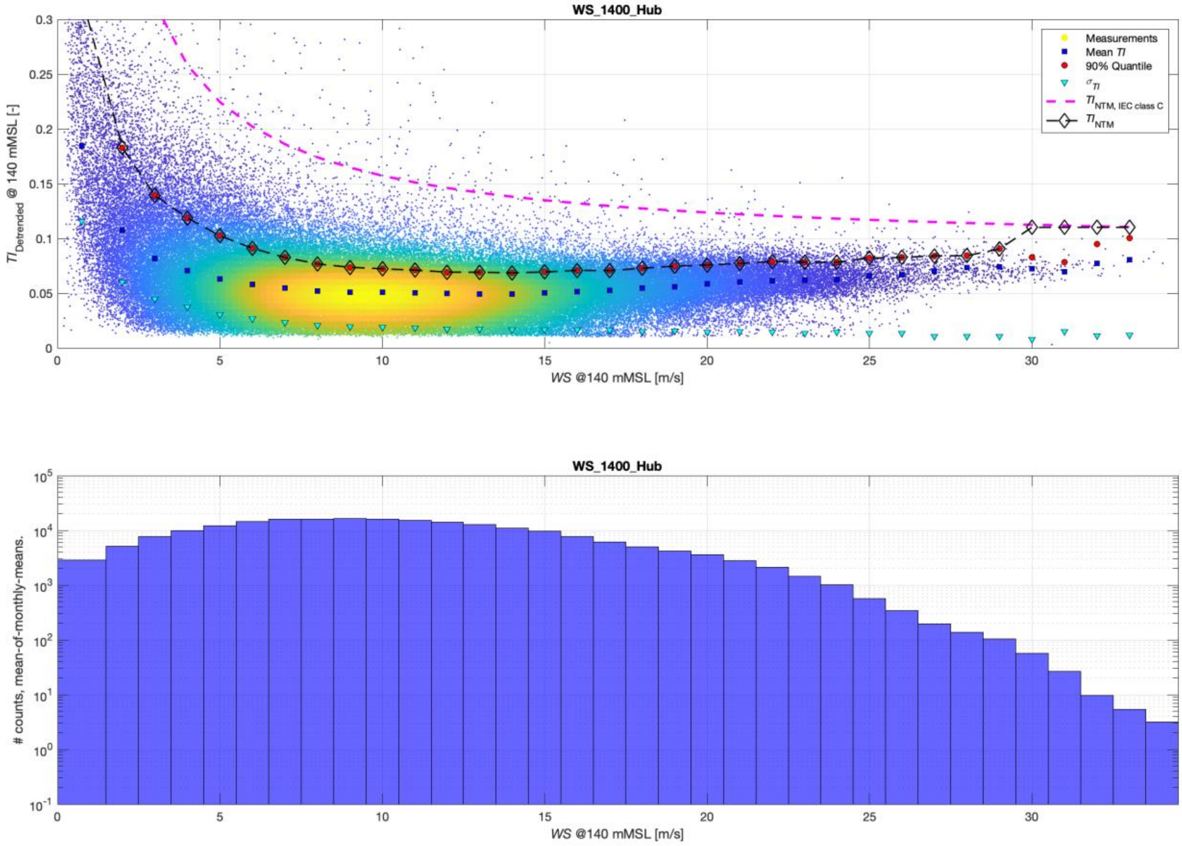

Figure 3-4: The top figure shows a density-scatter plot of detrended *TI* vs. *WS* @140 mMSL. The *WS*-binned mean values are shown with blue squares, the standard deviation values with cyan inverted triangles, and P_{90}-values with red dots. All these are calculated by the method of Mean-of-Monthly-means. The black diamonds joined by the dashed black line show the NTM-values chosen for use in the Integrated Load Analyses requiring this turbulence type. The bottom plot shows a *WS* occurrence frequency histogram, where the 2nd axis is logarithmic. As seen by comparing the upper and lower figures, the NTM values are chosen to equal the P_{90}-values for *WS*-values where there are a sufficient number of data points in each bin, and conservative upper estimates are made for bins that have fewer data points.

Free Stream Turbulence Intensity @140.0 mMSL statistics and TI_{NTM}							
***WS* bin**			***TI* statistics**				
[m/s]			μ	σ	P_{90}		TI_{NTM}
≤	<	Centre	[-]	[-]	[-]		[-]
0	1.5	0.75	0.184	0.116	0.320		0.320
1.5	2.5	2	0.107	0.060	0.183		0.183
2.5	3.5	3	0.082	0.045	0.139		0.139
3.5	4.5	4	0.071	0.038	0.119		0.119
4.5	5.5	5	0.063	0.031	0.102		0.102
5.5	6.5	6	0.058	0.027	0.091		0.091
6.5	7.5	7	0.054	0.023	0.083		0.083
7.5	8.5	8	0.052	0.021	0.077		0.077
8.5	9.5	9	0.051	0.019	0.074		0.074
9.5	10.5	10	0.051	0.019	0.072		0.072
10.5	11.5	11	0.050	0.018	0.071		0.071
11.5	12.5	12	0.050	0.017	0.069		0.069
12.5	13.5	13	0.049	0.017	0.069		0.069
13.5	14.5	14	0.049	0.017	0.068		0.068
14.5	15.5	15	0.050	0.017	0.069		0.069
15.5	16.5	16	0.052	0.017	0.071		0.071
16.5	17.5	17	0.052	0.016	0.071		0.071
17.5	18.5	18	0.055	0.015	0.073		0.073
18.5	19.5	19	0.056	0.015	0.075		0.075
19.5	20.5	20	0.058	0.015	0.076		0.076
20.5	21.5	21	0.060	0.015	0.077		0.077
21.5	22.5	22	0.061	0.014	0.079		0.079
22.5	23.5	23	0.062	0.014	0.078		0.078
23.5	24.5	24	0.063	0.014	0.078		0.078
24.5	25.5	25	0.065	0.014	0.082		0.082
25.5	26.5	26	0.067	0.013	0.082		0.082
26.5	27.5	27	0.070	0.011	0.084		0.084
27.5	28.5	28	0.073	0.011	0.084		0.084
28.5	29.5	29	0.074	0.011	0.090		0.090
29.5	30.5	30	0.073	0.008	0.083		**0.110**
30.5	31.5	31	0.070	0.015	0.078		**0.110**
31.5	32.5	32	0.077	0.011	0.095		**0.110**
32.5	33.5	33	0.081	0.012	0.100		**0.110**

Table 3-3: Free Stream Turbulence Intensity statistics and TI_{NTM} @140.0 mMSL to be used in Integrated Load Analysis requiring the use of NTM. All *TI* statistics values in non-bold are taken from the statistics shown in Figure 3-4.The values in bold text are assigned to conform with the assignment of TI_{NTM} in Figure 3-4. Should TI_{NTM}-values for $WS \geq 33.5$ m/s be needed, the TI_{NTM}-value for $WS = 33$ m/s can be used. The values in grey text are – as noted in the text – found using too few measurements to be trustworthy; thus, for these bins, only the TI_{NTM}-values may be used, while the binned μ- (mean), σ-, and P_{90}-values shall not be used. Should binned μ-values be needed for $WS \geq 29.5$ m/s, the value for the bin centred on $WS = 29$ m/s may be used.

3.1.3 Other normal conditions air parameters

The mean air temperature at hub height has been assessed using the [NEWA] dataset horizontally interpolated to the WINDSEA3 location (10 years-long time series available for download), see the air temperature time series at 150 mMSL in Figure 3-5. From this, the mean air temperature at hub height has been calculated:

Mean air temperature at hub height: 8.5 °C.

The mean air density has been assessed, from experience with measurements from the M2- and FINO3 met masts, to:

Mean air density at hub height: 1.23 kg/m^3.

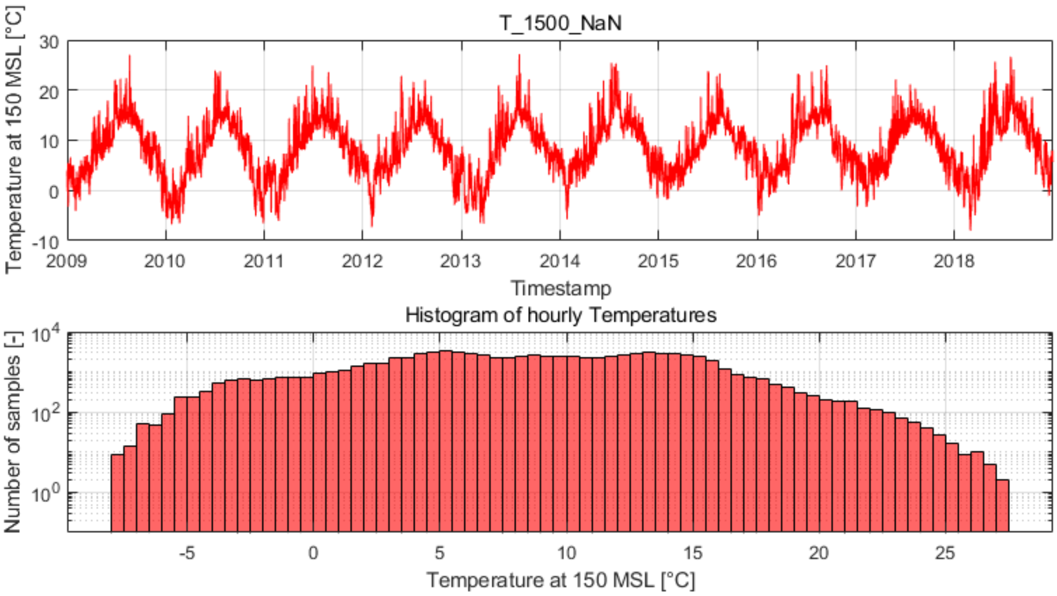

Figure 3-5: Time series and histogram of the NEWA 150 mMSL air temperature time series, horizontally interpolated to the WINDSEA3 FLS location.

3.2 Extreme Turbulence Model

A close inspection of the Høvsøre met mast measurements, see Figure 2 of [HANNESDÓTTIR19], show a considerable number of events seemingly exceeding the IEC Classes IC and IB Extreme Turbulence Model (ETM) thresholds, over a duration of 10 years.

As discussed in ibid., these events are likely not representative of extreme microscale turbulence (characterised by either the Mann- or Kaimal spectra in Annex C of [IEC611]), but instead originate from mesoscale flow features (fronts, mostly, but also convective structures).

In essence, the difficulty of distinguishing microscale turbulence from mesoscale flow features lies in the use of 10-minute statistics data: For each sample, having only the 10-minute mean- and standard deviation values does not allow discriminating between turbulence features (expressed in terms of eddies of frequencies *f*) which belong to the microscale inertial subrange (approximately defined as f > 1/300 Hz), and the smaller-frequency features which belong to the low-frequency part of the microscale spectra, i.e. the gap region and the mesoscale spectra (see Figure 3 of [LARSÉN18] for an illustration of these regions, as well as the discussion in Section 1 of [KANG16]). These mesoscale features are also present at other sites across Northern Europe (Høvsøre and Horns Rev, see Section 4 of [LARSÉN16], and at Østerild, see Section 3 of [LARSÉN18]), and up to 241 mASL (at Østerild in Figure 3 of ibid.). The spectral gap, and its corresponding (added) variance noticeable on the 10-minute standard deviation values, is thereby also present at the Thor project area.

C2Wind has replicated the findings from [HANNESDÓTTIR19] using the IJmuiden met mast data (this analysis is not shown in the present report), and there too, large microscale (small mesoscale) features, are responsible for seemingly large standard deviation values which exceed the IEC Class IC ETM threshold. The expression "seemingly large" is used here to underline that these values are real, but cannot readily be compared with the type of flow conditions prescribed for WTG design in [IEC611] (statistically stationary 10-minute time series generated using modified[5] Kaimal spectra, that is: a microscale spectrum which does not include such mesoscale features).

Regarding the Ultimate Limit State (ULS) load effects on the WTGs of Thor, it is helpful to compare with the results of Section 5 and its subsections of [HANNESDÓTTIR19]. In particular, Figure 9 and Table 3, both from ibid., show that the ULS load effects from DLC 1.3 using an IEC Class IC ETM are larger, in the absolute sense, than those of the constrained simulations therein, where these constrained simulations model the original (i.e. not high-pass filtered) measurement time series[6]. Due to the similarity of the DTU 10 MW reference WTG model used in [HANNESDÓTTIR19] (see its Section 1) to the WTG types that are likely considered for Thor, and due to the considerably larger values in Table 3 of ibid. of the DLC 1.3 load effects, obtained by using an IEC Class IC ETM, than the load effects from the constrained simulations, the present report concludes that an IEC Class IC ETM can be used for the Thor project area.

Thus, for Integrated Load Analysis using TI_{ETM}:

The largest of the $TI_{\mathrm{ETM}}(WS)$ from Table 3-4 and $TI_{\mathrm{Centre\text{-}Wake}}(WS)$ shall be used.

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[5] Compared to its original formulation in [KAIMAL72].

[6] In more detail, Section 5.2, particularly Figure 9 and Table 3, both of [HANNESDÓTTIR19], show that the IEC Class IC ETM yields larger maximum absolute load effects than those of the constrained simulations, when this maximum is taken over all wind speed bins. This is furthermore true for most wind speed bins individually, with very few exceptions. In all cases, as stated in the first sentence of this footnote, the load effects from these exceptional wind speed bins are always exceeded, in the absolute sense, by load effects from other wind speed bins. Moreover, although not the focus of [HANNESDÓTTIR19], several of the load effects of both IEC Class IC ETM- and constrained simulations for the support structure would be exceeded by load effects from other ULS DLCs. This is particularly true for the tower bottom fore-aft moment, shown in Figure 9c of ibid., which is the DLC where the IEC Class IC ETM has the smallest margin to the constrained simulation: For this structural elevation, gust DLCs almost invariably yield larger load effects, and if the WTG had been an offshore type, extreme wave loads in DLCs 6.1 and 6.2 could yield even larger load effects further down in the structure.

ETM Turbulence Intensity @140.0 mMSL			
WS bin			
[m/s]			TI_{ETM}
≤	<	Centre	[-]
0	1.5	0.75	2.532
1.5	2.5	2	0.993
2.5	3.5	3	0.685
3.5	4.5	4	0.531
4.5	5.5	5	0.439
5.5	6.5	6	0.377
6.5	7.5	7	0.333
7.5	8.5	8	0.300
8.5	9.5	9	0.274
9.5	10.5	10	0.254
10.5	11.5	11	0.237
11.5	12.5	12	0.223
12.5	13.5	13	0.211
13.5	14.5	14	0.201
14.5	15.5	15	0.192
15.5	16.5	16	0.185
16.5	17.5	17	0.178
17.5	18.5	18	0.172
18.5	19.5	19	0.166
19.5	20.5	20	0.161
20.5	21.5	21	0.157
21.5	22.5	22	0.153
22.5	23.5	23	0.149
23.5	24.5	24	0.146
24.5	25.5	25	0.143
25.5	26.5	26	0.140
26.5	27.5	27	0.138
27.5	28.5	28	0.135
28.5	29.5	29	0.133
29.5	30.5	30	0.131
30.5	31.5	31	0.129
31.5	32.5	32	0.127
32.5	33.5	33	0.125
33.5	34.5	34	0.123
34.5	35.5	35	0.122
35.5	36.5	36	0.120
36.5	37.5	37	0.119
37.5	38.5	38	0.118

Table 3-4: Extreme Turbulence Model values of TI_{ETM} @140.0 mMSL. In addition to application of these values, Integrated Load Analysis for any WTG at the Thor project area shall also be performed using *TI*(*WS*) corresponding to the largest centre-wake *TI*(*WS*) that the given WTG at the project area can experience; see item d of Section 11.9.3 of [IEC611] and Annex E.1 of ibid. Naturally, these centre-wake values cannot be tabulated before the WTG type and wind farm layout are known.

3.3 Extreme Wind speed Model

The present section contains parameters for the Extreme Wind speed Model (EWM). Explicitly, the wind shear and Free Stream Turbulence Intensity are provided in Section 3.3.1, the air density is provided in Section 3.3.2, and various estimates of the 50-year wind speed is discussed in the subsections of Section 3.3.3, and a conclusion on the 50-year wind speed is provided in Section 3.3.3.5.

3.3.1 Wind shear and Free Stream Turbulence

The shear exponent for the EWM is taken as prescribed in Section 6.3.3.2 of [IEC611]:

$\boldsymbol{\alpha_{\mathrm{EWM}} = 0.11}$.

The wind speed profile to be used is the same as prescribed in Section 3.1.2 (power law). This shear exponent shall be used for scaling extreme wind speeds with elevation, and for describing the wind shear in Integrated Load Analysis with extreme wind conditions.

For the EWM, the free stream Turbulence Intensity used for Integrated Load Analysis shall be set to a conservative value of 0.11 as suggested in Section 6.3.3.2 in [IEC611]:

$\boldsymbol{TI_{\mathrm{EWM}} = 0.11}$.

This value can be seen to be larger than the large-wind speed trend in measured Turbulence Intensities in Section 3.1.2.

3.3.2 Air density

Since westerly winter wind storms, which give rise to the largest wind speeds at the project area, are fast-moving low-pressure systems travelling across the North Sea, the atmospheric air pressure associated with the maximum wind speed in the storm is typically smaller than the mean annualised value. In C2Wind’s experience with several mast measurements in the North Sea, and in the region where the Thor project area is located in particular (e.g. the M2- and FINO 3 met masts), the following value can reasonably be assigned:

$$\boldsymbol{\rho_{\mathrm{Hub,EWM}} = 1.21\,\frac{\mathrm{kg}}{\mathrm{m}^3}}.$$

3.3.3 Extreme wind speeds

The 50-year extreme wind speed estimate has been found by comparing Extreme Value Analysis (EVA) results derived using the Høvsøre met mast time series with results derived using standards and guidelines: These derivations are made in the subsections of the present section. Thus, the intermediary results in Sections 3.3.3.1-3.3.3.4 (in grey text) shall not be used on their own. Instead, a conclusion on the 50-year extreme wind speed at hub height is provided in Section 3.3.3.5.

3.3.3.1 Eurocode 1 supplemented by DS472

The Danish national annex of [EN01] gives in its Section 4.2 (1)P Note 2 a value of 27 m/s for the basic wind speed at the Danish west coast, but no value is given for offshore sites. In addition, [EN01] also provides the tools and relations to convert the value given in the national annex to other elevations and recurrence periods. However, [EN01] is not intended to be valid offshore, so the results in the present section are for comparative purposes only.

The Danish standard DS472 [DS472] also gives in its Section A.2.1 a basic wind speed of 27 m/s at the Danish west coast, and in addition proposes a linear horizontal extrapolation to offshore conditions - increasing to 31 m/s 50 km from the coast. The parts of the Thor project area located farthest offshore are just shy of 50 km from the coast, yielding a largest basic wind speed of 31 m/s (50 years recurrence, 10-minute duration, at 10 mMSL). Hence:

$$v_{b,0} = 31\ \mathrm{m/s}.$$

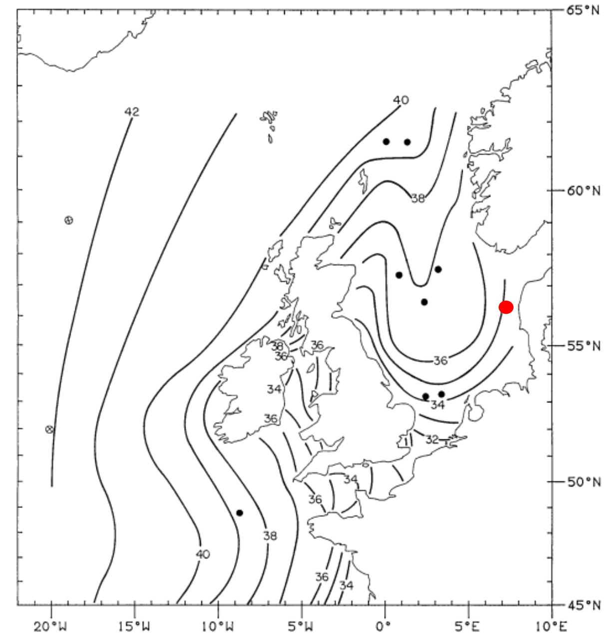
A roughness length of z_0 = 0.003 m is given for the sea in Table 4.1 of [EN01] and the basic wind speed value above is converted according to the method stated in Section 4.3 of ibid.:

$$WS(z) = 0.19\left(\frac{0.003\ \mathrm{m}}{0.05\ \mathrm{m}}\right)^{0.07} \ln\left(\frac{z}{0.003\ \mathrm{m}}\right) v_{b,0}$$

Please note that the above contains both a conversion to other elevations, but also a conversion from terrain category II to 0 (from roughness length 0.05 m to 0.003 m). The resulting 50-year 10-minute wind speed at 140 mMSL is then 52.0 m/s - not to be used; see Section 3.3.3.5 instead for the conclusion.

3.3.3.2 The UK Health and Safety Executive method

The UK Health and Safety Executive has published a number of guideline reports of which one, [UKHSE], specifically addresses environmental conditions. In its Figure 1, it provides estimates of 50-year return omnidirectional hourly-mean wind speeds at 10 m above Still Water Level, taken here to equal the long-term value at 10 mMSL. The project area is located near the 35 m/s contour line; therefore, a value of 35.0 m/s has been assigned. Converting this from 1-hour means to 10-minute means by Section 3.3b) of [UKHSE], and through Table 4 of ibid., one arrives at a 50-year 10-minute mean value @10 mMSL of 36.0 m/s. Using Section 3.3c) and Table 5, both of ibid., and interpolating between the 1-hour and 1-minute values therein, one arrives at a 50-year 10-minute mean wind speed of 47 m/s @140 mMSL - not to be used; see Section 3.3.3.5 instead for the conclusion.



Contours are in m/s. Estimated maximum error is ± 2 m/s.

Figure 3-6: Contours of 50-year 1-hour mean 10 mSWL wind speed over Northern Europe, from Figure 1 of [UKHSE]. According to Section 3.3b) of ibid., the values can be converted to 10-minute mean values at 10 mMSL as described in the text, and using Section 3.3c) of ibid., the value can be extrapolated to 140 mMSL.

3.3.3.3 ISO 19901-1

In Section B.9.1 of [ISO901], for a location in the Central North Sea, Table B.7 provides a 50-year 10-minute mean wind speed estimate of 36 m/s @10 mMSL. Using this 50-year 10-minute mean wind speed at 10 mMSL of 36.0 m/s, and Section A.7.3 of ibid. to extrapolate to 140 mMSL, one arrives at a 50-year 10-minute mean wind speed @140 mMSL of 47.1 m/s - not to be used; see instead Section 3.3.3.5 for the conclusion.

3.3.3.4 Extreme Value Analysis using the Høvsøre met mast dataset

Subsets of extreme values belonging to independent storms (separated in time by more than one day) were extracted from the 15-year duration Høvsøre met mast 116.5 mASL 10-minute wind speed time series, using various threshold values. For each of these subsets, a Generalised Pareto- and a two-parameters Weibull-distribution have been fitted to the histograms of extreme wind speeds.

To estimate the variability of the fit, a bootstrapping-method has been used: Each subset of extreme values has been resampled with replacement, and fitted 1000 times. The Weibull distribution performed better than the General Pareto (plot now shown), and the results are provided in Figure 3-7. These results show that median value results range between 41 and 45 m/s. For the purpose of this report, a 50-year 10-minute mean wind speed of 44 m/s at 116.5 mASL has been selected. Extrapolating this to 140 mMSL, using a shear exponent of 0.11, one arrives at 44.9 m/s - not to be used; see instead Section 3.3.3.5 for the conclusion.

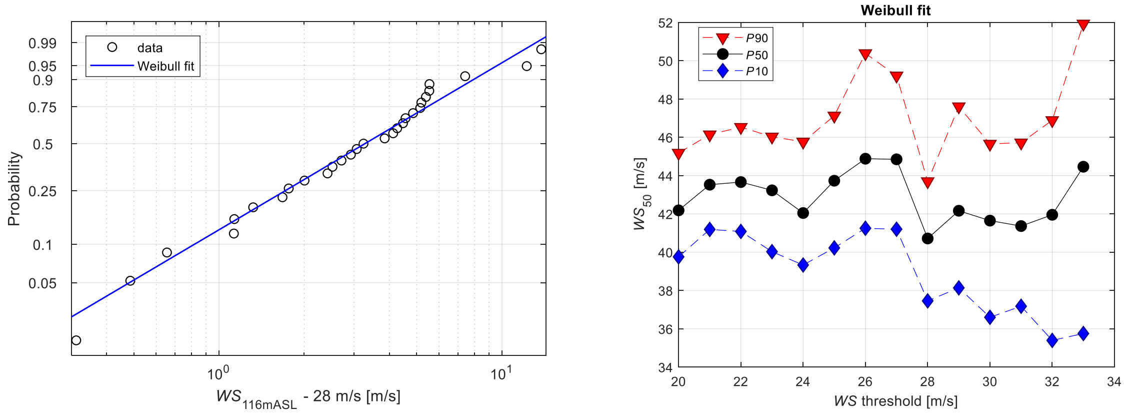


Figure 3-7: Left: example of Weibull fit to the extreme wind speed values. Right: results from the Extreme Value Analysis for various wind speed thresholds.

3.3.3.5 Comparison of, and conclusion on, extreme wind speed estimates

The results of the previous sections are listed in Table 3-5.

Elevation	Extreme wind speeds, 10-min mean values at 140 mMSL [m/s]			
[mMSL]	Eurocode 1991-1-4 / DK NA & DS472	UK HSE Guidelines	ISO 19901-1	Høvsøre met mast
140.0	52.0	47.0	47.1	44.9

Table 3-5: Overview of the extreme wind speed estimates from standards and guidelines, and from the EVA using the Høvsøre mast measurements; see text. Not to be used in ILA – see instead the conclusion below.

Carefully considering the relevance and uncertainties of the sources yielding the values in Table 3-5, the present report selects the following value of the 50-year 10-minute wind speed at hub height:

$WS_{\mathrm{Hub,50}}$ = 47.0 m/s.

4. Appendix A: the IJmuiden met mast- and LiDAR measurements

The IJmuiden met mast- and co-located LiDAR data have, in the main part of the present report, been used primarily to derive shear- and turbulence conditions for the Thor project area. This section provides a high-level description of these datasets, following the same structure as for the datasets described in [MEAS].

4.1 Location and context

The IJmuiden met mast (IJM) was located in the Dutch North Sea, see Figure 4-1. It was installed in 2011 by RWE and removed in 2016, see [WOZ][7]. A ZephIR LiDAR was installed at the mast platform, at the bottom of the tower.

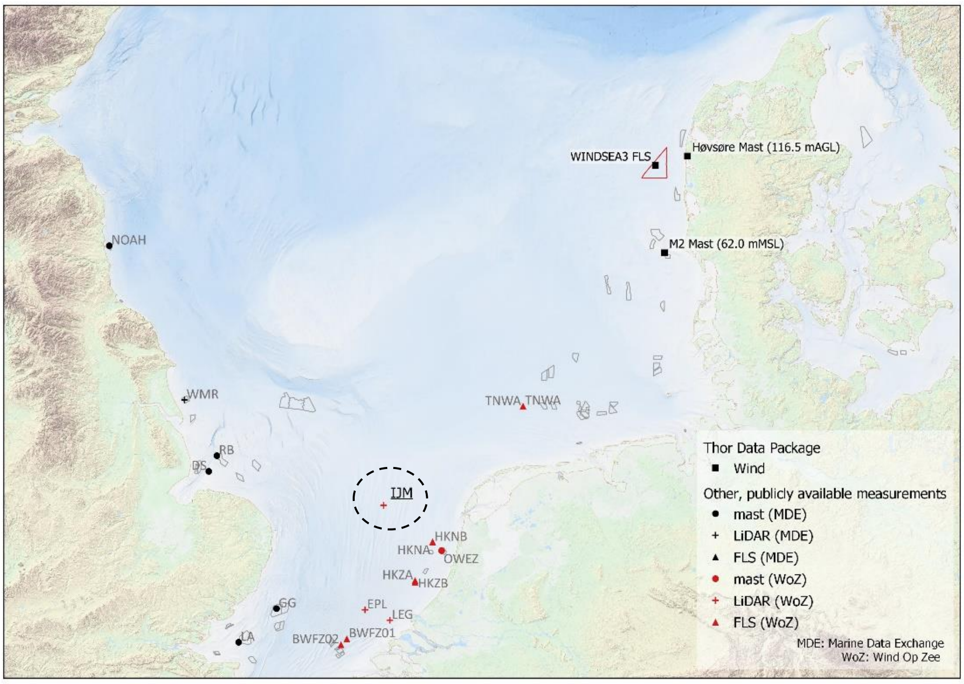


Figure 4-1: Location of the IJmuiden mast (labelled IJM, circled) in the Southern North Sea. The map also displays locations of other publicly available measurements from the Marine Data Exchange and Wind Op Zee [WOZ] databases, and from the Thor data package [THORDATA].

4.2 Instrumentation setup

The IJmuiden met mast is well documented in [IJMast1] and [IJMast2]. The exhaustive list of sensors is provided in Appendix A of the latter of these two references.

4.3 Data files and content of the dataset

The IJmuiden mast- and LiDAR data have been downloaded from [WOZ], the dataset covers the period 2011-11 to 2016-03.

4.4 Data quality and validity

It is understood from Section 5.3 of [IJMast1] that the 10-minute statistics are computed on a server located at ECN, from the raw data that are downloaded from the mast platform. Section 6.1 of ibid. states that all wind speed signals are calibrated; there is no reference to the calibration certificates, but a subset of those (at least valid for the period 2014-04-11 to

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[7] See https://www.windopzee.net/meet-locaties/meteomast-ijmuiden-mmij/.

2014-10-27) are included in Appendix A of [IJFLSvsMast]. Furthermore, this dataset has been used in [ECOBORS], a study that was consequently certified by DNV-GL (see page 3 of the pdf of *ibid*.). Therefore, it is considered to be readily useable for the present analysis as well, and no further validation of the wind speed readings has been performed.

5. Appendix B: On shear- and turbulence conditions

This section provides a regional- and a site-specific overview of the shear- and Turbulence Intensity (*TI*) conditions in the Southern- and Central North Sea. It concludes that these conditions at the Thor project area are expected to be very similar to those of other wind farm projects in this area. Furthermore, it argues for using the IJmuiden met mast LiDAR for characterising the shear parameters to be used in Integrated Load Analysis, and the IJmuiden met mast measurements (top cup anemometers) for characterising *TI*, at the Thor project area.

Several measurement datasets have been used for this analysis:

- The M2 and Høvsøre met masts dataset.
- The IJmuiden met mast- and co-located LiDAR datasets.

These datasets are not described in detail in this report, but high-level descriptions and references are provided in [MEAS] and in Section 4. Subsets of the [ERA5] reanalysis dataset have been used as well.

Following the requirements of 6.4.3.1 of [IEC6131], the present report prescribes, among other things, parametrisations of the stochastic wind field which should be used for Integrated Load Analysis. In essence, these stochastic wind fields are characterised by:

- A duration of 10 minutes.
- A power law mean shear exponent.
- For every hub height wind speed bin, a value of Turbulence Intensity (including wake turbulence) at hub height (be it Normal- or Extreme Turbulence); and from these two parameters: A three-dimensional power density spectrum using one of the spectral form expressions provided in Annex C of [IEC611].

Measurements of the wind profile across a modern WTG rotor span (approximately 30 to 250 mMSL) show that mean wind speed profile is approximately well modelled by a power law (one of the two analytical models listed in Section 3.76 of [IEC6131]), see Figure 5-1.

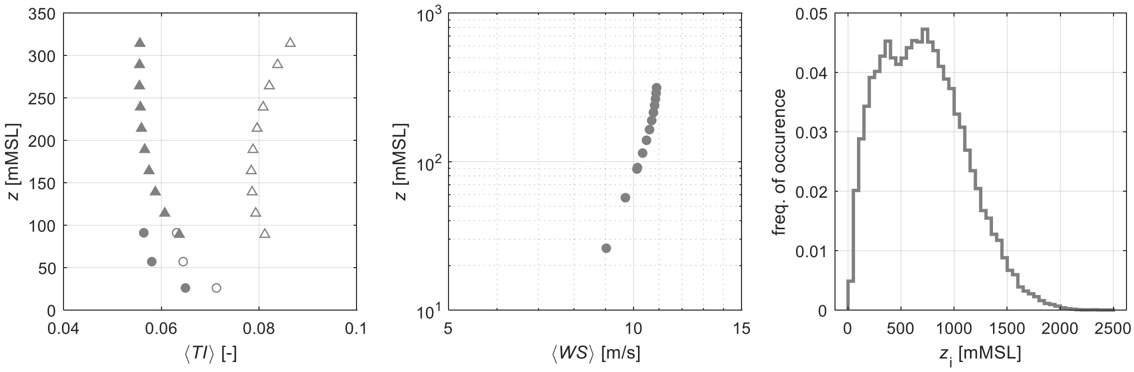

Figure 5-1: From the IJmuiden mast and co-located LiDAR datasets: time-averaged *TI* (left) and time-averaged *WS* (centre) profiles over the entire measurement period. Median values are shown with filled markers, and mean values with empty markers. Please note that the LiDAR (circles) and cups (triangles) measure turbulence differently. The plot to the right shows the histogram of corresponding boundary layer height z_i (from ERA5).

While this correspondence is true for the long-term mean conditions, for which the surface layer atmospheric stability is near-neutral or slightly unstable (see Figure 5-2), over shorter periods of time, the wind speed- and *TI* profiles vary with the atmospheric stability. In effect, using the ERA5 dataset, the distribution of atmospheric stability classes at the M2 and IJmuiden met masts show, as expected from the literature (see Section 7.2 of [NORSW]), that stable- and very unstable to unstable atmospheric conditions occur for a non-negligible part of the time in the Southern- and Central North Sea.

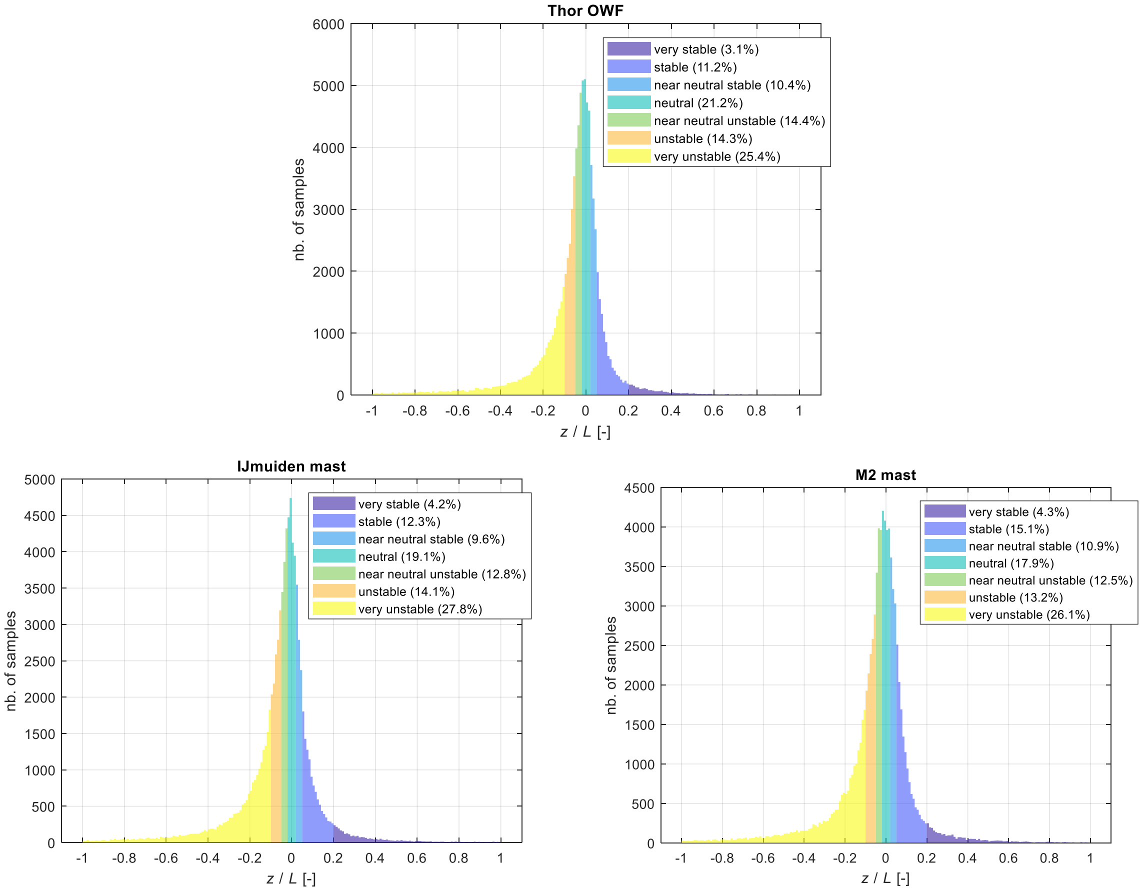

Figure 5-2: Histograms of atmospheric stability classes, at three locations, expressed in terms of z/L. Here, z = 10 mMSL, and L is the Monin-Obukhov length calculated using the method explicated in Section 6.2 of [NORSW], and the classification adapted from Table 1 of [SATHE10], and using the ERA5 dataset (time period: 2010-01 to 2020-05).

As shown in Figure 5-3:

- For stable atmospheric conditions (air temperature larger than the sea surface temperature), the mean wind speed profile follows a log- and/or power law only up to approximately 90 to 150 mMSL, above which it transitions to a much more modest increase with elevation. Above this transition elevation, the mean *TI*-value shown by the triangle markers reaches a constant value of 3 to 4 %.
- For unstable conditions, the wind speed profile follows a power law up to larger elevations than in stable conditions; the mean *TI* shown by the triangle markers is about 6% at 100 mMSL and steadily decreases above.

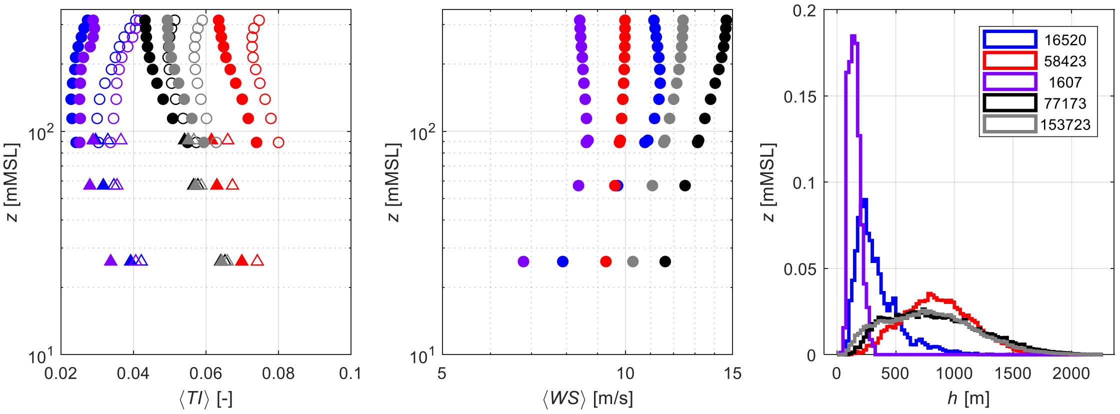

Figure 5-3: The filled- and empty symbols, and the circles and triangles, denote the same as in Figure 5-1, now with varying stability classes. Each colour represents a set of stability classes displayed in Figure 5-2: purple is "very stable", blue is "stable", black is "neutral and near neutral" and red is "unstable and very unstable"; the data plotted in grey include all stability classes. The numbers in the legend on the right-hand side show the number of 10-minute samples in each stability class.

These behaviours of the mean- and turbulent profiles are well described using the Monin-Obukhov Similarity Theory, valid within the surface layer and which can be extended up to the top of the atmospheric boundary layer; see Section 2 and its subsections of [PEÑA08]. The main difference between stable- and unstable atmospheric conditions is the presence of convection in the latter case, see this illustrated in Figure 5-4: the more stable the atmosphere, the larger the spectral gap (see also the discussion in Section 1.2 of [MIKKELSEN17]).

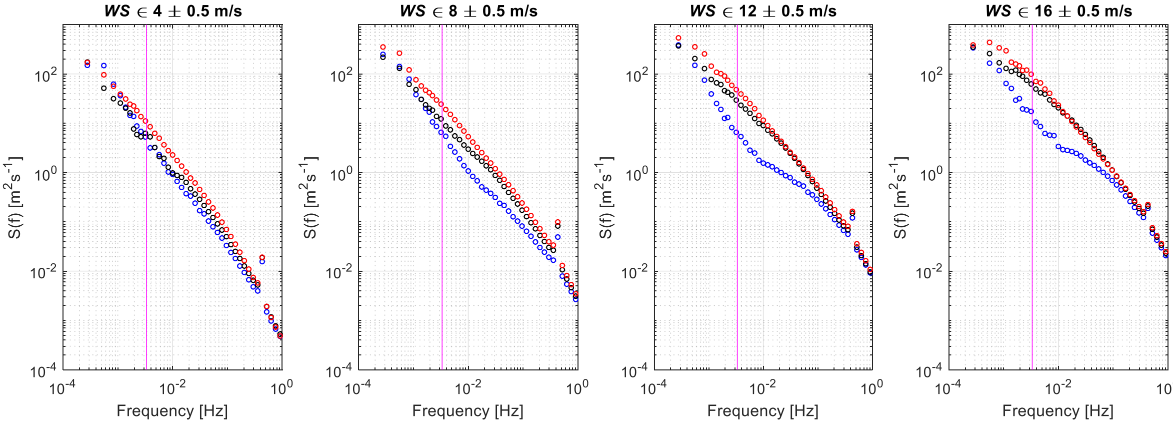

Figure 5-4: Mean hourly power spectra measured at the top of the IJmuiden met mast (91.1 mMSL), for various stability classes, and wind speed bins. The colours correspond to the ones in Figure 5-3. The low-frequency peak, at approximately 0.42 Hz, is an artefact caused by an eigenmode vibration of the mast[8].

It follows from the above that, since the atmospheric stability conditions are very similar across the North Sea (albeit with slightly more frequent occurrences of stable conditions along the British East Coast), that the Normal- and Extreme Turbulence conditions across these areas are similar. This has been well documented in [POLLAK] already, and here further confirmed by looking in Figure 5-5 at the similar dependence of the *TI* on the stability class, at IJmuiden and at M2.

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[8] See Section 2.3.2 here: http://pure.tudelft.nl/ws/portalfiles/portal/4369010/Thesis_Complete_FC.pdf.

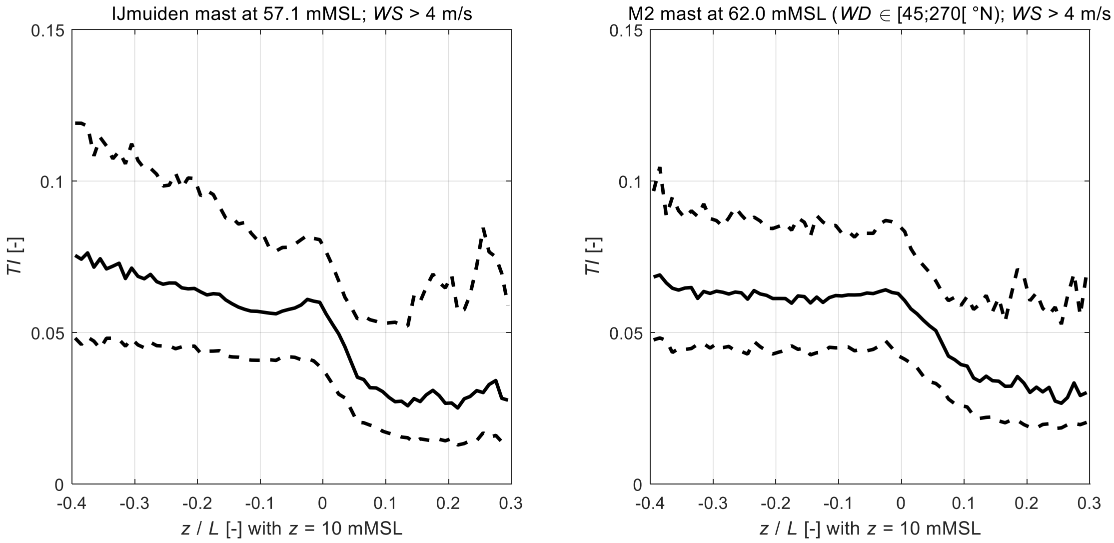

Figure 5-5: Dependence of *TI* on the atmospheric stability, for the IJmuiden and M2 met mast datasets (the stability is here expressed using the Monin-Obukhov length *L* and the ratio *z*/*L* where *z* = 10 mMSL. In the title of the rightmost plot, “Wind Direction” is abbreviated *WD*.

Please note that for M2, for the timestamps where the wind direction falls within the wind directional bin [270; 45[°N, the *TI*-values are slightly larger at M2 than at IJmuiden (plot not shown). This may be due to larger sea surface roughness, e.g. due to the presence of the reef (shallow waters), and thereby wave breaking[9]. Regardless, the events from this directional bin are not analysed further in the present report[10]. Instead, a comparison between M2 data for the wind directional bin [45; 270[°N with the IJmuiden and Høvsøre data is shown in Figure 5-6, and Figure 5-7 shows the directional bin and surrounding bathymetry.

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[9] Please note: it can also be due to unstable conditions being wrongly classified as stable due to inaccuracies in the ERA5 dataset.

[10] Since reasonable hub heights at the Thor project area are considerably larger than 62.0 mMSL, the surface roughness effects are much less important than for the M2 measurements, and the small unresolved difference of *TI*-values for the directional bin [270; 45] °N makes no substantial impact on the conclusions of this section.

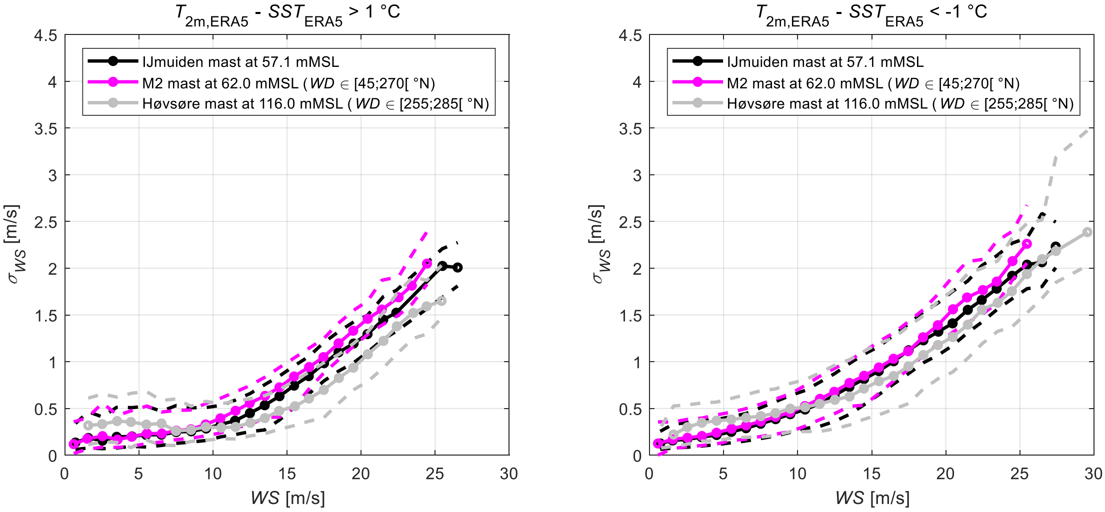

Figure 5-6: These plots show the *WS*-binned mean (fully drawn lines), and 10%- and 90% quantiles (dashed lines) of the standard deviation of the wind speed versus the mean wind speed (10-minutes samples), measured at the IJmuiden- and M2 met masts at similar elevations above mean sea level, and at the top of the Høvsøre met mast. Wind speed bins with less than 30 samples have been excluded from the analysis. For the M2- and Høvsøre met masts, only selected wind directions have been used, see the legend. Using the difference between air- and sea surface temperature as a proxy, this figure depicts stable- (left) and unstable atmospheric conditions (right). “Wind Direction” is abbreviated *WD*.

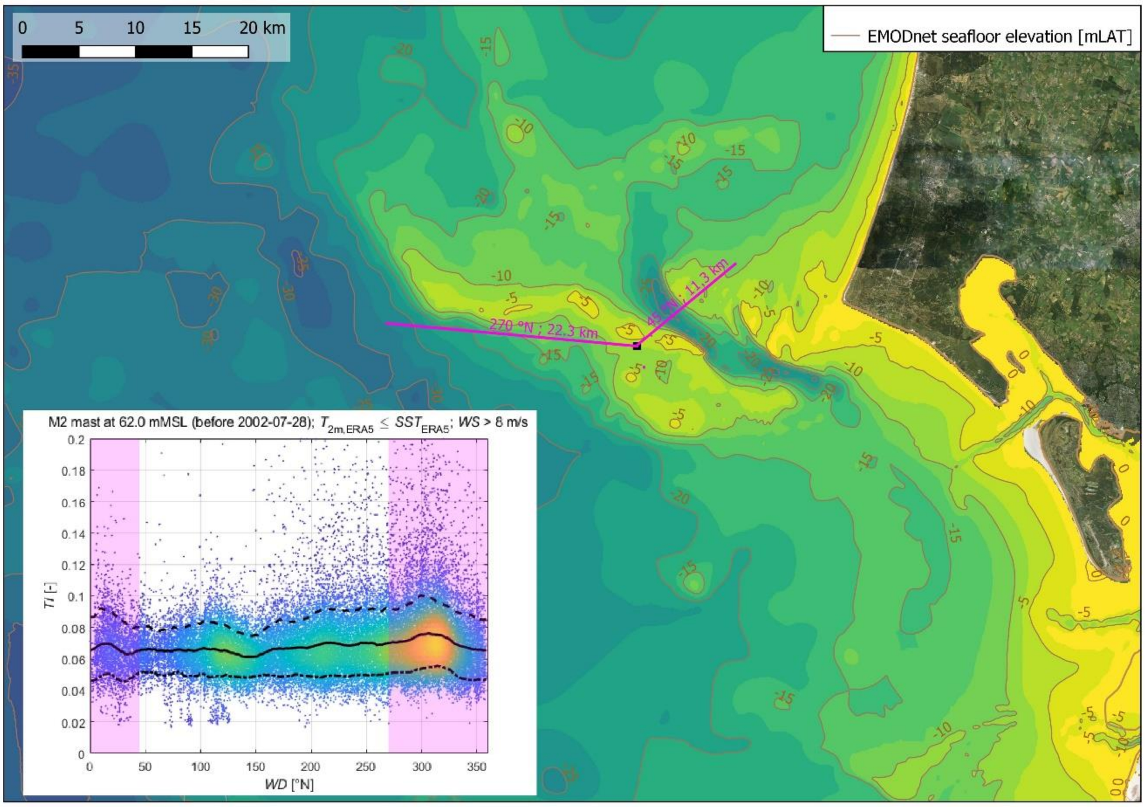

Figure 5-7: This figure shows bathymetry contour lines near the M2 met mast (marked with a black square), together with the insert at the bottom left: a plot of the mean (full line), 10%- and 90% quantiles (dashed lines) of the turbulence intensity measured in unstable conditions at the mast (10° moving average). The disregarded wind directional bin [270; 45] °N is marked in magenta (shaded area on the plot on the bottom-left, and headings on the map).

For ILA purposes, it is sufficient to use a single value of power law shear exponent for the NWP, and another for the EWM. Therefore, this is the approach chosen in Section 3.1.2. For the purpose of the analyses in this report, both the shear- and *TI* conditions are characterised using the IJmuiden met mast- and LiDAR dataset, since:

- Unlike the Høvsøre met mast, the IJmuiden met mast is located far offshore.
- The time series cover a larger part of the rotor span than the M2 met mast measurements do.
- The time series covers a longer period than the one at M2.
- The time series are well validated and of high quality.
- The atmospheric stability conditions at IJmuiden are similar to those of the Thor project area.

6. Appendix C: Method of Mean-of-Monthly-Means (MoMM)

To avoid that data gaps and non-integer number of years of data skew the results, all normal conditions analyses in this report have used the method of Mean-of-Monthly-Means. That said, the data from the IJmuiden met mast and IJmuiden LiDAR, which form the basis for much of the analysis, show exceptionally good availability.

For the Extreme Turbulence Model, Extreme Wind speed Model, and other extreme value analyses, no Mean-of-Monthly-Means method was applied since this method is not applicable to these types of analyses, and because the dataset analysed was sufficiently long that gaps and non-integer number of years did not influence the results.

The name of the method “Mean-of-Monthly-Means” has been taken from its use in the Windographer software documentation[11] to describe the method of weighting data points by how often they occur in a month of the year. In the present report, it is implemented in the following way:

- Ascribe to each measurement data point an integer $n \in [1,12]$, given by the month the data point is recorded in.
- Ascribe to each data point a weight, which will be used to weight the data point in all analyses where the Mean-of-Monthly-Means is used. This weight equals the maximum number of data points that are possible[12] in the month n divided by the actual number of data points.

For example, if we look at a dataset containing 3 separate months of January with full data coverage of 10-minute values, there will be:
3 · 31 days · 24 hours/day · 6 data points/hour = 13392 data points,
and each will be given a weight of:
(31 days · 24 hours/day · 6 data points/hour) / 13392 data points = 1/3.

The resulting weighting factors are used to calculate weighted statistical parameters: weighted means, weighted standard deviations, and weighted quantiles.

In this way, both non-integer number of years as well as gaps in the data will be corrected in a way that assumes the data is representative of both gaps and the missing fractions of years.

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[11] An example of using the expression “mean-of-monthly-means” is found in earlier versions of the documentation of the Windographer software.

[12] In this report, leap years are treated as if they have an extra day of measurements in February. Thus, a dataset with a single year, which has a leap-year February with all possible data points, will have each of these February-data points given a weight of 28/29.