Energinet Eltransmission A/S

Lot 2 (Kriegers Flak II)

Wind Assessment Supplementary Note

REPORT

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C2WIND

Document information and change log.

Revision	Date	Status / Reason for Issue	Author	Checker
0	2024-10-14	For internal QC	JOG	DWH
1	2024-10-18	Issued for Client	DWH	RGA
2	2024-11-13	Implementing Client comments	JOG	DWH
3	2024-11-26	Final version to Client	JOG	DWH

Section	Summary of Changes (latest revision only)
All	Final version to Client

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Abbreviations	
AGL	Above Ground Level
ASL	Above Surface Level. This is used when a surface-following vertical reference is needed for measurements on land, whereas SWL is typically used for the same purpose at sea (although ASL could in principle be used there as well).
CRS	Coordinate Reference System
DLC	Design Load Case Table
ECD	Extreme Direction Change
ECN	Energy research Centre of the Netherlands
EDC	Extreme Direction Change
EOG	Extreme Operating Gust
ETM	Extreme Turbulence Model
EVA	Extreme Value Analysis
EWM	Extreme Wind Model
EWS	Extreme Wind Shear
FEED	Front-End Engineering Design
FLS	Floating LiDAR System, Fatigue Limit State
HAT	Highest Astronomical Tide
ibid.	From Latin ibidem (“in the same place”), it is used to save space in textual references to a quoted work, or another section in the present document, which has been mentioned in a previous reference.
IFORM	Inverse first-order reliability method
ILA	Integrated Load Analysis
LAT	Lowest Astronomical Tide
MoMM	Mean Of Monthly Means
MSL	Mean Sea Level
NaN	Not a Number
NSS	Normal Sea State
NTM	Normal Turbulence Model
NWP	Normal Wind Profile
RNA	Rotor-Nacelle Assembly
SWL	Still Water Level
WTG	Wind Turbine Generator

Subscripts	
Hub	Value at Hub height
Free	Undisturbed inflow, i.e. Free Stream
Mean	Mean value
Ref	Reference
Agg	Aggregate (i.e. composed of several parts)

Symbols	
Latin characters	
WS, V	Wind Speed
WD	Wind Direction
N	Number of independent environmental states
A	Weibull scale parameter
k	Weibull shape parameter
g	9.816 m/s^2 is the gravitational acceleration[1]
h	Height
P	Pressure
P_x	Upper *x* % quantile of a set of values; e.g. P_{90} is the 90 % quantile
TI	Turbulence Intensity
t	Timestamp, i.e. a time-coordinate
T	Temperature, Time period (two separate meanings)
R	Ideal gas constant
RelH	Relative humidity
z	Elevation (i.e. vertical coordinate) above a vertical reference.
Greek characters	
ρ	Density
μ	Mean value
σ	Standard deviation
α	Power-law wind shear exponent

[1] See: https://www.wolframalpha.com/input?i=acceleration+of+gravity+at+r%C3%BCgen

Executive Summary

The present document gives input to the document *WTG Site Conditions Assessment* for the Kriegers Flak II Offshore Wind farm (KFII), and it is intended for this project only. It covers the analysis of wind conditions and other atmospheric conditions.

The document provides input to:

- The site-specific design of support structures (including towers) for the Wind Turbine Generators (WTGs).
- The evaluation of site suitability of the Rotor-Nacelle Assemblies (RNAs).

The results are referenced below:

Still Water Levels		**Reference**
0 mMSL = 0 mDVR90		Section 1.2 of [KFIIWA]
Normal conditions parameters. Given at h_{Hub} = 150.0 mDVR90		**Reference**
Weibull Mean wind speed	Not summarised; see Table 6-1	Appendix A and Table 6-1
Omni-directional Weibull wind speed distribution parameters	Not summarised; see Table 6-1	Appendix A and Table 6-1
Wind profile for wind speed extrapolation with elevation	$WS(z) = WS_{\mathrm{Hub}} \left(\frac{z}{h_{\mathrm{Hub}}}\right)^{0.09}$ Here, z and h_{Hub} are in mMSL.	Section 6.2.1
Wind profile for load calculations, Normal Wind Profile (NWP)	$WS_{\mathrm{NWP}}(z) = WS_{\mathrm{NWP,Hub}} \left(\frac{z}{h_{\mathrm{Hub}}}\right)^{0.126}$ Here, z and h_{Hub} are in mMSL.	Section 6.2.2
Normal Turbulence Model (NTM)	Not summarised; see Table 6-4 of [KFIIWA].	Section 6.3.1 of [KFIIWA]
Extreme Turbulence Model (ETM)	Largest of: ➢ IEC Class IB in Table 6-5 of [KFIIWA] ➢ Centre-wake *TI*(*WS*)	Section 6.3.2 of [KFIIWA]
Normal ambient air temperature range	-7 °C ≤ T < 26.0 °C	Section 6.4.1 of [KFIIWA]
Design temperature (lowest daily mean temperature)	0.1 °C	Section 6.4.1 of [KFIIWA]
Relative humidity limit	*RelH* ≤ 100 %	Section 6.4.2 of [KFIIWA]

Extreme conditions parameters (Extreme Wind speed Model, EWM). Given at h_{Hub} = 150.0 mDVR90		Reference
Wind profile for load calculations	$WS(z) = WS_{\text{Hub}} \left(\frac{z}{h_{\text{Hub}}}\right)^{0.11}$ Here, z and h_{Hub} are in mMSL.	Section 8.1 of [KFIIWA]
Wind profile for extreme wind speed extrapolation with elevation	$WS(z) = WS_{\text{Hub}} \left(\frac{z}{h_{\text{Hub}}}\right)^{0.11}$ Here, z and h_{Hub} are in mMSL.	Section 8.1 of [KFIIWA]
Mean air density	$\rho_{\text{Hub,EWM}} = 1.21\ \frac{\text{kg}}{\text{m}^3}$	Section 8.2 of [KFIIWA]
Maximum 10-minute mean wind speed for a 1-year EWM	$WS_{1,\text{Hub}}$ = 30.2 m/s	Section 8.3.6 of [KFIIWA]
Maximum 10-minute mean wind speed for a 5-year EWM	$WS_{1,\text{Hub}}$ = 33.3 m/s	Section 8.3.6 of [KFIIWA]
Maximum 10-minute mean wind speed for a 10-year EWM	$WS_{1,\text{Hub}}$ = 34.7 m/s	Section 8.3.6 of [KFIIWA]
Maximum 10-minute mean wind speed for a 25-year EWM	$WS_{1,\text{Hub}}$ = 36.3 m/s	Section 8.3.6 of [KFIIWA]
Maximum 10-minute mean wind speed for a 50-year EWM	$WS_{50,\text{Hub}}$ = 38.0 m/s	Section 8.3.6 of [KFIIWA]
Turbulence Intensity for use with EWM	TI_{EWM} = 11 %	Section 8.4 of [KFIIWA]
Other Conditions Given at h_{Hub} = 150.0 mDVR90		**Reference**
Extreme ambient air temperature range, 1-hour mean:	- 10.0 °C ≤ T < 31.0 °C	Section 6.4.1 of [KFIIWA]
Mean air temperature at hub height	8.7 °C	Section 6.4.1 of [KFIIWA]
Highest temperature in 25 years	31.0 °C	Section 6.4.1 of [KFIIWA]
Highest temperature while WTG in production	31.0 °C	Section 6.4.1 of [KFIIWA]
Lowest temperature in 25 years	-10.0 °C	Section 6.4.1 of [KFIIWA]
Lowest temperature while WTG in production	-10.0 °C	Section 6.4.1 of [KFIIWA]

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1. Introduction

Energinet Eltransmission A/S (EE, or "the Client") has appointed C2Wind ApS (C2Wind) to carry out Site Wind Conditions Assessment for the Kriegers Flak II project (Lot 2), located in the Danish Baltic Sea. The purpose of this document is to serve as a supplement to the Site Wind Conditions Assessment carried out with 8 months of on-site floating Lidar measurements [KFIIWA], updating the results after the measurement campaign gathered a full year of measurements. Thus, the present document repeats the structure of [KFIIWA], but only provides content in the sections where the additional months of measurements have resulted in changes to the conclusions of the analysis.

The numbering of tables and figures in this document preserves the numbering used in [KFIIWA]. Similarly, the list of references in this document does not reproduce in full that of [KFIIWA], but rather lists only the documents that are cited herein. Finally, the Executive Summary clearly indicates which results can be found in [KFIIWA] and which have been updated in the present document.

1.1 Geographical location

[There are no changes in this section]

1.2 General considerations

[There are no changes in this section]

2. Applied standards and guidelines

[There are no changes in this section]

3. Overview of available data and review of data quality

[There are no changes in this section]

3.1 Available data

[There are no changes in this section]

3.2 Sensor naming convention

[There are no changes in this section]

3.3 High-level quality check filters

[There are no changes in this section]

4. Generic methods

The updated analysis uses the same approach and methods as those in [KFIIWA].

4.1 Turbulence intensity detrending

[There are no changes in this section]

4.2 Method of Mean-of-Monthly-Means: Handling missing data

[There are no changes in this section]

4.3 Calculation of wind shear and extrapolating to hub height

[There are no changes in this section]

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5. Selection of representative analysis points

[There are no changes in this section]

6. Normal wind conditions

6.1 Normal conditions wind Weibull distribution and wind roses

This section has been updated with the results of a long-term correction using the full 1-year of measurements.

The wind speed distribution Weibull parameters at hub height have been derived in Appendix A for the analysis points found in Section 5 of [KFIIWA]. The analysis in Appendix A consisted of an update of that in [KFIIWA], namely the long-term correction of the measurements with an MCP approach, followed by spatial extrapolation to the analysis points.

The Weibull parameters describing the wind speed distribution at the analysis points are summarised in Table 6-1, while the wind rose applicable to all points is shown in Figure 6-1.

Site	Point	A	k	Mean wind speed
		[m/s]	[-]	[m/s]
KFII North	P1	11.13	2.19	9.89
KFII South	P2	11.00	2.15	9.79
KFII-1-LB		10.98	2.15	9.72
KFII-2-LB		10.92	2.19	9.67

Table 6-1: Weibull parameters estimated at the analysis points and FLS locations at hub height. The mean wind speed is calculated from the fitted Weibull parameters.

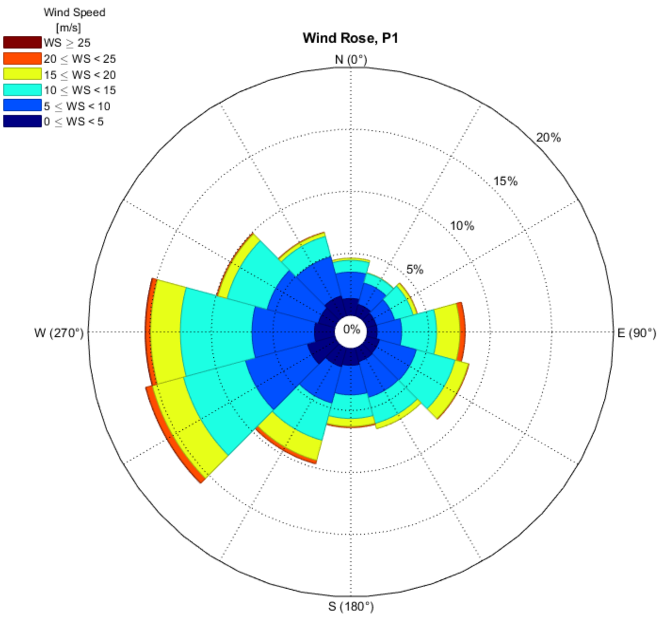


Figure 6-1: Wind rose corresponding to the long-term wind distribution at point P1, applicable to all analysis points.

For use in Fatigue Limit State (FLS) Design Load Cases (DLCs) in Integrated Load Analysis, particularly those involving Normal Sea States (NSS), joint directional occurrence frequencies for the wind speed and (Wind-Sea) wave directions are needed.

These are unambiguously provided through the misalignment tables in a Marine Assessment.

For some purposes, e.g. calculation of Wind Farm Turbulence, it is necessary to use directional occurrence frequencies of wind speeds. These can be found through summing over (Wind-Sea) wave directions in the aforementioned misalignment tables provided in the project's Marine Assessment. Alternatively, and requiring that the user first justifies its applicability for that purpose, the Marine Assessment provides directional Weibull fits that can be used for input to Wind Farm Turbulence analyses.

6.2 Wind shear and wind shear profile for normal conditions

The updated datasets resulted in no changes to the discussion and conclusions in this section. The precise numerical value of the fitted wind shear exponents did change, and thus Figure 6-2 has been updated.

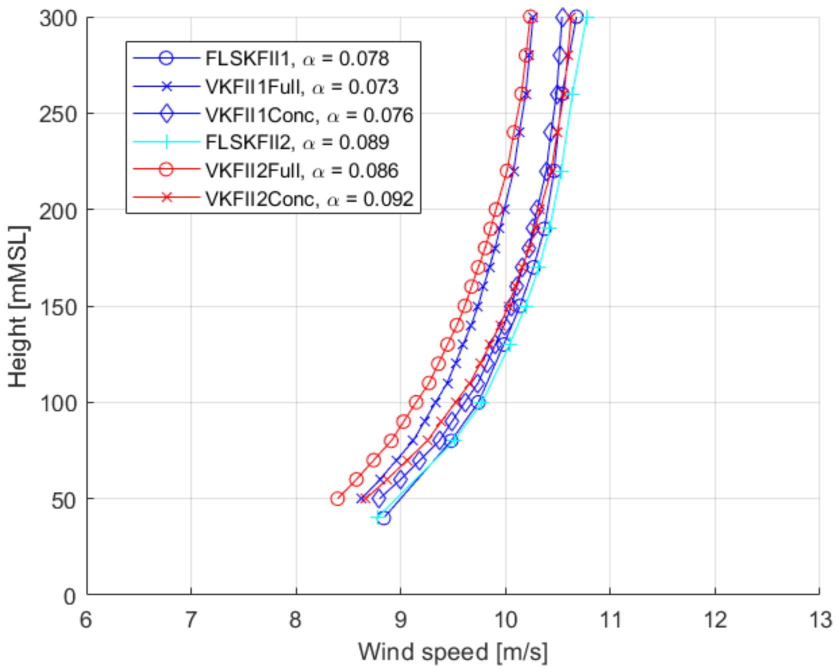


Figure 6-2: Mean wind speed profiles and fitted shear exponents to the 2 main KFII FLSs and their co-located Vortex model time series. Update to the corresponding Figure 6-2 of [KFIIWA] with updated datasets.

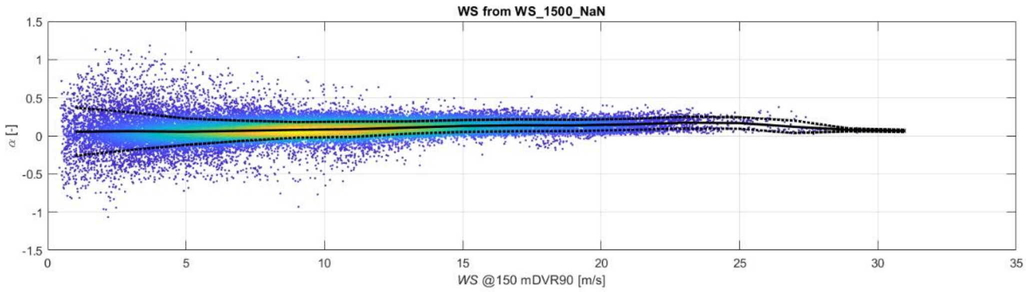
6.2.1 Normal conditions wind climate scaling

The results in this section have been updated, now assessing wind shear with the full year of measurements at the two FLSs and selecting the most conservative (numerically larger) value among the two.

Normal conditions wind speeds shall, for all wind directions, be transformed to other heights using a shear exponent of 0.09.

$$WS(h) = WS_{Hub}\left(\frac{h}{h_{\text{Hub}}}\right)^{0.09} \quad \text{Eq. 6-2}$$

Here, z and h_{Hub} are measured in metres above Mean Sea Level (MSL), i.e. mMSL.



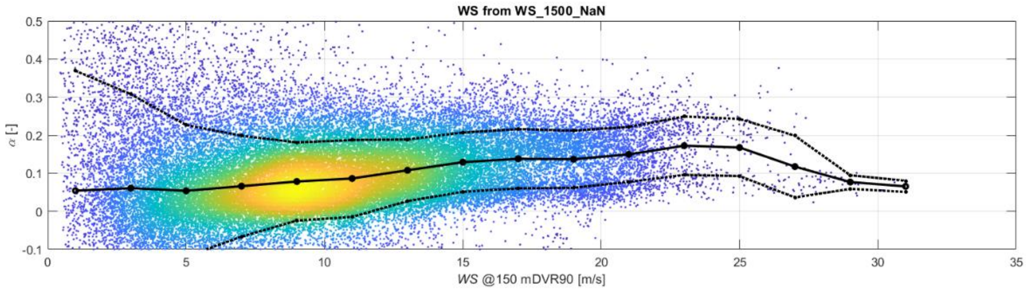


Figure 6-3: Scatter plots of wind shear exponents vs. hub height wind speed, obtained from the hub height sensor at the KFII-2-LB and fitting the wind profile across all elevations covering the rotor plane and up to 300 mMSL as listed in Section 1.2. The plots show the points coloured according to density. 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, show the mean-of-monthly means wind-speed binned mean values. The 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.

			Wind Direction [°N]												
WS bin		**Min**	-15	15	45	75	105	135	165	195	225	255	285	315	
[m/s]		**Max**	15	45	75	105	135	165	195	225	255	285	315	345	**Omni**
≤	**<**	**Centre**	**0**	**30**	**60**	**90**	**120**	**150**	**180**	**210**	**240**	**270**	**300**	**330**	
0	2	**1**	0.060	0.101	0.022	0.037	0.041	0.118	0.059	-0.061	0.014	0.081	0.059	0.137	0.054
2	4	**3**	0.098	0.071	0.092	0.050	0.024	0.048	-0.030	0.015	0.067	0.143	0.095	0.122	0.061
4	6	**5**	0.059	0.001	0.026	0.019	0.027	-0.031	0.009	0.038	0.102	0.118	0.096	0.066	0.054
6	8	**7**	0.063	0.048	0.037	-0.013	0.012	0.047	0.083	0.092	0.104	0.078	0.086	0.079	0.066
8	10	**9**	0.046	0.010	0.021	0.051	0.038	0.107	0.088	0.100	0.103	0.090	0.094	0.048	0.078
10	12	**11**	0.068	-0.003	0.023	0.016	0.038	0.124	0.121	0.128	0.124	0.100	0.101	0.061	0.086
12	14	**13**	0.053	-0.021	0.067	0.055	0.071	0.103	0.147	0.132	0.134	0.108	0.114	0.090	0.108
14	16	**15**	0.060	-	0.077	0.094	0.116	0.126	0.162	0.163	0.157	0.128	0.112	0.092	0.129
16	18	**17**	-	-	0.137	0.096	0.172	0.127	0.182	0.164	0.170	0.143	0.097	0.067	0.138
18	20	**19**	-	-	0.108	0.090	0.186	0.185	0.175	0.162	0.195	0.149	0.117	0.071	0.137
20	22	**21**	-	-	0.126	0.131	0.052	-	0.201	0.128	0.196	0.178	0.114	-	0.149
22	24	**23**	-	-	0.070	0.172	-	-	0.200	0.180	0.218	0.203	0.112	-	0.172
24	26	**25**	-	-	0.030	0.120	-	-	0.171	0.209	0.206	0.221	0.096	-	0.167
26	28	**27**	-	-	0.066	0.072	-	-	-	0.233	0.222	0.164	0.320	-	0.117
28	30	**29**	-	-	-	0.077	-	-	-	-	-	-	-	-	0.077
30	32	**31**	-	-	-	0.065	-	-	-	-	-	-	-	-	0.065
Mean over *WS*:			**0.065**	**0.033**	**0.047**	**0.069**	**0.052**	**0.082**	**0.083**	**0.099**	**0.123**	**0.117**	**0.098**	**0.078**	**0.089**

Table 6-2: Mean shear exponent measured at KFII-2-LB, binned as function of wind speed and wind direction.

6.2.2 Wind shear exponent to use in load calculations requiring Normal Wind Profile

The results in this section have been updated, now assessing wind shear with the full year of measurements at the two FLSs and selecting the most conservative (numerically larger) value among the two.

WS bin [m/s]		# 10-min samples [-]	Mean shear exponent [-]	Std. dev. of shear exponent [-]	Mean absolute shear exponent [-]	Std. dev. of absolute shear exponent [-]
≤	<					
0	2	1162	0.054	0.315	0.245	0.205
2	4	3883	0.061	0.247	0.174	0.185
4	6	5305	0.054	0.173	0.123	0.133
6	8	6237	0.066	0.133	0.104	0.106
8	10	7274	0.078	0.103	0.096	0.086
10	12	6383	0.086	0.101	0.105	0.081
12	14	5178	0.108	0.081	0.114	0.071
14	16	3626	0.129	0.078	0.130	0.075
16	18	2613	0.138	0.078	0.140	0.075
18	20	1944	0.137	0.075	0.140	0.069
20	22	1332	0.149	0.072	0.149	0.072
22	24	407	0.172	0.077	0.172	0.077
24	26	97	0.167	0.075	0.167	0.075
26	28	56	0.117	0.081	0.117	0.081
28	30	18	0.077	0.018	0.077	0.018
30	32	2	0.065	0.015	0.065	0.015

Table 6-3: Statistical shear exponent values to use as input for the selection of shear exponent to use for deriving the Normal Wind Profile (NWP); i.e. for use in the Integrated Load Analyses that require this wind profile type. The values shaded with light blue are the ones that Section 12.3 in [IEC6131] requires are used to evaluate the shear exponent to be used for Integrated Load Analysis with NWP for an IEC Class I site (0.2-0.4·V_{Ref}); as noted in the text above, this is in line with the suggestions in Section 6.4.3.1 of [IEC6131]. The values for the largest WS_{Hub}-bins have their values listed in grey text to highlight that they are found using only a few data points.

The wind shear exponent for the NWP is found as the (unweighted) mean of the values in the cells shaded light blue in Table 6-3 to 0.126:

$$WS_{\mathrm{NWP}}(z) = WS_{\mathrm{NWP,Hub}} \left(\frac{z}{h_{\mathrm{Hub}}}\right)^{0.126} \qquad \text{Eq. 6-3}$$

Here, *z* and h_{Hub} are measured in metres above Mean Sea Level (MSL), i.e. mMSL.

This value of 0.126 is larger than the mean value from Table 6-2, but smaller than the mean value for some individual wind directional bins such as [225; 285[°N. This is expected, as the largest shear values do not occur for the most frequent wind directional bin. Also, this is acceptable since these mean shear values remain smaller than the value of 0.2 used for RNA type certification.

6.3 Free Stream Turbulence Intensity

The general discussion in this section has been updated, and the analysis of directional dependence in FLS-measured turbulence intensity has been updated with the full year of measurements. The additional months have mostly added northeasterly and easterly winds, offshore directions that change little to the overall picture and discussion in [KFIIWA].

Figure 6-5 and Figure 6-6 have been updated as shown below, but the discussion and conclusion remain valid:

- While the absolute FLS-measured turbulence intensity values are likely biased compared to cup anemometer measurements applicable for deriving an NTM, their directional dependence is useful in assessing whether the FLSs see differences in the incoming flow that can be clearly attributable to land or neighbouring OWFs.
- The plots in Figure 6-5 show no conclusive signs of any impact of neighbouring OWFs or land on the Lidar-measured *TI* at 150 mMSL, that is, the three datasets are seen to have the same *TI* trends in the approximate wind direction range [75; 300]°, despite having very different upstream features regarding both neighbouring OWFs and land. While the slight differences in the wind direction range [320; 60]° could seem to indicate a sector of higher turbulence for onshore directions at FLSs 2 & 3, closer inspection reveals this is not the case. The reason for the differences in the wind direction range [320; 60]° and the higher variance – as seen by the gap between the 50- and 90-percent quantile lines in all three subplots – in those directions is likely the small number of datapoints in those directions, as seen in Figure 6-6, where the plots from Figure 6-5 have been reproduced now removing the point clouds and adding histograms to indicate the amount of data points in each directional bin. The differences and higher variance in the wind direction range [320; 60]° are more likely caused by the low number of data points rather than upstream onshore conditions. Furthermore, the fact that no clear impact of neighbouring OWF wake is visible is expected, since the measurement height at 150 mMSL is much higher than the hub height at the OWFs (between 80 m and 110 m), and since the nearest possible WTG in each OWF is at least 7 km away from any given FLS – equivalent to between 42 and 58 rotor diameters for the WTGs with 167 m and 120 m rotor diameters installed at these parks.
- Thus, the turbulence intensity is treated omnidirectionally in the present document. Furthermore, following the analyses in Appendix C of [KFIIWA], it is characterized using measurements from the top-mounted cup anemometers at the FINO2 met mast, extrapolated to hub height by using the instantaneous measured wind shear exponent fitted to the anemometers at 72, 82 & 92 mMSL.

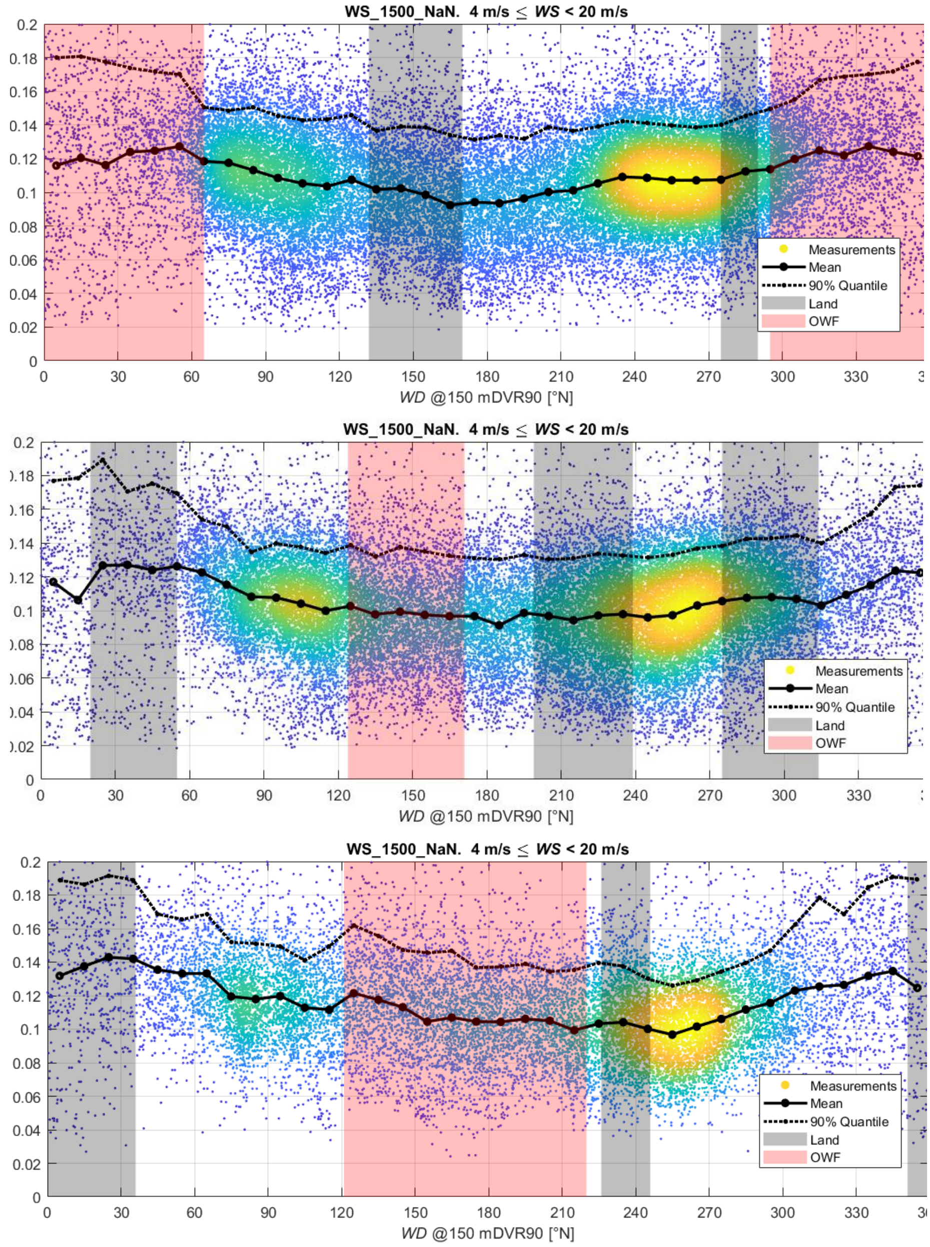


Figure 6-5: FLS-measured TI at 150 mMSL as a function of wind direction at 150 mMSL for KFII-1-LB (top), KFII-2-LB (middle) and KFII-3-LB (bottom). Please note that the bottom plot is unchanged from that in [KFIIWA], as no new data has been measured there. Binned mean values are plotted with a solid black and the 90% quantiles are plotted with a dotted black line. The grey areas indicate wind directions where the wind comes from land, while the red areas indicate directions where there is an operational OWF upstream.

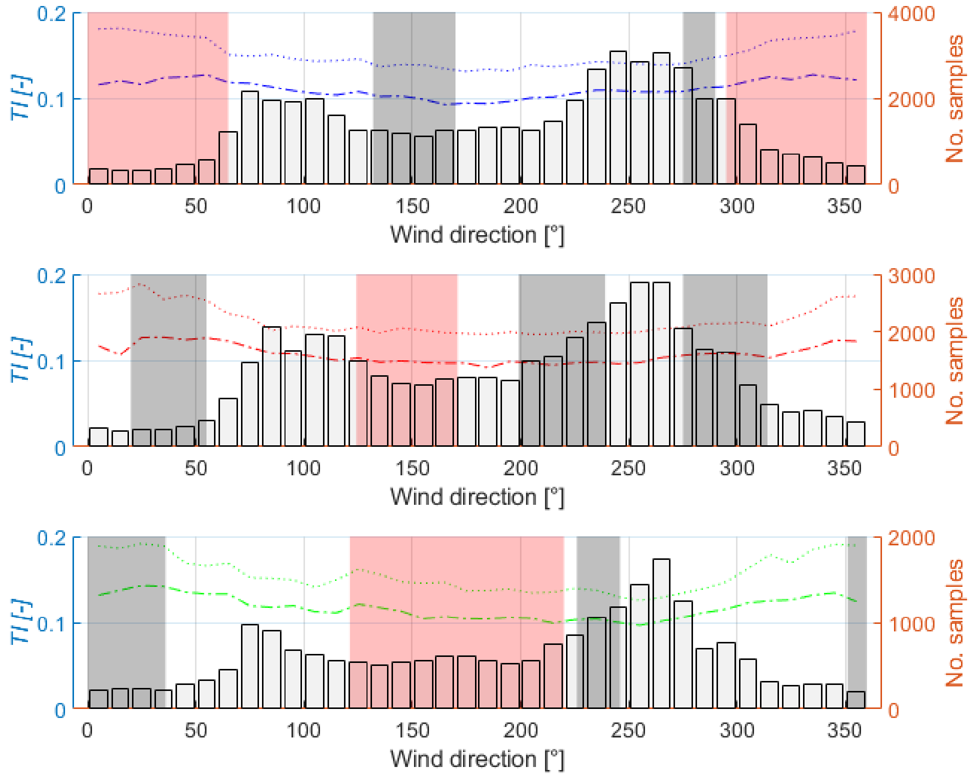


Figure 6-6: Reproduction of the plots from Figure 6-5, removing the point clouds and adding histograms to indicate the amount of data points in each directional bin example.

6.3.1 Normal Turbulence Model and turbulence statistics

[There are no changes in this section]

6.3.2 IFORM analysis and discussion of ETM

[There are no changes in this section]

6.4 Other normal conditions air parameters

6.4.1 Air temperature

The comparisons between the Vortex model and the FLS measurements have been repeated with the additional data. The correlation remains strong, the bias remains small, and the conclusion to use the Vortex model data to describe air temperatures remains valid, see Figure 6-8.

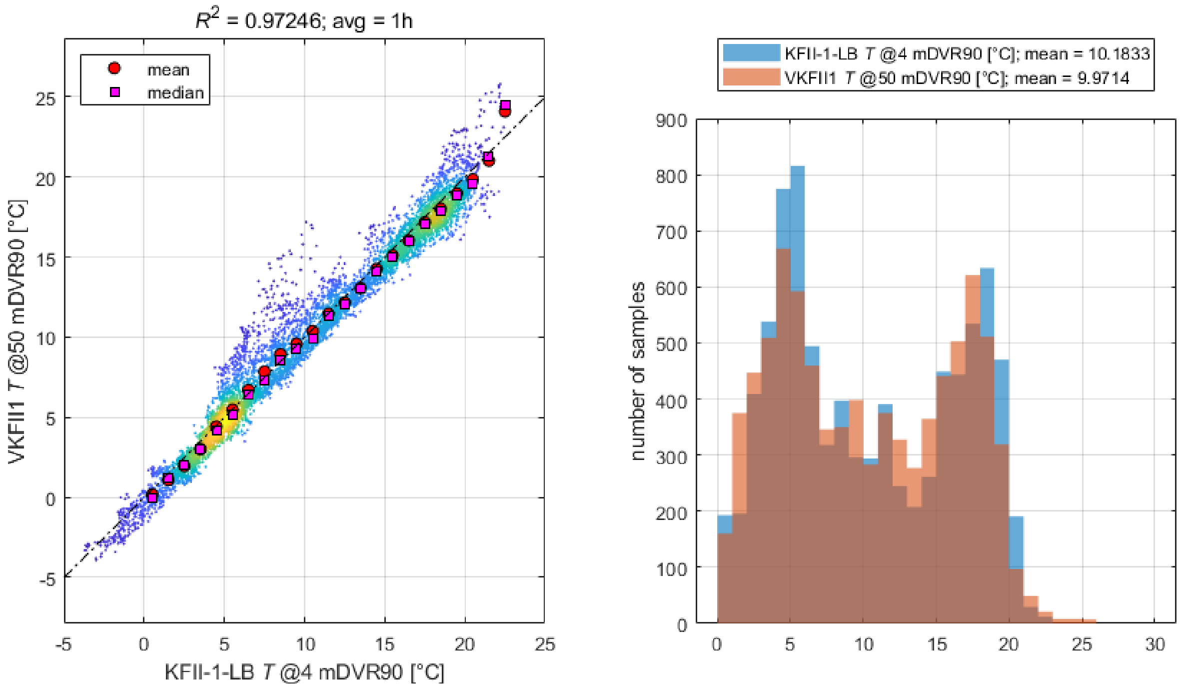


Figure 6-8: Scatter plot and histograms between air temperatures measured by KFII-1-LB and from the co-located Vortex model. The air temperature measured by the FLS is at 4.1 mSWL while the model data is at 50 mMSL.

6.4.2 Air humidity

The comparisons between the Vortex model and the FLS measurements have been repeated with the additional data. The correlation remains strong and the conclusion to use the Vortex model data to describe air temperatures remains valid, see Figure 6-11.

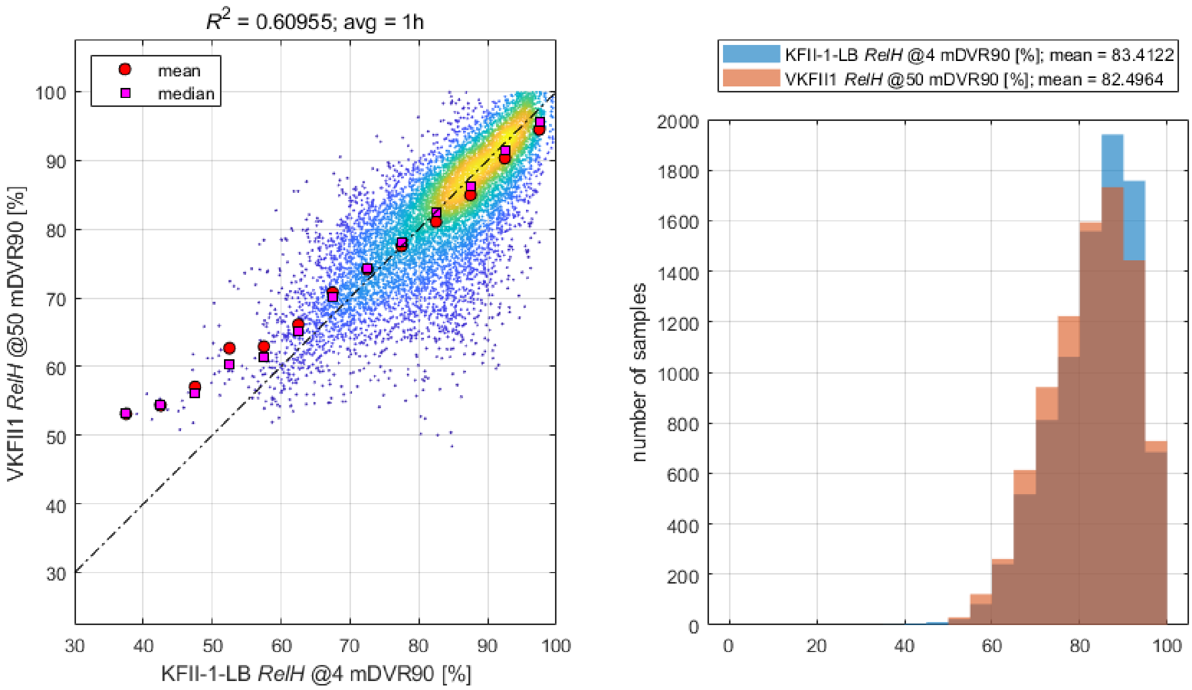


Figure 6-11: Scatter plot and histograms between relative humidity measured by KFII-3-LB at 4.1 mSWL and from the co-located Vortex model at its lowest elevation, 50 mMSL.

6.4.3 Air pressure

The comparisons between the Vortex model and the FLS measurements have been repeated with the additional data. The correlation remains strong and the conclusion to use the Vortex model data to describe air temperatures remains valid, see Figure 6-13.

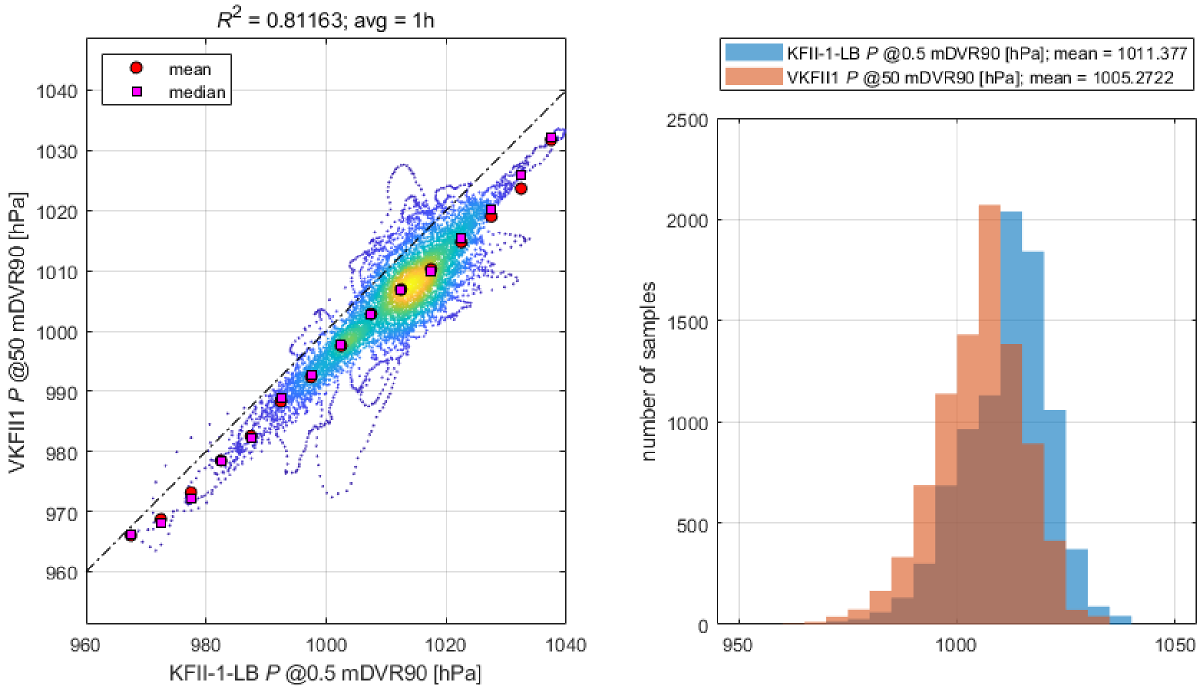


Figure 6-13: Scatter plot and histograms between atmospheric pressure measured by KFII-1-LB at 0.5 mSWL and from the co-located Vortex model at its lowest elevation, 50 mMSL.

6.4.4 Air density

The comparisons between the Vortex model and the FLS measurements have been repeated with the additional data. The correlation remains strong and the conclusion to use the Vortex model data to describe air temperatures remains valid, see Figure 6-16 and Figure 6-17.

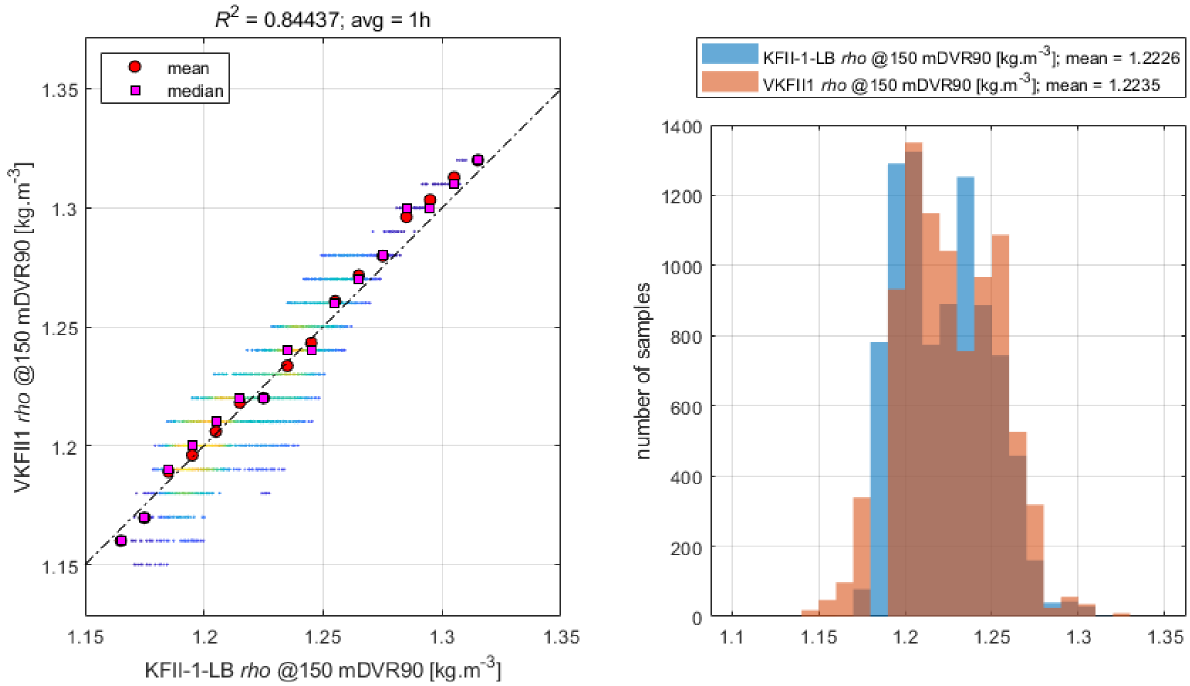


Figure 6-16: Scatter plot and histograms between air density at hub height derived from KFII-1-LB measurements as explained in the text, and modelled by the co-located Vortex model at hub height.

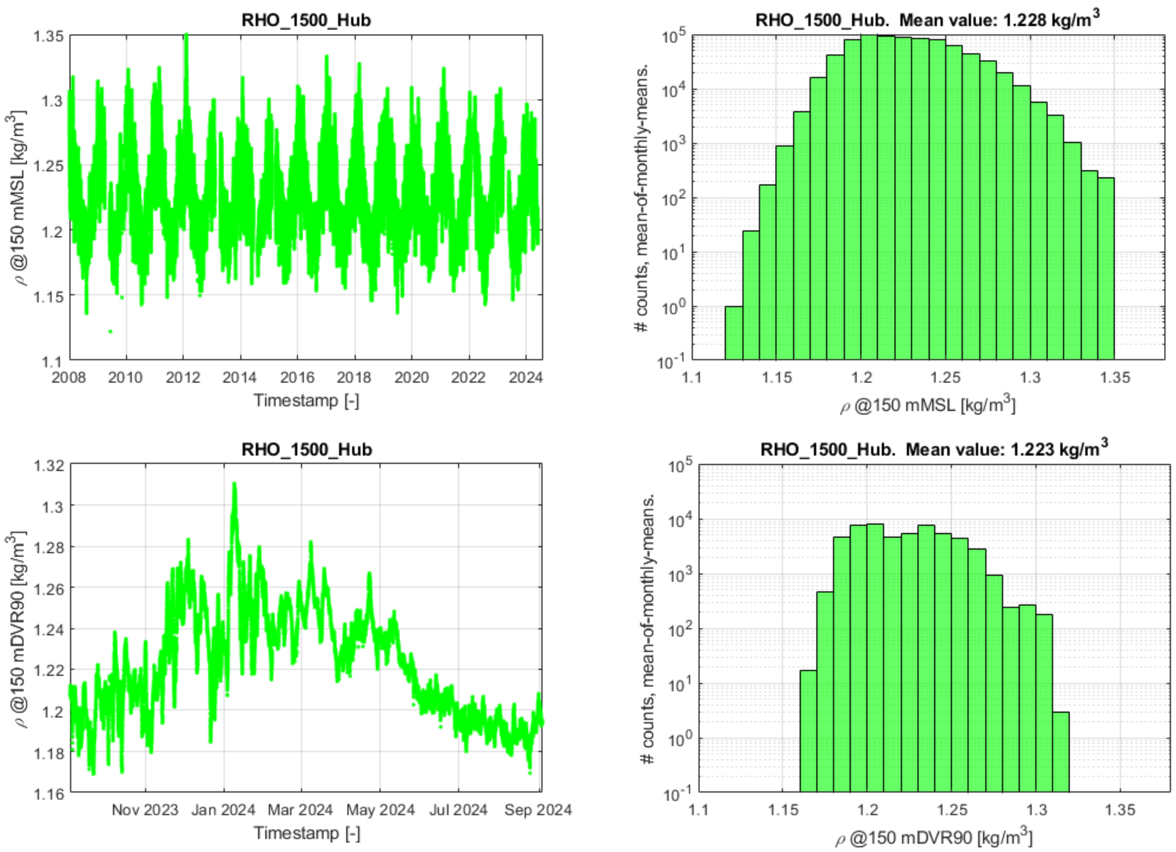


Figure 6-17: Air density at 150 mMSL from the FINO2 measurements (top) and 150 mDVR90 from the KFII-1-LB measurements (bottom). The left part of the figure shows the model time series, and the right part of the figure shows an MoMM histogram of the values with a logarithmic 2nd axis. The MoMM mean value is shown in the title above the histogram.

7. Wind farm induced conditions and gust conditions

7.1 Operational conditions – Wake and Wind Farm Turbulence

[There are no changes in this section]

7.2 Operational conditions – Gust amplitudes

[There are no changes in this section]

7.3 Extreme wind speed conditions

[There are no changes in this section]

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8. Extreme wind speed model

8.1 Wind shear for the Extreme Wind speed Model
[There are no changes in this section]

8.2 Air density for the Extreme Wind speed Model
[There are no changes in this section]

8.3 Extreme Wind speeds
[There are no changes in this section]

8.3.1 Eurocode 1 supplemented by DS 472
[There are no changes in this section]

8.3.2 Extreme Value Analysis using the FINO2 met mast dataset
[There are no changes in this section]

8.3.3 Extreme Value Analysis using the Arkona met mast dataset
[There are no changes in this section]

8.3.4 Estimates from X-WiWa
[There are no changes in this section]

8.3.5 Estimates from Global Atlas of Siting Parameters
[There are no changes in this section]

8.3.6 Comparison of, and conclusion on, extreme wind speed estimates
[There are no changes in this section]

8.4 Turbulence for the Extreme Wind speed Model
[There are no changes in this section]

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9. Other environmental conditions

9.1 Lightning

[There are no changes in this section]

9.2 Solar radiation

[There are no changes in this section]

9.3 Earthquakes

[There are no changes in this section]

9.4 Icing on blades

[There are no changes in this section]

9.5 Precipitation

[There are no changes in this section]

9.5.1 Seasonal precipitation

[There are no changes in this section]

9.5.2 Hail

[There are no changes in this section]

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10. References

[DOW30DR] **Energinet Eltransmission**. Stations and deployment record – DOW2030. Filename: *Stations and deployment record - DOW2030.xlsm*

[DOW30GR] **Fugro**. Gap Report 01, Kriegers Flak II. Danish Offshore Wind 2030 – Floating LiDAR Measurements. Doc No. C75517-KFII-GAP-01 03. (2024-02-28).

[DOW30MR] **Fugro.** Danish Offshore Wind 2030 – Floating LiDAR Measurements. Monthly Reports for Kriegers Flak II. *Sharepoint folder containing 12 monthly reports for the two FLSs in KFII, covering the period 2023-09 to 2024-09.*

[IEC613] **IEC.** IEC 61400-3-1: Wind energy generation systems – Part 3-1: Design requirements for fixed offshore wind turbines. Edition 1.0. International Electrotechnical Commission (2019-04-05).

[IEC6131] **IEC.** IEC 61400-3-1: Wind energy generation systems – Part 3-1: Design requirements for fixed offshore wind turbines. Edition 1.0. International Electrotechnical Commission (2019-04-05).

[KFIIWA] **C2Wind.** Lot 2 (Kriegers Flak II) – Wind Assessment. Doc. no. 23072-04-03, Rev. 4. (2024-09-24).

[SHAREP] **Energinet Eltransmission**. Sharepoint site: 505-Site Wind Conditions Assessment North Sea I. Link: https://energinet.sharepoint.com/sites/PR_505-SiteWindConditionsAssessmentNorthSeaI

[SWLB083] **DNV.** SWLB083. Independent performance verification of SEAWATCH Wind Lidar Buoy at Frøya, Norway. Doc. No. 10422674-R-14-A (2023-07-28).

[ZX1646] **DNV.** ZX1646. Independent analysis and reporting of ZX Lidars performance verification executed by ZX Lidars at the UK Remote Sensing Test Site. Doc. No. 10422597-A-7-C (2023-03-24).

Appendices

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Appendix A. Derivation of Weibull parameters

A.1 Long-term hub height wind speed at the KFII FLSs

The changes in this section relate to updating the long-term correction to use the full 1-year of measurements.

The long-term correction can be done using another available time series which better represents the distribution of the wind speed in the long-term. The following model datasets were considered as potential long-term references:

- **NORA3**: This mesoscale time series was found to have a good correlation with the FLS measurements collected at KFII and Energy Island Bornholm (EIB), but are only available until 2024-02-31, thus having only 4 concurrent months with the KFII-1-LB and KFII-2-LB datasets. Since such a short concurrent period would exacerbate the risk of seasonal bias already present with the short measurement duration, it was decided not to use NORA3 for the long-term correction of the FLS measurements.
- **Vortex**: This mesoscale time series was found to have a good correlation with the FLS measurements at KFII and is available for the period from 1994-01-01 to 2024-10-04, thus allowing for the use of the full FLS measured dataset.
- **ERA5**: This reanalysis time series was found to have a good correlation with the FLS measurements at KFII and EIB and is available for the period from 1940-01-01 to 2024-09-15, thus also allowing for the use of the entire measured dataset. Since ERA5 was used as input to the Vortex time series, these two datasets are not independent, and only the higher quality Vortex dataset was included in the long-term correction.
- **MERRA2**: This reanalysis time series was found to have a good correlation with the FLS measurements at KFII and EIB and is available for the period from 1980-01-01 to 2024-09-01, thus also allowing for use of the entire measured dataset.

The methodology is unchanged from that in [KFIIWA] with regards MCP regression and sensitivities to averaging windows and long-term period definition. The updated MCP results are summarised in Table A-2.

Results from MCP analysis Long-term WS at KFII FLSs @ 150 mMSL [m/s]								
Location	Long-term reference	LT start 2019-09 (5 y)	LT start 2014-09 (10 y)	LT start 2009-09 (15 y)	LT start 2006-09 (18 y)	LT start 2004-09 (20 y)	LT start 1999-09 (25 y)	LT start 1994-09 (30 y)
KFII-1-LB	Vortex	9.65	9.72	9.72	9.78	9.72	9.68	9.66
KFII-1-LB	MERRA2	9.65	9.71	9.70	9.74	9.69	9.65	9.65
KFII-2-LB	Vortex	9.61	9.70	9.69	9.74	9.68	9.64	9.63
KFII-2-LB	MERRA2	9.68	9.74	9.73	9.77	9.71	9.68	9.67
Long-term *WS* for KFII-1-LB		9.65	9.71	9.71	**9.76**	9.71	9.66	9.65
Long-term *WS* for KFII-2-LB		9.65	9.72	9.71	**9.75**	9.70	9.66	9.65

Table A-2: MCP results for the 150 mMSL wind speed time series at each of the FLS locations. The results selected to continue the analysis are highlighted in bold.

The resulting long-term wind speed at 150 mMSL at the KFII-1-LB and KFII-2-LB locations are 9.76, and 9.75 m/s, respectively. These results were obtained as the average of the MCP results regressions with the two reference datasets shown in Table A-2 for a long-term period of 18 years. The 150 mMSL wind speed and wind direction time series resulting from the MCP analysis with the Vortex time series as a long-term reference has been scaled to the long-term mean wind speed obtained at each FLS location. The decision to use the time series resulting from MCP with the Vortex dataset was taken because:

- The Vortex time series was found to have the best correlation with the FLS measurements, see for instance Figure A-1 for comparisons for KFII-1-LB. Results for the other two FLSs are consistent with this trend.
- The shape of the wind speed- and direction frequency distributions from the Vortex time series is the most similar to those of the FLS measurements, see Figure A-1 for comparisons for KFII-1-LB. Results for the other two FLSs are consistent with this trend.
- When comparing the time series resulting from the MCP with their respective short-term measurements over the concurrent period and using the fitted Weibull parameters as metric, the MCP time series obtained using the Vortex time series as long-term reference is consistently found to be the closest to the measurements, see Table A-3.

FLS	MCP time series	A FLS	A MCP time series	k FLS	k MCP time series
		[m/s]	[m/s]	[-]	[-]
KFII-1-LB	MCPVortexKFII1	12.05	12.17	2.18	2.16
	MCPERA5KFII1	12.05	12.32	2.18	2.12
	MCPMERRA2KFII1	12.05	12.46	2.18	2.11
KFII-2-LB	MCPVortexKFII2	11.58	11.74	2.21	2.12
	MCPERA5KFII2	11.58	11.91	2.21	2.06
	MCPMERRA2KFII2	11.58	12.06	2.21	2.08

Table A-3: Weibull parameters from the measurements of the FLSs deployed within Kriegers Flak II and MCP time series obtained when using different long-term reference time series.

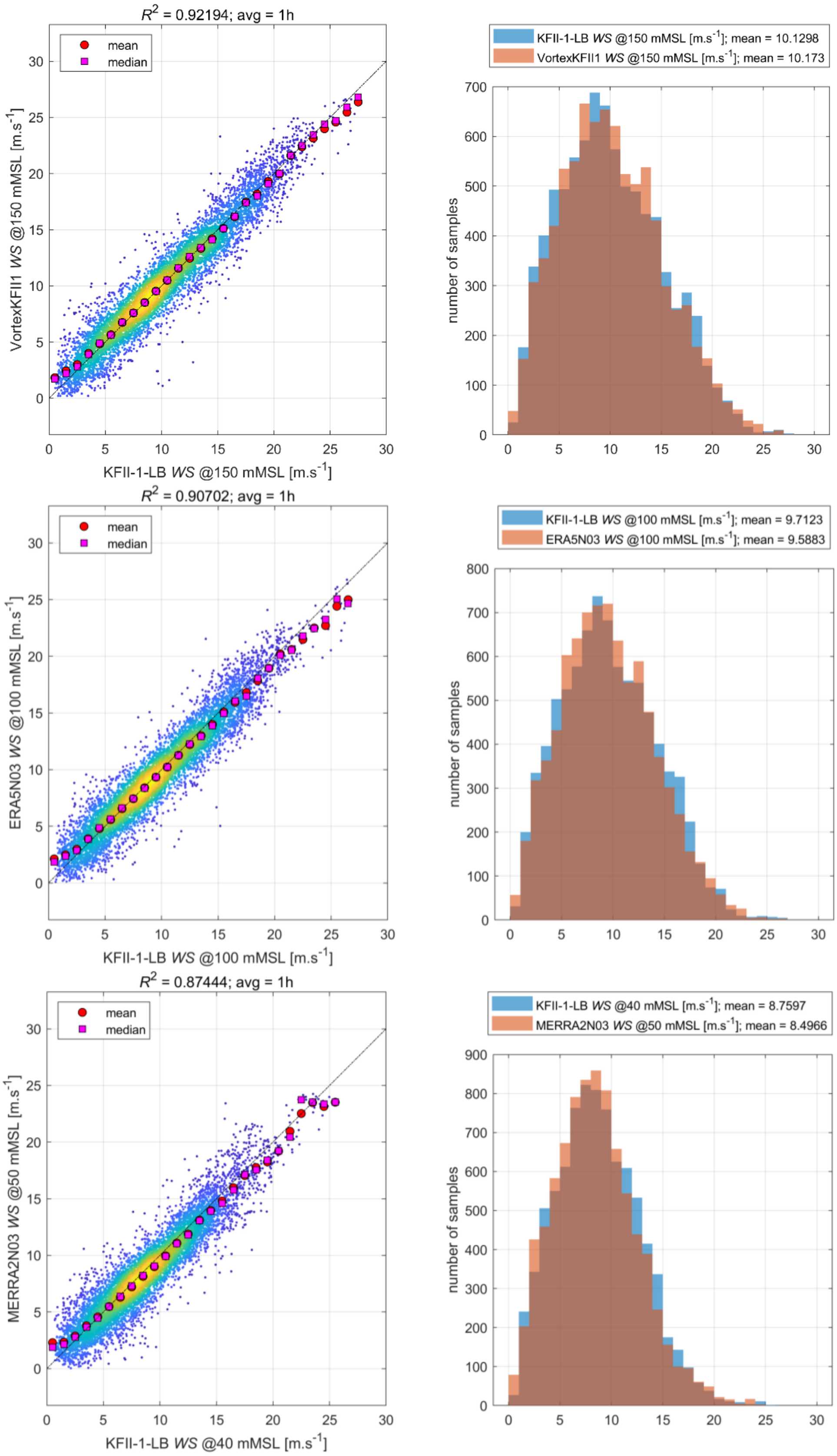

Figure A-1: Wind speed scatter plot (left) and histogram (right) of the FLS measurements and three candidate long-term reference time series (top: Vortex, middle: ERA5, bottom: MERRA2) for KFII-1-LB.

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A.2 Horizontal extrapolation to the analysis points location

[There are no changes in this section]

A.3 Summary of Weibull parameters

The resulting wind speed distributions and Weibull parameters estimated at each of the analysis points and at the two FLSs are illustrated in Figure A-2 and summarised in Table A-5.

Site	Point	A	k	Mean wind speed
		[m/s]	[-]	[m/s]
North	P1	11.13	2.19	9.89
South	P2	11.00	2.15	9.79
KFII-1-LB		10.98	2.15	9.72
KFII-2-LB		10.92	2.19	9.67

Table A-5: Weibull parameters estimated at the analysis points.

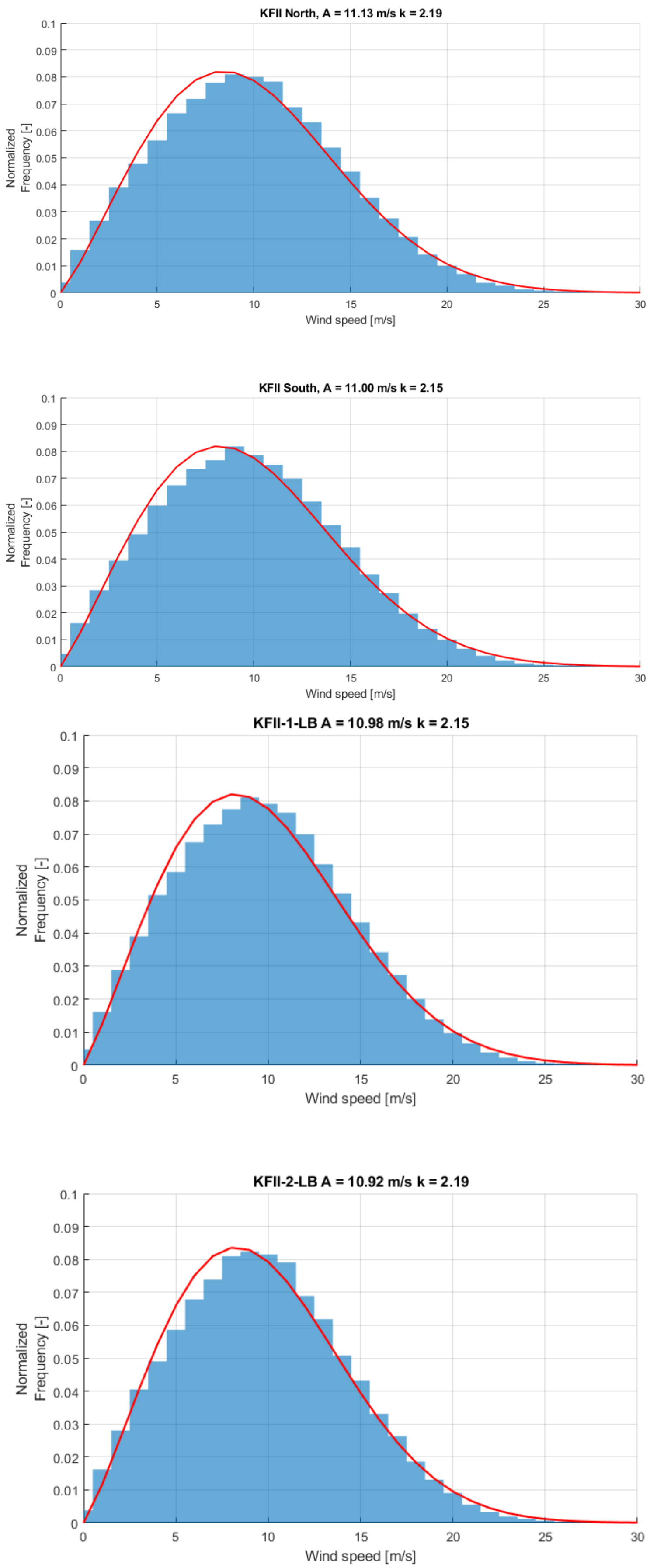

Figure A-2: Wind speed histogram of the wind climate estimated at each of the analysis points and the locations of the FLSs.

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Appendix B. Description of Wind Measurement Datasets

B.1 Kriegers Flak II FLS measurement campaign

[There are no changes in this section]

B.1.1 Instrumentation setup

An additional FLS has been swapped-in at the KFII sites since the writing of [KFIIWA]. Its details are summarised in Table B-2, intended as a supplement to Table B-2 of [KFIIWA].

Parameters	Instrument	Serial Number	Calibration certificate
SWLB083			
Wind speed & direction	ZX Lidars ZX300M	ZX1646	[ZX1646]
Wind speed & direction	Gill Instruments 1405-PK-300	23100157	Y
Wave parameters	Fugro Oceanor Wavesense 3.2	375	Y
Current profile & water temp.	Nortek Signature500	104511	Y
Air temp. & humidity	Vaisala HMP155	V0831117	Y
Air pressure	Vaisala PTB330	V0831798	Y
Precipitation	Young 50203	03028	Y
Visibility (fog)	Netsens MiniOFS	23150083	Y
Water level	Thelma Biotel ADT-HP16_v3.0	02YM-0017	N*
Position	Iridium 9602	0033217	NA
Position	Septentrio DualGPS AsteRx4	22453089844	NA
Motions	Fugro LMCU	2319-00109	NA

* While these instruments are listed as having a calibration certificate in [DOW30DR] the documents uploaded to [SHAREP] are either quality certificates or declarations of conformity issued by the instrument manufacturers.

Table B-2: Instruments installed on the different FLS deployed as part of the DOW2030 campaign. The table supplements Table B-2 of [KFIIWA] with details of an additional buoy swapped-in at the KFII sites since the drafting of ibid.

B.1.2 Data description

The only change in this section is related to mentions of the length of the measurement campaign, which now covers the period up to 03 September 2024.

B.1.3 Data availability

The FLS measurements collected at Kriegers Flak II are available for the following periods:

- KFII-1-LB: From 2023-09-03 17:00:00 to 2024-09-03 16:40:00
- KFII-2-LB: From 2023-09-03 11:40:00 to 2024-09-03 11:20:00
- KFII-3-LB: From 2023-11-01 16:10:00 to 2024-04-14 03:20:00

The monthly data availability of all three FLSs is summarized in Table B-4. From the data in the table and a high-level analysis of the measurements, the most significant data gaps identified are:

- KFII-1-LB:
  - Wind speed- and direction from the LiDAR device between 2024-02-12 and 2024-02-16: According to Table A-1 of the monthly report of month 6 in

[DOW30MR], this gap was due to low input power. The data gap was resolved with the swap of buoy WS190 with WS172 on 2024-02-16.

- KFII-2-LB:
  - Wind speed- and direction from the LiDAR device between 2023-12-24 and 2024-01-16: According to monthly reports #4 and #5 in [DOW30MR] and gap report #1 [DOW30GR], LiDAR unit ZX709 presented a problem in its wedge motor and no measurements were collected during this period. This problem was resolved when spare buoy SWLB085 was deployed at KFII-2-LB and buoy WS172 was recovered. LiDAR unit 709 initially installed on buoy WS172 was replaced by LiDAR unit 757.
  - Gaps in all measurements between 2024-05-27 and 2024-06-07. Resolved by recovering unit SWLB085 from position KFII-2-LB and replacing it with unit SWLB083, as explained in monthly report #10 in [KFIIWA].

- KFII-3-LB: No significant data gaps were identified in the measurements available at this location, see Figure B-4.

The data availability of Lidar wind speed and wind direction measurements for all elevations and for the KFII-1-LB and KFII-3-LB is higher than 90%, as shown in Table B-5. Wind speed and direction data availability of KFII-2-LB is higher than 83% for all elevations due to the 2 data gaps listed above.

FLS	Year	Month	System data availability	WS @ 4 mMSL	WD @ 4 mMSL	WS @ 150 mMSL	WD @ 150 mMSL	T @ 4.1 mMSL	RelH @ 4.1 mMSL	P @ 0 mMSL
KFII-1-LB	2023	9	0.9097	0.9088	0.9088	0.8958	0.8958	0.9095	0.9095	0.9083
	2023	10	1.0000	0.9989	0.9991	0.9933	0.9935	0.9998	0.9998	0.9996
	2023	11	1.0000	0.9993	0.9995	0.9817	0.9819	1.0000	1.0000	0.9991
	2023	12	1.0000	0.9993	0.9996	0.9828	0.9830	1.0000	1.0000	0.9993
	2024	1	1.0000	0.9993	0.9996	0.9608	0.9610	1.0000	1.0000	0.9996
	2024	2	1.0000	0.9962	0.9964	0.7859	0.7862	0.9966	0.9966	0.9758
	2024	3	1.0000	0.9984	0.9987	0.9283	0.9285	0.9908	0.9908	0.9830
	2024	4	1.0000	0.9984	0.9986	0.9551	0.9553	0.9988	0.9988	0.9958
	2024	5	1.0000	0.9989	0.9991	0.9388	0.9388	0.9993	0.9993	0.9973
	2024	6	1.0000	0.9988	0.9991	0.9660	0.9660	0.9993	0.9993	0.9986
	2024	7	1.0000	0.9966	0.9969	0.9702	0.9702	0.9971	0.9971	0.9935
	2024	8	1.0000	0.9987	0.9989	0.9760	0.9760	0.9991	0.9991	0.9978
	2024	9	0.0900	0.0898	0.0898	0.0898	0.0898	0.0900	0.0900	0.0900
KFII-2-LB	2023	9	0.9171	0.9162	0.9162	0.8928	0.8928	0.9167	0.9167	0.8877
	2023	10	1.0000	0.9989	0.9991	0.9875	0.9877	0.9991	0.9991	0.9859
	2023	11	1.0000	0.9986	0.9988	0.9785	0.9787	0.9993	0.9993	0.9741
	2023	12	1.0000	0.9989	0.9991	0.7511	0.7513	0.9962	0.9962	0.9711
	2024	1	1.0000	0.9982	0.9984	0.4839	0.4841	0.9982	0.9982	0.9935
	2024	2	1.0000	0.9990	0.9993	0.9097	0.9100	0.9983	0.9983	0.9988
	2024	3	1.0000	0.9980	0.9982	0.9297	0.9299	0.9991	0.9991	0.9989
	2024	4	1.0000	0.9993	0.9995	0.9516	0.9519	0.9993	0.9993	0.9993
	2024	5	1.0000	0.7845	0.7847	0.7661	0.7661	0.7870	0.7870	0.7870
	2024	6	1.0000	0.7824	0.7826	0.7713	0.7713	0.7829	0.7829	0.7829
	2024	7	1.0000	0.9964	0.9966	0.9848	0.9848	0.9969	0.9969	0.9969
	2024	8	1.0000	0.9991	0.9993	0.9940	0.9940	0.9998	0.9998	0.9998
	2024	9	0.0826	0.0826	0.0826	0.0824	0.0824	0.0826	0.0826	0.0826
KFII-3-LB	2023	11	0.9775	0.9604	0.9604	0.9542	0.9542	N/A	N/A	N/A
	2023	12	1.0000	0.9973	0.9973	0.9879	0.9879	N/A	N/A	N/A
	2024	1	1.0000	0.9512	0.9512	0.9220	0.9220	N/A	N/A	N/A
	2024	2	1.0000	0.9966	0.9966	0.9140	0.9140	N/A	N/A	N/A
	2024	3	1.0000	0.9971	0.9971	0.9332	0.9332	N/A	N/A	N/A
	2024	4	0.4382	0.4359	0.4359	0.3963	0.3963	N/A	N/A	N/A

Table B-4: Monthly data availability of wind speed and wind direction at 4 and 150 mMSL, as well as surface level air temperature, relative humidity and air pressure for the three FLSs. The data availability cells are colour coded, light green cells indicate data availability between 0.75 and 1, light yellow cells mean data availability is between 0.5 and 0.75, while light orange cells highlight data availability between 0 and 0.5.

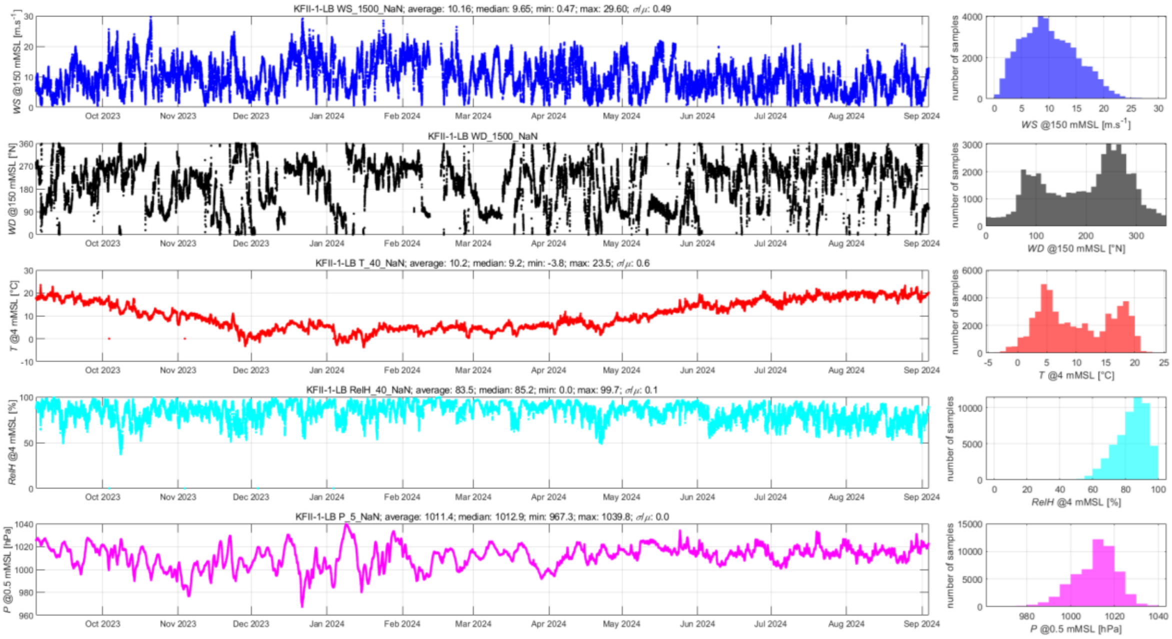

Figure B-2: Time series of wind speed and wind direction at 150 mMSL, as well as surface level air temperature, relative humidity and air pressure collected at KFII-1-LB.

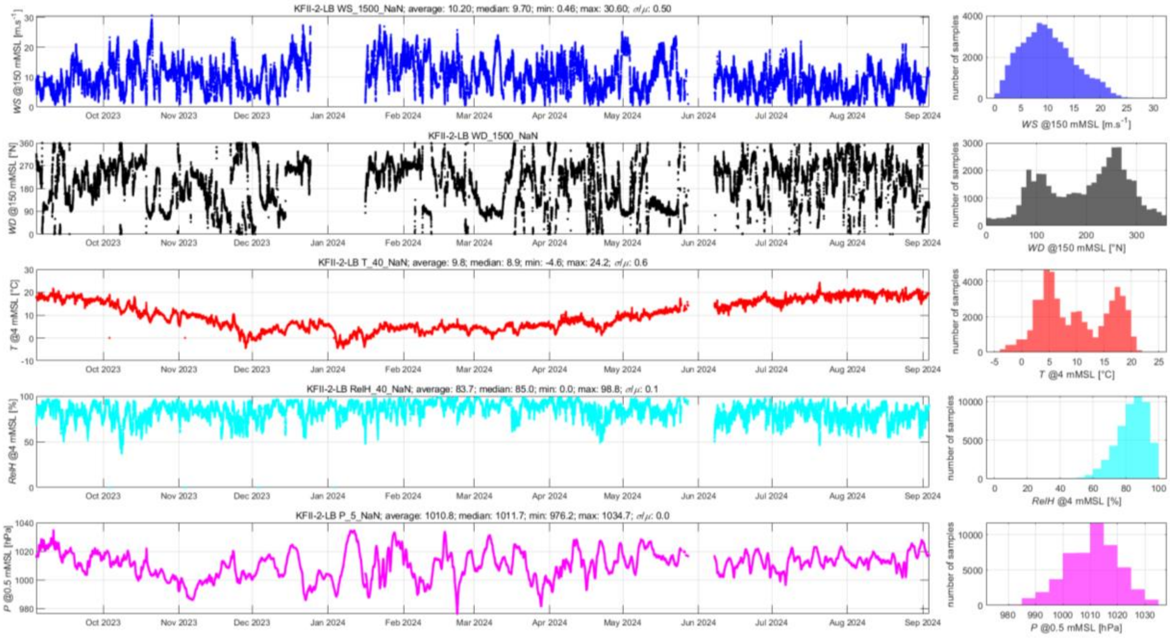

Figure B-3: Time series of wind speed and wind direction at 150 mMSL, as well as surface level air temperature, relative humidity and air pressure collected at KFII-2-LB.

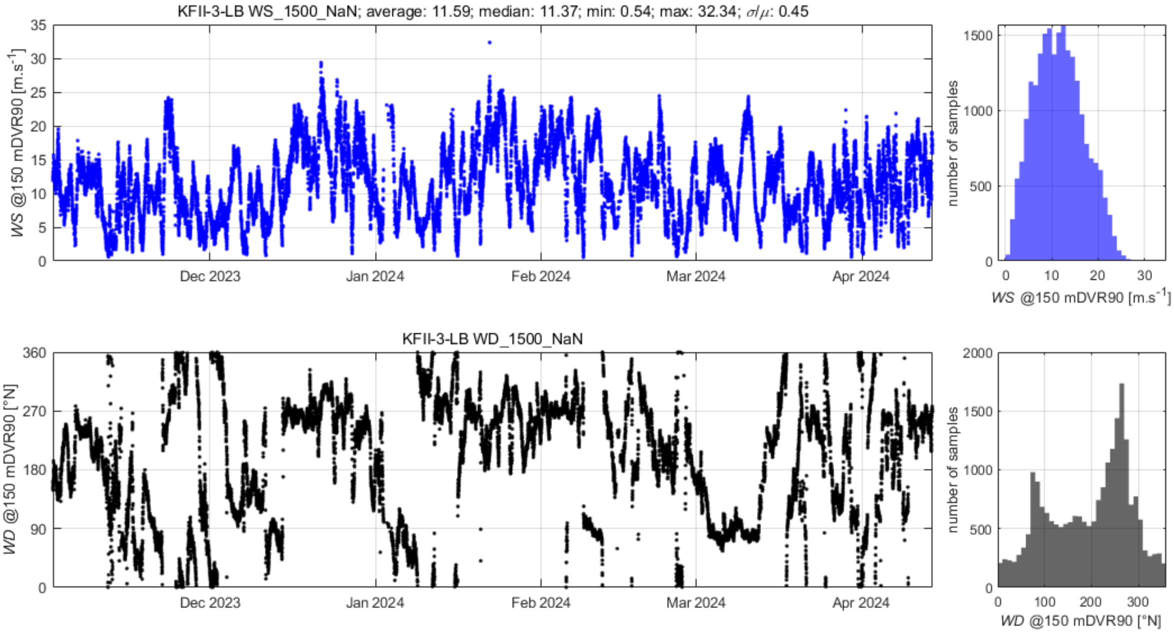

Figure B-4: Time series of wind speed and wind direction at 150 mMSL, as well as surface level air temperature, relative humidity and air pressure collected at KFII-3-LB. Please note that the only changes in this subfigure relative to that presented in [KFIIWA] are related to plotting the correct elevation.

KFII-1-LB		
Elevation	Availability [-]	
[mMSL]	WS	WD
12	0.9563	0.9563
40	0.9667	0.9667
80	0.9551	0.9551
100	0.9396	0.9396
130	0.9360	0.9360
150	0.9336	0.9336
170	0.9299	0.9299
190	0.9262	0.9262
220	0.9215	0.9215
260	0.9136	0.9136
300	0.9073	0.9073

KFII-2-LB		
Elevation	Availability [-]	
[mMSL]	WS	WD
12	0.8806	0.8806
40	0.8922	0.8922
80	0.8773	0.8773
100	0.8627	0.8627
130	0.8578	0.8578
150	0.8542	0.8542
170	0.8515	0.8515
190	0.8485	0.8485
220	0.8451	0.8451
260	0.8376	0.8376
300	0.8352	0.8352

KFII-3-LB		
Elevation	Availability [-]	
[mMSL]	WS	WD
12	0.9833	0.9833
40	0.9831	0.9831
80	0.9613	0.9613
100	0.9544	0.9544
130	0.9478	0.9478
150	0.9455	0.9455
170	0.9434	0.9434
190	0.9406	0.9406
220	0.9383	0.9383
260	0.9340	0.9340
300	0.9332	0.9332

Table B-5: Data availability of the LiDAR measurements collected by the three FLSs at Kriegers Flak II.

B.1.4 Data reliability and validity

With the deployment of unit SWLB083 at KFII-2-LB, the only changes in this section revolve around including the references to the unit's pre-deployment offshore validation report [SWLB083] and Lidar unit onshore validation report [ZX1646]. The discussion and conclusions regarding data reliability and validity are unchanged, as the validations for this unit were successful. Table B-6 summarises some of the main results in the pre-deployment validation reports of the Lidar unit and SWLB, intended as a supplement to Table B-6 of [KFIIWA].

Elev. [m]	WS ref. [m/s]	WS Lidar [m/s]	Rel. diff. [%]
	[ZX1646]		
92	6.92	6.89	-0.43%
71	6.55	6.54	-0.15%
46	6.18	6.14	-0.65%
	[SWLB083]		
250	7.88	7.91	0.38%
200	7.76	7.79	0.39%
180	7.69	7.71	0.26%
160	7.63	7.64	0.13%
140	7.60	7.61	0.13%
120	7.48	7.50	0.27%
100	7.38	7.41	0.41%
80	7.19	7.22	0.42%
60	7.16	7.22	0.84%
40	6.91	7.04	1.88%

Table B-6: Mean relative wind speed differences between the Lidar- and floating Lidar measurements, and the reference measurements, for units SWLB083 and ZX1646. The table supplements Table B-6 of [KFIIWA] with details of an additional buoy swapped-in at the KFII sites since the drafting of ibid.

B.2 Energy Island FLS measurement campaign

[There are no changes in this section]

B.2.1 Instrumentation setup

[There are no changes in this section]

B.2.2 Data description

[There are no changes in this section]

B.2.3 Data availability

[There are no changes in this section]

B.2.4 Data reliability and validity

[There are no changes in this section]

B.3 FINO2 met mast

[There are no changes in this section]

B.3.1 Instrumentation setup

[There are no changes in this section]

B.3.2 Data description

[There are no changes in this section]

B.3.3 Data availability

[There are no changes in this section]

B.3.4 Data reliability and validity

[There are no changes in this section]

B.4 Arkona met mast

[There are no changes in this section]

B.4.1 Instrumentation setup

[There are no changes in this section]

B.4.2 Data description

[There are no changes in this section]

B.4.3 Data availability

[There are no changes in this section]

B.4.4 Data reliability and validity

[There are no changes in this section]

Appendix C. Turbulence Intensity Conditions

[There are no changes in this section]

C.1 Note on measurement datasets

[There are no changes in this section]

C.2 Introduction

[There are no changes in this section]

C.3 Turbulence Intensity Modelling

[There are no changes in this section]

C.4 Application to Kriegers Flak II

[There are no changes in this section]