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Enviro INSIGHT
environmental impact assessments

Appendix D11:

Wake Impact Assessment

BOTTERBLOM WIND FARM

Wake Impact Assessment Report

Energyteam (Pty) Ltd

Report No.: L2C226699-ZACT-R-01, Rev. A
Date: 2022/02/11

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Objective: Independent assessment of the external turbine interaction effect of the proposed wind project.

for DNV South Africa (Pty) Ltd

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A	2022/02/11	First issue	J. Basson	I. Y. Kolbasi	J. Ziegler

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1 EXECUTIVE SUMMARY

Energyteam (Pty) Ltd (or the Customer) has retained DNV South Africa (Pty) Ltd (DNV) to complete an independent assessment of the turbine interaction losses caused by the proposed Botterblom Wind Farm on its operational and proposed neighbouring wind farms. The site is situated in gently undulating terrain with minimal ground cover, approximately 50 km north of the town of Loeriesfontein in the Northern Cape Province of South Africa.

The Customer is currently considering two layouts for the Botterblom Wind Farm:

- Botterblom Layout 1 consists of 30 Nordex, N163 5.7 MW turbines at a 118 m hub height
- Botterblom Layout 2 consists of 32 Nordex, N163 5.7 MW turbines at a 118 m hub height

The table below summarises the projects and results of the analysis.

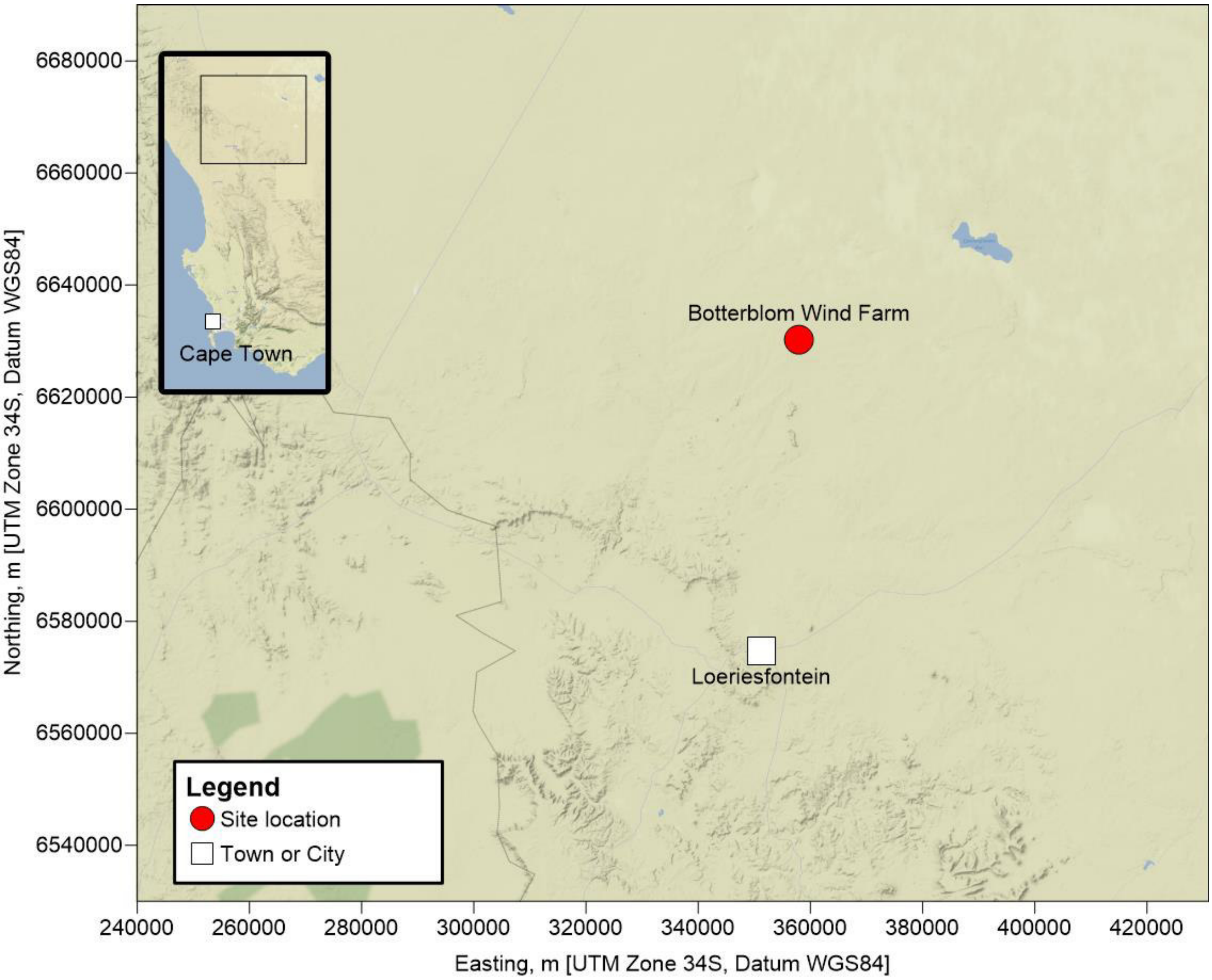
Neighbouring wind farm	External turbine interaction effect caused by Botterblom Layout 1	External turbine interaction effect caused by Botterblom Layout 2
Loeriesfontein	98.2%	98.3%
Khobab	98.4%	98.4%
Kokerboom 1	99.2%	99.2%
Kokerboom 2	99.7%	99.7%
Kokerboom 3	99.7%	99.7%
Kokerboom 4	99.2%	99.2%

2 INTRODUCTION

Energyteam (Pty) Ltd (Energyteam or the Customer) is developing the proposed Botterblom Wind Farm in South Africa. Energyteam has instructed DNV South Africa (Pty) Ltd (DNV) to an independent assessment of the turbine interaction losses caused by the proposed Botterblom Wind Farm on its operational and proposed neighbouring wind farm. The results of the work are reported here.

The location of the proposed Botterblom Wind Farm, which has a proposed capacity between 171.0 and 182.4 MW, is shown in Figure 2-1.

Figure 2-1 Location of the proposed Botterblom Wind Farm



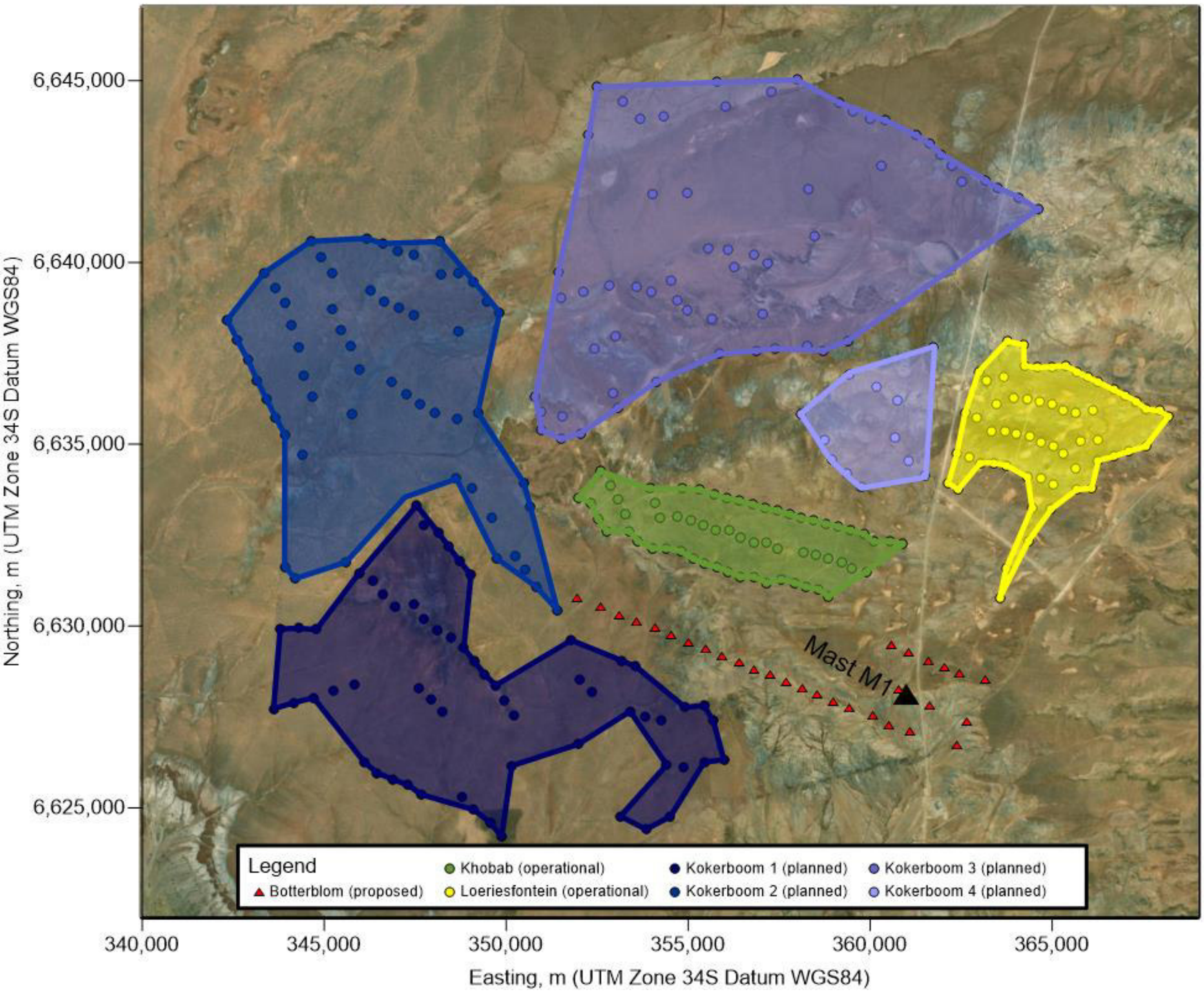
3 PROJECT DESCRIPTION

3.1 Site description

The Botterblom site is located approximately 50 km north of Loeriesfontein in the Northern Cape Province, South Africa.

A map showing the site is presented in Figure 3-1, including the location of the meteorological mast, the proposed turbines for Botterblom Layout 1 and the surrounding wind farms. A similar map of the site showing Botterblom Layout 2 is shown in Appendix A.

Figure 3-1 Map of the proposed Botterblom Wind Farm



The site is situated in gently undulating terrain on top of an extensive plateau, with turbine base elevations of the Botterblom Wind Farm and its neighbouring wind farms ranging from 901 m to 1000 m above sea level (asl).

Ground cover on site comprises open land with low scattered bushes and bare earth.

The following table summarises the key inputs to the analysis which describe the site characteristics. It is noted that DNV has not undertaken a site visit, and therefore the terrain characteristics and details of the measurements have been taken from information supplied by the Customer and publicly available sources.

Table 3-1 Inputs describing site characteristics

Site characteristic	Resulting input into analysis		Source
Terrain	Digital terrain map with 10 m contours. Derived from terrain grid with horizontal resolution of 38 m.		Publicly available SRTM terrain model /3/.
Roughness	Roughness map:		Freely available satellite images based on the Davenport classification /1/.
	Site and surrounding areas	0.03 m	

3.2 Proposed turbine configurations

The following turbine models are under consideration for the proposed Botterblom Wind Farm and its neighbouring wind farms.

Table 3-2 Proposed turbine model parameters

Turbine	Rated power [MW]	Hub height [m]	Peak power coefficient (C_p)	Density [kg/m^3]	Turbulence Intensity [%]
Nordex, N163 5.7 MW	5.7	118	0.46	1.075	9 – 20
Siemens, SWT-2.3-108	2.3	99	0.46	1.080	unknown
Vestas, V162 5.6 MW	5.6	120	0.47	1.075	6 – 12

The power curves used in this analysis have/has been supplied by the Customer /2/, /3/, /4/,and the characteristics and performance data of these turbines are presented in Appendix B. The power curves are based on calculations and exhibit peak power coefficients, Cp, as shown in the above table.

Table 3-3 Project configurations

Wind farm	Turbine	Rated power [MW]	Hub height [m]	Number of turbines
Botterblom L1 Botterblom L2	Nordex, N163 5.7 MW	5.7	118	30 32
Loeriesfontein Khobab	Siemens, SWT-2.3-108	2.3	99	59 61
Kokerboom 1 Kokerboom 2 Kokerboom 3 Kokerboom 4	Vestas, V162 5.6 MW	5.6	120	60 57 60 12

Measured power curves from independent tests of the performance of the turbines have not been supplied therefore DNV has been unable to verify that the power performance levels provided by the turbine manufacturers are attainable. It is recommended that independently measured power curves for the specific turbine models proposed for the site are obtained to confirm the performance levels supplied.

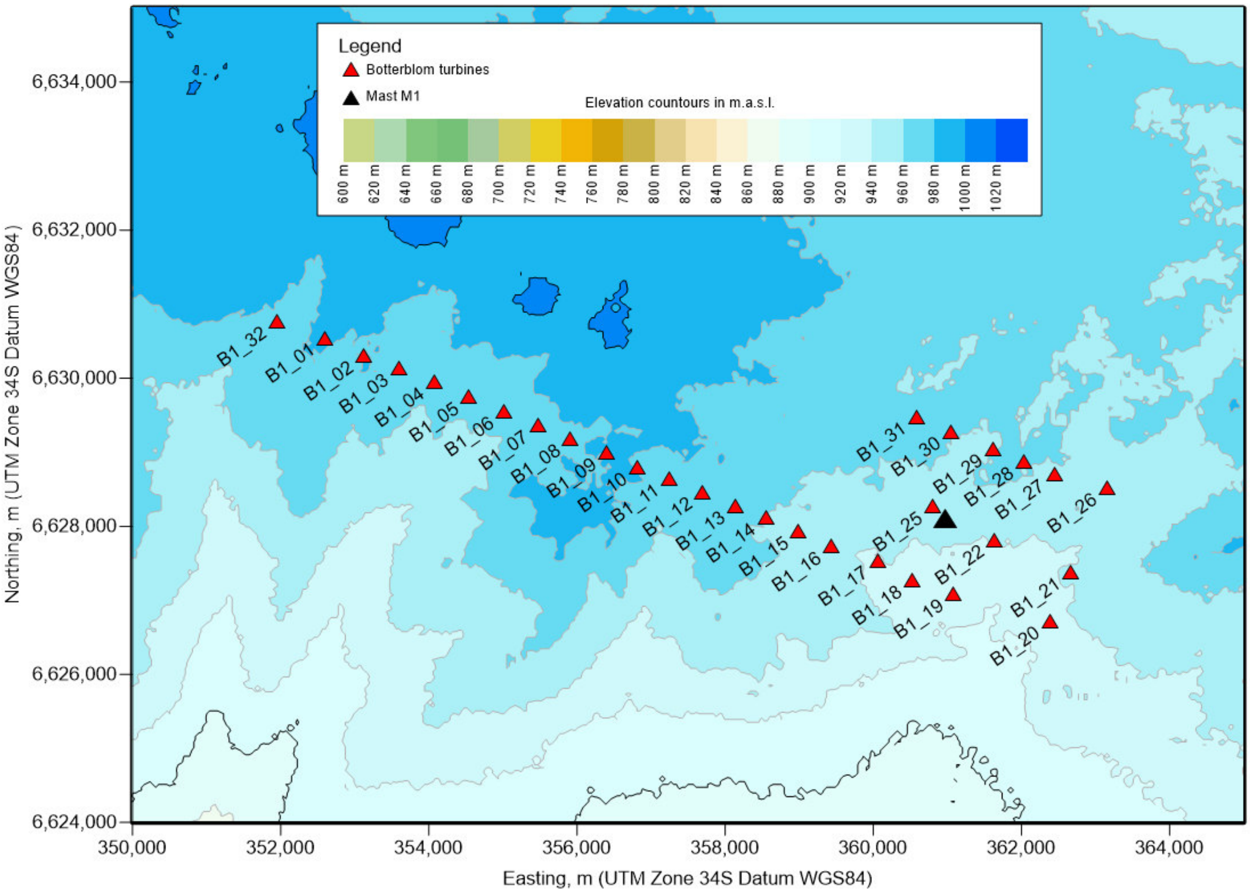
DNV has obtained historical pressure and temperature records from 10 nearby meteorological stations with a maximum distance of 400 km and maximum elevation difference of 300 m from the site. On the basis of these data and using standard lapse rate assumptions, DNV has estimated the long-term air density at the site to be 1.067 kg/m³ at an average hub elevation of 1078 m above sea level.

The supplied power curves used in this analysis have been adjusted to the predicted site air density in accordance with the recommendations of the IEC /5/. This has been undertaken on an individual turbine basis.

3.3 Proposed turbine layout

Energyteam has supplied two proposed layouts for the wind farm /6/, which features 30 to 32 turbines in three separate rows. A map of the site showing the Botterblom Layout 1 turbine layout is shown in Figure 3-2; also shown in this figure are elevation contours on the site. The grid coordinates of the turbines and a similar map showing Botterblom Layout 2 are shown in Appendix A.

Figure 3-2 Map of the proposed Botterblom Wind Farm showing elevations



3.4 Neighbouring wind farms

The Botterblom site is proposed within a region of high wind farm development activity and the following wind farms exist or are proposed in the vicinity of the site:

- Neighbouring Kokerboom 1 Wind Farm (proposed) – Immediately southwest and west of the site. Consisting of 60 Vestas, V162 5.6 MW turbines, with a hub height 120 m. Turbine locations provided by Energyteam /7/. Coordinates given in Appendix A and shown in Figure 3-1.
- Neighbouring Kokerboom 2 Wind Farm (proposed) – Immediately northwest of the site. Consisting of 57 Vestas, V162 5.6 MW turbines, with a hub height 120 m. Turbine locations provided by Energyteam /7/. Coordinates given in Appendix A and shown in Figure 3-1.
- Neighbouring Kokerboom 3 Wind Farm (proposed) – Approximately 5 km north of the site. Consisting of 60 Vestas, V162 5.6 MW turbines, with a hub height 120 m. Turbine locations provided by Energyteam /7/. Coordinates given in Appendix A and shown in Figure 3-1.
- Neighbouring Kokerboom 4 Wind Farm (proposed) – Approximately 5 km north of the site. Consisting of 12 Vestas, V162 5.6 MW turbines, with a hub height 120 m. Turbine locations provided by Energyteam /7/. Coordinates given in Appendix A and shown in Figure 3-1.
- Neighbouring Khobab Wind Farm (operational) – Wind Farm commissioned in 2017 and located immediately north of the site. Consisting of 61 Siemens, SWT 2.3-108 turbines, with a hub height of 99 m. Turbine locations provided by Energyteam /7/. Coordinates given in Appendix A and shown in Figure 3-1. Wake effects are not considered to have had an effect on the site mast.
- Neighbouring Loeriesfontein Wind Farm (operational) – Wind Farm commissioned in 2017 and located immediately northeast of the site. Consisting of 59 Siemens, SWT 2.3-108 turbines, with a hub height of 99 m. Turbine locations provided by Energyteam /7/. Coordinates given in Appendix A and shown in Figure 3-1. Wake effects are not considered to have had an effect on the site mast.

DNV

4 DESCRIPTION OF THE ON-SITE WIND MONITORING

Wind measurements have been undertaken at the Botterblom site at a single mast, summarised in the following table.

Table 4-1 Measurements summary

Device	Measurement heights		Period of measurements	Duration	Compliance with IEC mounting guidelines[1]	Calibrated by MEASNET facility?
	Wind speed [m]	Wind direction [m]		[Years]		
Mast M1	124, 120, 100, 80, 60, 40	120, 100	2020-09-05 to 2021-12-31	1.3	fully	yes

Notes:
1 Instruments are installed in accordance with guidelines issued by the IEC /5/.

Full details of the individual mast configuration are presented in Appendix C.

4.1 Monitoring equipment

4.1.1 Meteorological mast

The mast was not independently inspected by DNV as a site visit was not part of the scope of this work.

Mast installation reports and maintenance records for the site measurements have been provided. The standard of documentation is good and sufficient to ensure traceability of the instrumentation throughout the monitoring campaign. Calibration certificates have been supplied for all the anemometers mounted on the masts, and DNV has ensured that these calibrations have been applied in the analysis here, as detailed in Appendix C.

The mounting arrangements of all instrumentation at the site masts are considered fully consistent with the recommendations of the IEC /5/ and are therefore considered to be in accordance with industry best practice for good quality wind measurements.

4.2 Wind data quality control and data processing

4.2.1 Meteorological mast

Energyteam has supplied DNV with raw data from the masts installed on the Botterblom site.

The wind data have been subject to a quality checking procedure by DNV to identify records which were affected by equipment malfunction and other anomalies, as described in Appendix E-2. These records were excluded from the analysis.

DNV has checked the data for time and direction offsets and concluded that none was required. Time zone in the logger file was UTC+2 and direction offset check was done using the reanalysis dataset at the closest grid point. The duration, basic statistics and data coverage for the mast are summarised in Appendix C. Wind data coverage is generally good, with only negligible data loss. Overall data coverage levels for the key parameters and instruments on each mast are shown in the following table:

Table 4-2 Measurements summary

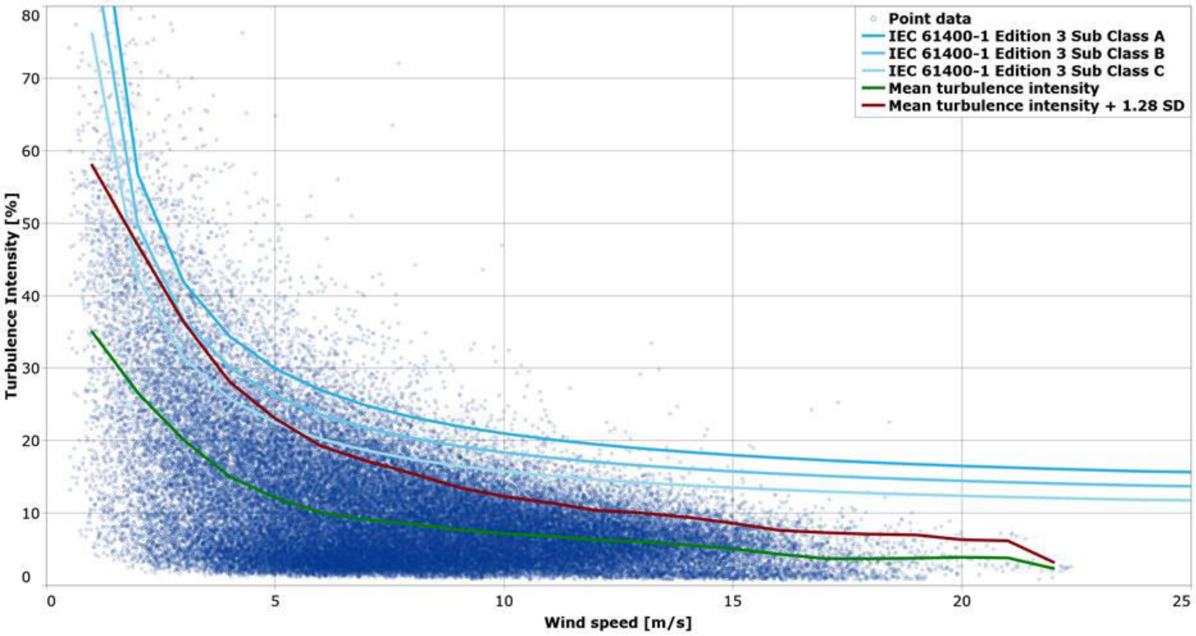
Mast	Parameter	Instrument height [m]	Measurement period [yrs][2]	Data coverage [%]	Valid data period [yrs]
M1	Wind speed[1]	124	1.3	99.6%	1.3
	Wind direction	120	1.3	98.6%	1.3

1 Wind speed coverage at the mast is based on the measurements from the top-mounted anemometer at 124 m.
2 Measurement period before data cleaning is undertaken.

4.3 Measured turbulence intensity

A plot of the measured turbulence intensity as a function of wind speed for Mast M1 at 124 m, is shown below along with the profiles for IEC turbulence subclasses A, B and C /8/. These results will include some mast and mounting effects but no allowance for turbine wake effects.

Figure 4-1 Measured turbulence intensity at Mast M1 at 124 m



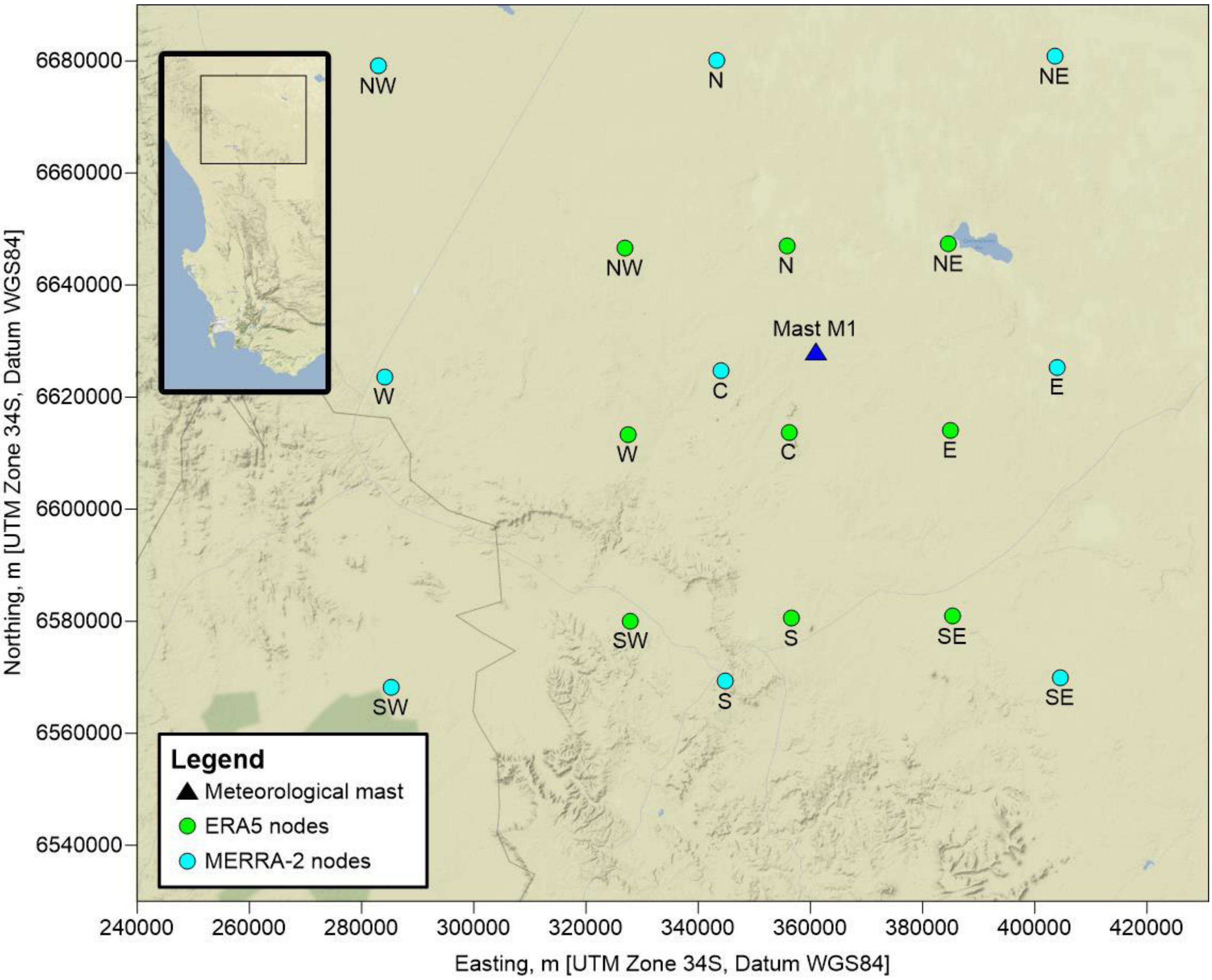
5 DESCRIPTION OF REFERENCE DATA

5.1 Selection of reference data

In the assessment of the wind regime at a potential wind farm site, it is desirable to correlate data recorded at the site with data recorded at a nearby long-term source of reference wind data. This allows the estimate of the long-term wind regime at the site to be representative of a longer historical period. When selecting an appropriate reference source for this purpose it is important that data are consistent over the measurement period being considered. When this data source is a long-term measurement mast, such as a meteorological station, it is also important that it has good exposure in all key wind sectors.

DNV has investigated potential sources of consistent long-term reference data in the surrounding area, including the MERRA-2 and ERA5 Reanalysis datasets.

Figure 5-1 Location of the proposed Botterblom Wind Farm and reference sources



5.2 MERRA-2 Reanalysis data

The Modern Era Retrospective-analysis for Research and Applications, Version 2 (MERRA-2) data set has been produced by the National Aeronautics and Space Administration (NASA) by assimilating satellite observations with conventional land-based meteorology measurement sources using the Goddard Earth Observing System Data

Assimilation System Version 5.12.4 (GEOS-5.12.4) atmospheric data assimilation system /9/. The analysis is performed at a spatial resolution of 0.625° longitude by 0.5° latitude. MERRA-2 replaces the MERRA dataset previously produced by NASA. DNV typically procures hourly time series of two-dimensional diagnostic data at a surface height of 50 m for suitable grid cells near the project site.

DNV has some concerns over the long-term consistency of reanalysis data and has conducted investigations into the consistency of the MERRA-2 dataset. On the basis of these investigations, the long-term reference period considered for the MERRA-2 dataset is from January 2002 to the present.

DNV has obtained hourly averaged wind speed and direction data at a 50 m height level for the period of January 2002 to November 2021 at the nine grid cells closest to the site.

Table 5-1 MERRA-2 grid cells considered

Grid cell	Grid cell centre location	Grid cell	Grid cell centre location
C	30.5°S 19.4°E	S	31.0°S 19.4°E
N	30.0°S 19.4°E	SW	31.0°S 18.8°E
NE	30.0°S 20.0°E	W	30.5°S 18.8°E
E	30.5°S 20.0°E	NW	30.0°S 18.8°E
SE	31.0°S 20.0°E		

DNV has undertaken correlations between each of the above grid cells and the site on a monthly and 10-daily averaging period. The correlations were found to be or a low quality with R^2 values ranging between 0.39 and 0.69 in monthly and 10-daily averaging period. As a result, the MERRA-2 dataset was disregarded from the analysis.

5.3 ERA5 Reanalysis data

ERA5 /10/ is the fifth generation of ECMWF's atmospheric reanalyses of the global climate. ERA5 incorporates vast amounts of historical measurement data, including both satellite-based, commercial aircraft, and ground-based data to produce a description of the state of the atmosphere, including wind speed. Hourly analysis fields are available at a horizontal resolution of 31 km and include wind data at 100 m above ground level, as well as surface air temperature and air pressure. DNV typically procures data at a surface height of 100 m for suitable grid cells near the project site.

DNV has some concerns over the long-term consistency of reanalysis data. In order to mitigate against potential inclusion of inconsistent data in the long-term analysis, DNV has considered the long-term reference period for the ERA5 dataset from January 2002 to the present.

DNV has obtained hourly averaged wind speed and direction data at a 100 m height level for the period of January 2002 to October 2021 at the nine grid cells closest to the site.

Table 5-2 ERA5 grid cells considered

Grid cell	Grid cell centre location	Grid cell	Grid cell centre location
C	30.6°S 19.5°E	S	30.9°S 19.5°E
N	30.3°S 19.5°E	SW	30.9°S 19.2°E
NE	30.3°S 19.8°E	W	30.6°S 19.2°E
E	30.6°S 19.8°E	NW	30.3°S 19.2°E
SE	30.9°S 19.8°E		

DNV has undertaken correlations between each of the above grid cells and the site on a monthly and 10-daily averaging period. The most robust correlation, with an R^2 value of 0.93, was observed for the correlation between the site and ERA5 grid cell C on a 10-daily averaging period. The long-term wind speed predicted at the site based on this correlation was supported by predictions using the other ERA5 grid cells on a monthly and 10-daily basis.

The monthly average wind speeds for the ERA5 dataset are presented in Appendix C.

5.4 Conclusion

Having considered the merits of the MERRA-2 and ERA5 Reanalysis datasets, DNV considers that the lowest uncertainty approach is to use the ERA5 dataset to derive a long-term wind speed adjustment for the measured site wind data, as detailed further in Section 6.1.1. This is due to the long period of consistent data available and the superior quality of correlation to the site data.

6 LONG-TERM WIND REGIME AT THE SITE

6.1 Long-term wind speed at the mast

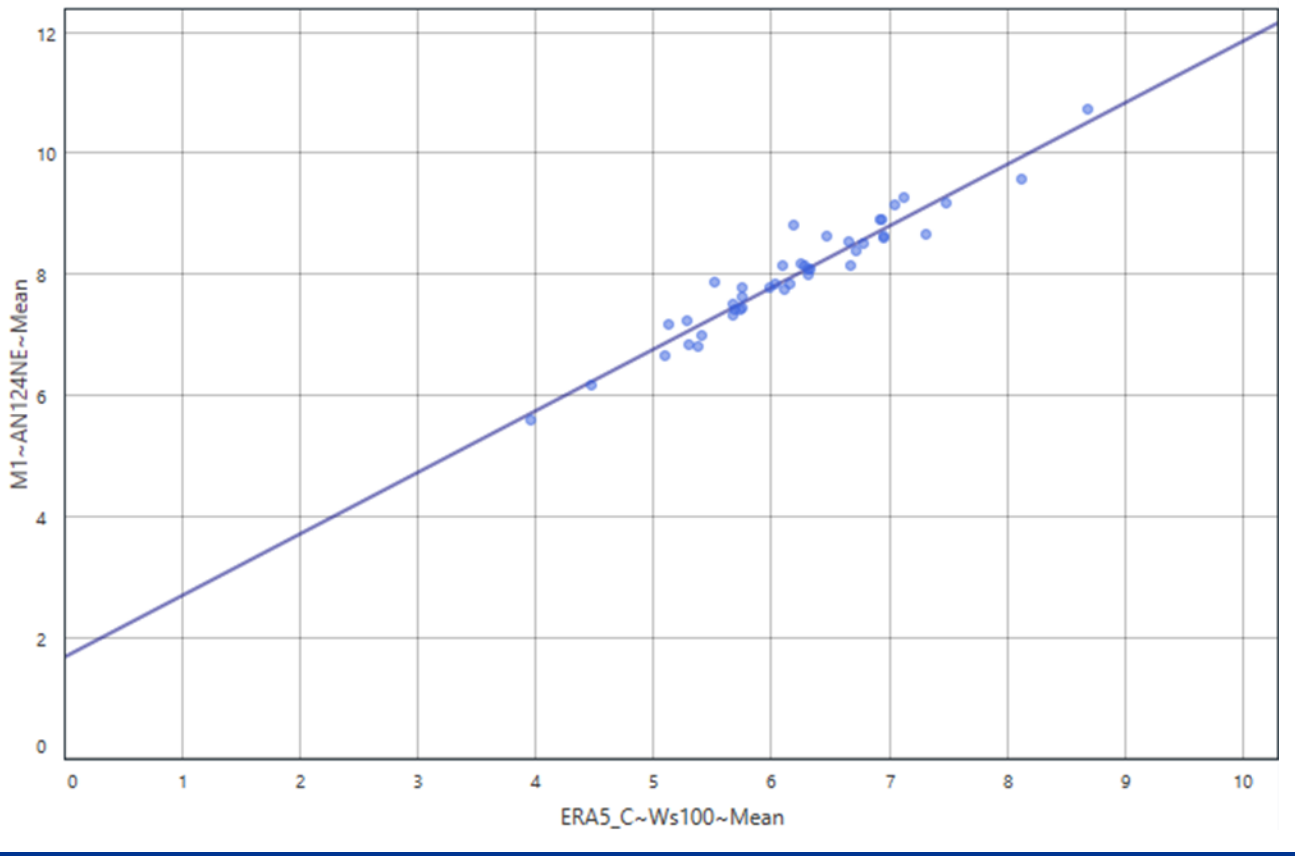
6.1.1 Derivation of long-term wind speed at the mast

As discussed in Section 5, the ERA5 dataset was identified as the most suitable source of long-term reference data for the analysis. The method used to obtain the long-term wind speed at the mast from the reference source relies upon a correlation approach on a 10-daily averaging period.

Figure 6-1 presents the correlation of 10-daily mean wind speeds between Mast M1 at 124 m and the ERA5 C dataset. 10-daily periods for which the data coverage at either the site or reference source is less than 90% have been excluded from the correlation. The correlation is of reasonable/good quality, with a coefficient of determination, R^2, of 0.93.

Figure 6-1 Long-term correlation

10-Daily correlation between ERA5 at 100 m and Mast M1 at 124 m



The slope and intercept of the correlation were applied to the 10-daily mean wind speeds recorded at the reference source to synthesise historical 10-daily mean wind speeds at the mast at the primary anemometer. The measured and synthesised 10-daily means were then combined, with priority given to measured data, to derive the long-term annual wind speed at the mast. To avoid the introduction of bias into the long-term wind speed estimate from seasonally uneven data coverage, the following procedure was followed:

- The mean wind speed for each month was determined from the valid measured and synthesised data in that month over the period. This was taken as the monthly mean thereby assuming that the valid data are representative of any missing data.

- The mean wind speeds for each of the twelve months were averaged, weighted by the number of days in each month, to determine the long-term annual mean wind speed.

By this method, the long-term wind speed at the mast is as given in the following table:

Table 6-1 Long-term wind speed at site

Device	Height	Measurement period	Period defining the long-term wind speed	Measured wind speed	Long-term wind speed	Long-term wind speed adjustment
	[m]	[years]	[years]	[m/s]	[m/s]	[%]
Mast M1	124.0	1.3	19.8	8.0	8.0	-0.1

6.1.2 Hub-height wind regime

6.1.2.1 Vertical wind speed extrapolation at the mast

The measured variation in wind speed with height at the site mast has been defined using the power law shear exponent and has been used to predict the wind resource at the proposed hub heights. Given the good quality of the site measurement campaign, and the height of the measurements in relation to the proposed hub heights, this is considered an appropriate method.

The power law wind shear exponent is defined by:

$$\frac{\bar{U}(z_1)}{\bar{U}(z_2)} = \left(\frac{z_1}{z_2}\right)^{\alpha}$$

where α is power law wind shear exponent,

$\bar{U}$ is the wind speed, and

z is the height above ground level.

The shear exponent measured at the site mast has been predicted and used to extrapolate the mast-measured wind speed to the proposed hub height, as given in the following table.

Table 6-2 Measured wind shear exponents at the site

Device	Heights	Long-term wind speed at Measurement height	Measured wind shear exponent	Long-term wind speed at 99 m	Long-term wind speed at 118 m	Long-term wind speed at 120 m
	[m]	[m/s]		[m/s]	[m/s]	[m/s]
Mast M1	40, 60, 80, 100	8.0	0.12	7.8	7.9	7.9

Through review of the mast measurements, DNV considers that the lowest uncertainty approach is to exclude the 120 m anemometer measurements in the definition of the shear profile at the mast. This is mainly due to a 3-month period of low coverage and one full month of data loss starting in July 2021 for the anemometer at this height, leading to a bias. Furthermore, the anemometer at 124 m was excluded from the definition of the shear profile because, being top-mounted, it is not equally impacted by the mast shadow to the boom-mounted anemometers at the other measurement heights.

The long-term hub height frequency distribution at Mast M1 has been derived by extrapolating the measured wind speed data on a time series basis, as described in Appendix E-5. This method captures the variation of wind shear with time and direction. The resulting time series has been used to derive a frequency distribution, which has then been scaled to the predicted long-term hub height wind speed given in Table 6-2.

The following procedure has been used to avoid the introduction of bias into the annual wind regime prediction from seasonally uneven data coverage at the site mast.

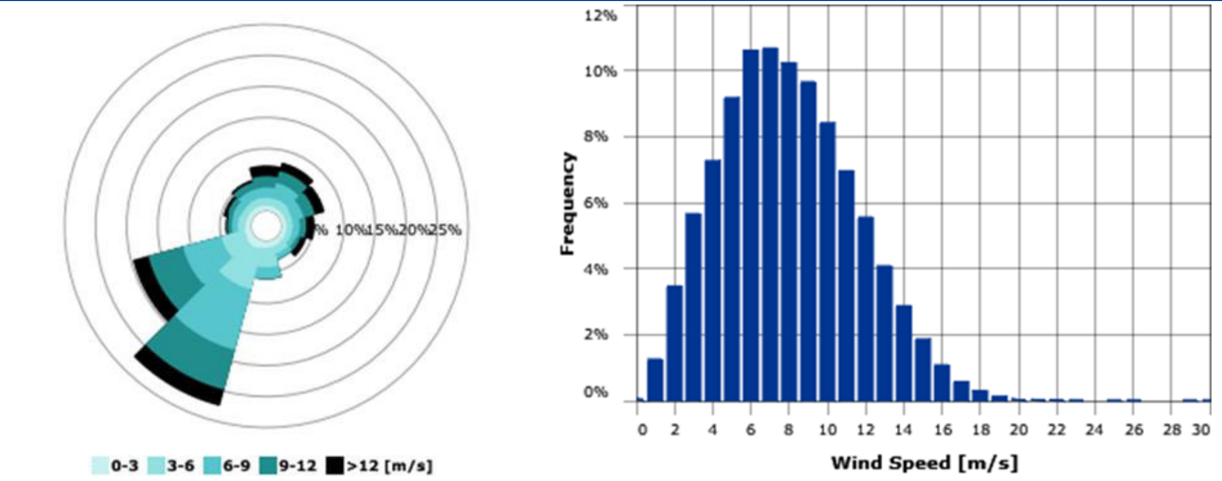
- The mean wind speed and direction frequency distribution for each month was determined from the valid data recorded in that month over the period. The frequency distribution for each month was considered to be representative of the long-term for that month thereby assuming the valid data are representative of any missing data.

- The frequency distributions for each of the twelve months were averaged, weighted by the number of days in each month, to determine the long-term annual frequency distribution.

The resulting hub height wind rose and frequency distribution for Mast M1 at 118 m, which is considered representative of the site, is shown in Figure 6-2 below and is presented in tabular form in Appendix D, alongside the other hub heights.

Figure 6-2 Long-term wind speed and direction frequency distribution

Mast M1 at 118 m



6.2 Wind regime across the site

6.2.1 Wind flow modelling

The variation in wind speed over the wind farm site has been predicted using the WAsP computational flow model, as described in Appendix E-6.

The inputs listed in Section 3.1 have been used to develop terrain contour and roughness maps for the site as input to the flow model.

The WAsP wind flow model has been initiated from the hub height wind regime determined at Mast M1 to predict the long-term wind regimes at the turbine locations.

7 WAKE ANALYSIS

7.1 Modelled wake losses

Wind turbines extract energy from the wind, and downstream there is a wake from the wind turbine where the wind speed is reduced. As the flow proceeds downstream, there is a spreading of the wake, and the wake recovers towards free stream conditions. The wake effect loss is the aggregated influence on the energy production of the wind farm which results from the changes in wind speed caused by the impact of the turbines on each other. These effects are calculated using the WindFarmer computational model. The eddy viscosity model within WindFarmer is employed using a site-specific definition of the turbulence intensity as an input, combined with a Large Wind Farm Wake Model developed by DNV /11/, /12/, /13/. In addition, turbine interaction also includes lateral as well as upstream effects, which together contribute to a resistance, or blockage, on the wind flow, deflecting some of the flow above and around the wind farm. Consequently, the first-row turbines produce less than they each would operating in isolation. DNV has developed an empirical model based on over 50 CFD simulations of generic wind farm configurations to capture the impact of wind farm blockage /14/.

Conventional Eddy Viscosity wake calculation

The Eddy Viscosity wake model is a CFD calculation representing the development of the velocity deficit field using a finite-difference solution of the thin shear layer equation of the Navier-Stokes equations in axi-symmetric co-ordinates. The Eddy Viscosity model automatically observes the conservation of mass and momentum in the wake. An eddy viscosity, averaged across each downstream wake section, is used to relate the shear stress to gradients of velocity deficit. The mean field can be obtained by a linear superposition of the wake deficit field and the incident wind flow.

The Eddy Viscosity model within WindFarmer is employed in a scheme which, taking each wind speed and direction in turn calculates the wake loss and power production of a project. The important parameters used in this process are:

- Turbine layout and inter-turbine spacing;
- Adjusted wind speed from site wind flow calculations;
- Ambient turbulence profile;
- Wind turbine thrust characteristic;
- Wind turbine power characteristic; and
- Rotor speed characteristic.

Any air density adjustments required due to differences between the hub-height air density at the turbine locations and that at the reference mast location is applied and included in the array effect.

WindFarmer Large Wind Farm Model

DNV has developed a model implemented within the WindFarmer software which corrects the Eddy Viscosity model based on the development of an inner boundary layer for a Large Wind Farm (LWF). Instead of modelling an area of increased roughness in the flow model, the disturbance caused by each individual turbine is modelled. This allows the effect for a wider variation of turbine layouts to be considered for the purposes of design and optimisation. This correction was developed primarily on the basis of operational data from the Horns Rev Project. More information on this model can be found in /13/. The model has been employed in a scheme which, taking each wind speed and direction in turn calculates the external wake losses at each turbine.

7.2 External wake estimates

To assess the magnitude of the effect of the two proposed Botterblom Wind Farm layouts on the energy production of its neighbouring wind farms, the methodology described above has been applied, and the results are shown in the table below.

Table 7-1: External turbine interaction effect

Neighbouring wind farm	External turbine interaction effect caused by Botterblom Layout 1	External turbine interaction effect caused by Botterblom Layout 2
Loeriesfontein	98.2%	98.3%
Khobab	98.4%	98.4%
Kokerboom 1	99.2%	99.2%
Kokerboom 2	99.7%	99.7%
Kokerboom 3	99.7%	99.7%
Kokerboom 4	99.2%	99.2%

8 REFERENCES

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APPENDIX A: WIND FARM SITE INFORMATION

Figure A-1 Map of the proposed Botterblom Wind Farm Layout 2 and neighbouring wind farms

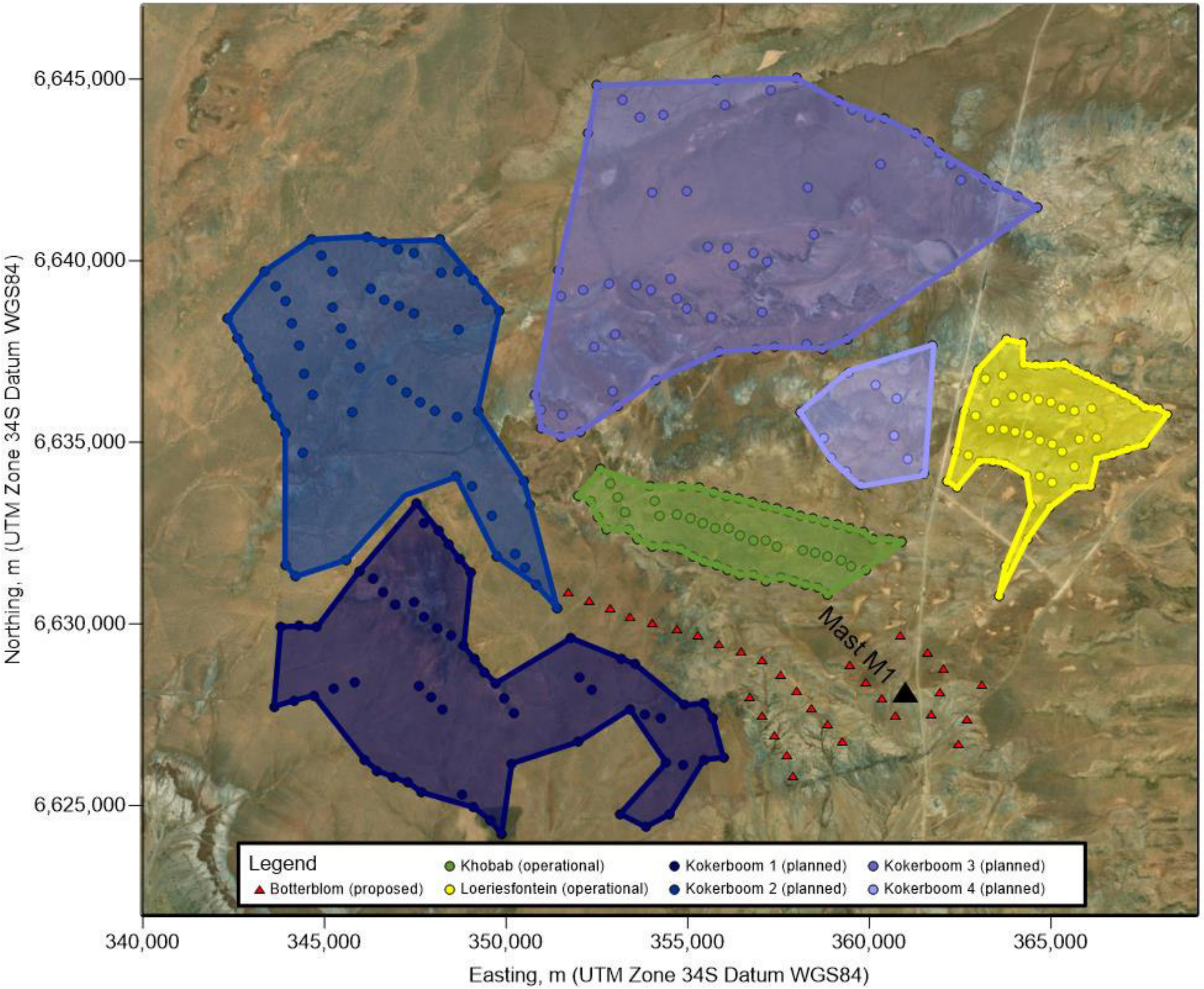


Figure A-2 Map of the proposed Botterblom Wind Farm Layout 2 showing elevations

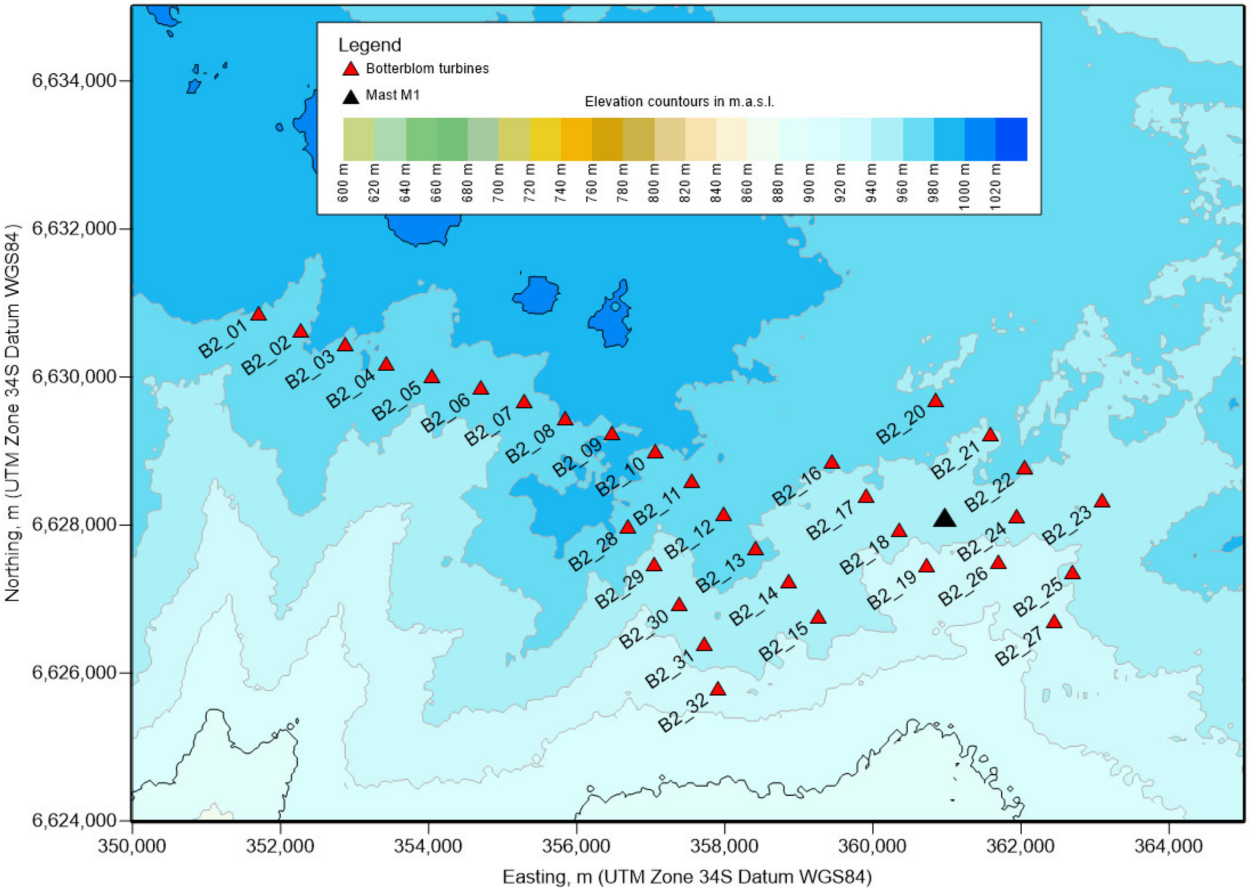


Table A-1 Turbine co-ordinates of the proposed Botterblom Wind Farm – Layout 1

Turbine	Easting [1] [m]	Northing [1] [m]	Height of base [m]
B1_01	352597	6630544	982
B1_02	353114	6630303	980
B1_03	353591	6630131	972
B1_04	354073	6629948	967
B1_05	354539	6629745	968
B1_06	355015	6629553	967
B1_07	355476	6629362	969
B1_08	355912	6629181	976
B1_09	356394	6628991	980
B1_10	356811	6628798	979
B1_11	357251	6628647	972
B1_12	357690	6628466	971
B1_13	358136	6628277	966
B1_14	358547	6628114	959
B1_15	358991	6627931	953
B1_16	359432	6627728	947
B1_17	360061	6627532	939
B1_18	360520	6627271	933
B1_19	361081	6627087	927
B1_20	362381	6626721	932
B1_21	362660	6627378	942
B1_22	361633	6627819	942
B1_25	360796	6628267	950
B1_26	363152	6628518	951
B1_27	362446	6628700	957
B1_28	362030	6628873	961
B1_29	361610	6629045	960
B1_30	361043	6629282	963
B1_31	360580	6629478	982
B1_32	351942	6630766	980

1. Co-ordinate system is UTM Grid Zone 34S WGS84.

DNV

Table A-2 Turbine co-ordinates of the proposed Botterblom Wind Farm – Layout 2

Turbine	Easting [1] [m]	Northing [1] [m]	Height of base [m]
B2_01	351697	6630857	978
B2_02	352273	6630630	975
B2_03	352868	6630440	979
B2_04	353421	6630185	975
B2_05	354036	6630015	967
B2_06	354698	6629853	969
B2_07	355289	6629670	973
B2_08	355841	6629437	981
B2_09	356479	6629251	980
B2_10	357059	6628990	978
B2_11	357560	6628596	974
B2_12	357987	6628143	967
B2_13	358412	6627689	964
B2_14	358862	6627242	953
B2_15	359264	6626765	951
B2_16	359443	6628862	962
B2_17	359906	6628400	955
B2_18	360358	6627935	950
B2_19	360727	6627459	934
B2_20	360851	6629698	964
B2_21	361590	6629221	959
B2_22	362042	6628779	960
B2_23	363090	6628336	951
B2_24	361943	6628113	951
B2_25	362701	6627360	942
B2_26	361689	6627508	934
B2_27	362454	6626698	933
B2_28	356693	6627977	971
B2_29	357051	6627469	953
B2_30	357379	6626931	951
B2_31	357729	6626394	952
B2_32	357906	6625800	931

1. Co-ordinate system is UTM Grid Zone 34S WGS84.

Table A-3 Turbine co-ordinates of neighbouring Khobab Wind Farm (operational)

Turbine	Easting [1] [m]	Northing [1] [m]	Height of base [m]	Turbine	Easting [1] [m]	Northing [1] [m]	Height of base [m]
Kho01	360903	6632254	971	Kho51	353938	6633779	992
Kho02	360532	6632341	970	Kho52	353625	6632323	1000
Kho03	360092	6632316	973	Kho53	353388	6632609	1000
Kho04	359887	6631493	975	Kho54	353272	6633077	998
Kho05	359832	6632541	977	Kho55	353066	6633496	997
Kho06	359485	6631597	979	Kho56	352879	6633858	998
Kho07	359468	6632630	980	Kho57	352772	6632613	999
Kho08	359207	6631770	979	Kho58	352593	6634255	995
Kho09	359130	6632732	979	Kho59	352512	6632939	1000
Kho10	358857	6631857	980	Kho60	352324	6633395	1000
Kho11	358857	6630807	980	Kho61	351981	6633531	996
Kho12	358793	6632820	982				
Kho13	358589	6631005	986				
Kho14	358523	6631964	982				
Kho15	358454	6632909	989				
Kho16	358226	6631075	991				
Kho17	358182	6632023	984				
Kho18	358116	6632963	990				
Kho19	357914	6631192	992				
Kho20	357794	6633074	990				
Kho21	357570	6631273	991				
Kho22	357468	6633175	990				
Kho23	357451	6632113	987				
Kho24	357165	6632283	989				
Kho25	357156	6631191	995				
Kho26	357105	6633236	990				
Kho27	356813	6632305	990				
Kho28	356802	6631352	997				
Kho29	356772	6633345	992				
Kho30	356441	6632418	990				
Kho31	356422	6631352	997				
Kho32	356408	6633450	993				
Kho33	356130	6632627	991				
Kho34	356111	6631495	994				
Kho35	356047	6633523	996				
Kho36	355792	6631616	993				
Kho37	355755	6632623	993				
Kho38	355717	6633630	1000				
Kho39	355455	6631711	992				
Kho40	355421	6632759	996				
Kho41	355308	6633748	1000				
Kho42	355127	6631854	990				
Kho43	355084	6632919	1000				
Kho44	354823	6633782	1000				
Kho45	354797	6632049	993				
Kho46	354692	6633018	1000				
Kho47	354397	6632134	1000				
Kho48	354229	6632983	1000				
Kho49	354088	6633388	1000				
Kho50	354027	6632136	1000				

1. Co-ordinate system is UTM Grid Zone 34S WGS84.

Table A-4 Turbine co-ordinates of neighbouring Loeriesfontein Wind Farm (operational)

Turbine	Easting [1] [m]	Northing [1] [m]	Height of base [m]	Turbine	Easting [1] [m]	Northing [1] [m]	Height of base [m]
Loe01	363661	6636847	949	Loe51	364686	6634076	961
Loe02	364236	6637159	951	Loe52	365042	6633898	961
Loe03	364587	6637106	951	Loe53	365672	6633751	954
Loe04	364983	6637137	952	Loe54	366084	6633783	951
Loe05	365375	6637149	952	Loe55	364444	6633256	959
Loe06	365672	6637002	952	Loe56	364970	6633208	960
Loe07	365977	6636844	950	Loe57	364338	6632322	960
Loe08	366271	6636707	949	Loe58	363731	6631574	964
Loe09	366697	6636497	948	Loe59	363565	6630782	962
Loe10	366998	6636347	948				
Loe11	367301	6636186	948				
Loe12	368194	6635757	949				
Loe13	367949	6635918	948				
Loe14	367581	6635969	947				
Loe15	364216	6637725	940				
Loe16	363768	6637839	937				
Loe17	363699	6635352	950				
Loe18	364027	6635272	950				
Loe19	364394	6635226	947				
Loe20	364698	6635045	944				
Loe21	365033	6634964	944				
Loe22	365292	6634736	947				
Loe23	365653	6634331	947				
Loe24	365781	6635074	944				
Loe25	366266	6635126	944				
Loe26	366272	6634550	950				
Loe27	366687	6634661	952				
Loe28	367122	6634810	960				
Loe29	367569	6634941	959				
Loe30	365644	6635872	943				
Loe31	366113	6635944	941				
Loe32	365290	6635928	943				
Loe33	364999	6636089	945				
Loe34	364655	6636177	946				
Loe35	364321	6636233	947				
Loe36	363951	6636272	948				
Loe37	363472	6636092	950				
Loe38	362980	6636994	950				
Loe39	363199	6636733	950				
Loe40	363741	6634418	961				
Loe41	363393	6634481	961				
Loe42	363027	6634483	962				
Loe43	362734	6634651	962				
Loe44	362383	6634743	965				
Loe45	362412	6633749	970				
Loe46	362150	6633941	970				
Loe47	362914	6635723	952				
Loe48	362604	6635858	952				
Loe49	363335	6635364	951				
Loe50	364324	6634091	961				

1. Co-ordinate system is UTM Grid Zone 34S WGS84.

Table A-5 Turbine co-ordinates of neighbouring Kokerboom 1 Wind Farm (proposed)

Turbine	Easting [1] [m]	Northing [1] [m]	Height of base [m]	Turbine	Easting [1] [m]	Northing [1] [m]	Height of base [m]
K1_01	343791	6629923	955	K1_51	355434	6627811	977
K1_02	344288	6629937	963	K1_52	355691	6627390	972
K1_03	344785	6629905	965	K1_53	351981	6626751	940
K1_04	343606	6627725	931	K1_54	354409	6626182	946
K1_05	344177	6627894	940	K1_55	354876	6626125	955
K1_06	344706	6628028	950	K1_56	355443	6626255	959
K1_07	345269	6628207	955	K1_57	355979	6626323	950
K1_08	345829	6628391	958	K1_58	353137	6624766	926
K1_09	346104	6626254	939	K1_59	353841	6624410	919
K1_10	346453	6625958	946	K1_60	354511	6624760	927
K1_11	346872	6625788	943				
K1_12	347308	6625623	933				
K1_13	347668	6625365	919				
K1_14	348780	6625294	916				
K1_15	349104	6624949	919				
K1_16	349564	6624595	910				
K1_17	349873	6624201	901				
K1_18	347586	6628275	967				
K1_19	347924	6627966	969				
K1_20	348229	6627634	958				
K1_21	350153	6626155	941				
K1_22	345956	6631458	979				
K1_23	346340	6631253	990				
K1_24	346627	6630855	997				
K1_25	346945	6630526	1000				
K1_26	347463	6630583	1000				
K1_27	347725	6630191	996				
K1_28	348108	6629880	993				
K1_29	348488	6629665	990				
K1_30	348835	6629395	986				
K1_31	349121	6629023	982				
K1_32	349412	6628672	976				
K1_33	349713	6628371	972				
K1_34	349948	6627945	966				
K1_35	350228	6627555	955				
K1_36	347541	6633319	979				
K1_37	347733	6632786	981				
K1_38	348126	6632579	984				
K1_39	348427	6632179	990				
K1_40	348718	6631786	992				
K1_41	349033	6631416	990				
K1_42	351789	6629611	971				
K1_43	353180	6629047	959				
K1_44	353561	6628886	953				
K1_45	352011	6628518	960				
K1_46	352350	6628190	960				
K1_47	353405	6627654	937				
K1_48	353804	6627507	949				
K1_49	354244	6627394	959				
K1_50	354915	6627766	969				

1. Co-ordinate system is UTM Grid Zone 34S WGS84.

Table A-6 Turbine co-ordinates of neighbouring Kokerboom 2 Wind Farm (proposed)

Turbine	Easting [1] [m]	Northing [1] [m]	Height of base [m]	Turbine	Easting [1] [m]	Northing [1] [m]	Height of base [m]
K2_01	342336	6638419	951	K2_51	347456	6640205	968
K2_02	342610	6637861	953	K2_52	348193	6640575	968
K2_03	342899	6637321	953	K2_53	348206	6639680	970
K2_04	343156	6636758	950	K2_54	348693	6639690	969
K2_05	343405	6636253	947	K2_55	349108	6639482	971
K2_06	343664	6635743	951	K2_56	349465	6638913	971
K2_07	343917	6635260	944	K2_57	349822	6638625	970
K2_08	344399	6634697	941				
K2_09	343913	6631632	953				
K2_10	344210	6631305	960				
K2_11	345602	6631759	972				
K2_12	343351	6639720	946				
K2_13	343645	6639306	950				
K2_14	343930	6638876	953				
K2_15	344109	6638266	957				
K2_16	344314	6637678	958				
K2_17	344426	6636876	959				
K2_18	344663	6636323	959				
K2_19	345760	6635820	961				
K2_20	348635	6634049	976				
K2_21	349065	6633804	979				
K2_22	349606	6632969	986				
K2_23	349733	6631863	990				
K2_24	350257	6631922	990				
K2_25	350537	6631540	990				
K2_26	350819	6631084	990				
K2_27	351406	6630440	967				
K2_28	344625	6640579	950				
K2_29	344918	6640143	954				
K2_30	345221	6639700	958				
K2_31	345230	6638725	966				
K2_32	345446	6638137	975				
K2_33	345744	6637692	980				
K2_34	345963	6637060	971				
K2_35	346861	6636719	966				
K2_36	347257	6636371	967				
K2_37	347633	6636114	971				
K2_38	348050	6635879	972				
K2_39	348644	6635706	973				
K2_40	349220	6635870	975				
K2_41	350486	6633938	993				
K2_42	350662	6633287	989				
K2_43	346289	6639232	974				
K2_44	346632	6638909	980				
K2_45	347050	6638736	972				
K2_46	347455	6638544	970				
K2_47	348688	6638096	971				
K2_48	346165	6640664	958				
K2_49	346603	6640519	961				
K2_50	347025	6640314	968				

1. Co-ordinate system is UTM Grid Zone 34S WGS84.

Table A-7 Turbine co-ordinates of neighbouring Kokerboom 3 Wind Farm (planned)

Turbine	Easting [1] [m]	Northing [1] [m]	Height of base [m]	Turbine	Easting [1] [m]	Northing [1] [m]	Height of base [m]
K3_01	350799	6636290	979	K3_51	360311	6642653	940
K3_02	350957	6635913	992	K3_RE52	361255	6643502	940
K3_03	350975	6635386	999	K3_RE53	361624	6643270	940
K3_04	351537	6635773	989	K3_54	361956	6642979	939
K3_05	351513	6635136	995	K3_55	362248	6642674	939
K3_06	352034	6635291	990	K3_56	362520	6642206	935
K3_07	352939	6636401	968	K3_57	363171	6642253	937
K3_08	353055	6635985	968	K3_RE58	363504	6642053	939
K3_09	352414	6637632	966	K3_59	364089	6641793	944
K3_10	353017	6637960	970	K3_60	364610	6641459	943
K3_11	354140	6636708	958				
K3_12	351430	6639731	950				
K3_13	351507	6639027	958				
K3_14	352122	6639202	959				
K3_15	352847	6639360	958				
K3_16	353583	6639324	970				
K3_17	353972	6639200	967				
K3_18	354531	6639497	963				
K3_19	354687	6638944	963				
K3_20	354973	6638699	961				
K3_21	355663	6638444	953				
K3_22	355850	6637479	950				
K3_23	357036	6638580	950				
K3_24	356878	6637575	949				
K3_25	357402	6637624	950				
K3_26	358275	6637712	944				
K3_27	358708	6637575	946				
K3_28	359378	6637835	939				
K3_29	355549	6640374	960				
K3_30	356096	6640359	960				
K3_31	356260	6639889	960				
K3_32	356821	6640226	953				
K3_33	357173	6639976	951				
K3_34	354008	6641891	938				
K3_35	354985	6641922	940				
K3_36	358318	6641998	940				
K3_37	358486	6640718	940				
K3_38	352271	6643521	950				
K3_39	352500	6644827	947				
K3_40	353196	6644443	938				
K3_41	353665	6643967	937				
K3_42	354325	6644024	940				
K3_43	355777	6644955	928				
K3_44	356035	6644275	930				
K3_45	357297	6644705	929				
K3_46	358001	6645021	930				
K3_47	359146	6644399	934				
K3_48	359542	6644145	939				
K3_49	359989	6643943	937				
K3_50	360425	6643904	938				

1. Co-ordinate system is UTM Grid Zone 34S WGS84.

Table A-8 Turbine co-ordinates of neighbouring Kokerboom 4 Wind Farm (planned)

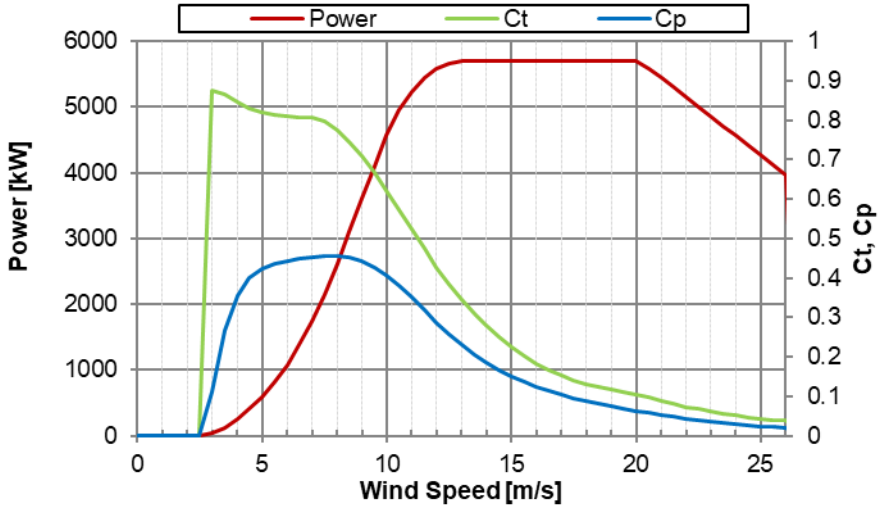
Turbine	Easting [1] [m]	Northing [1] [m]	Height of base [m]
K4_01	358104	6635817	970
K4_02	358744	6635128	971
K4_03	358956	6634574	980
K4_04	359347	6634193	981
K4_05	359759	6633832	978
K4_06	361497	6634129	970
K4_07	361065	6634546	972
K4_08	360689	6635190	971
K4_09	359411	6636924	951
K4_10	360184	6636582	953
K4_11	360748	6636212	951
K4_12	361741	6637677	934

1. Co-ordinate system is UTM Grid Zone 34S WGS84..

APPENDIX B: WIND TURBINE DATA

Table B-1 Turbine data for the Nordex N163 5.7 MW

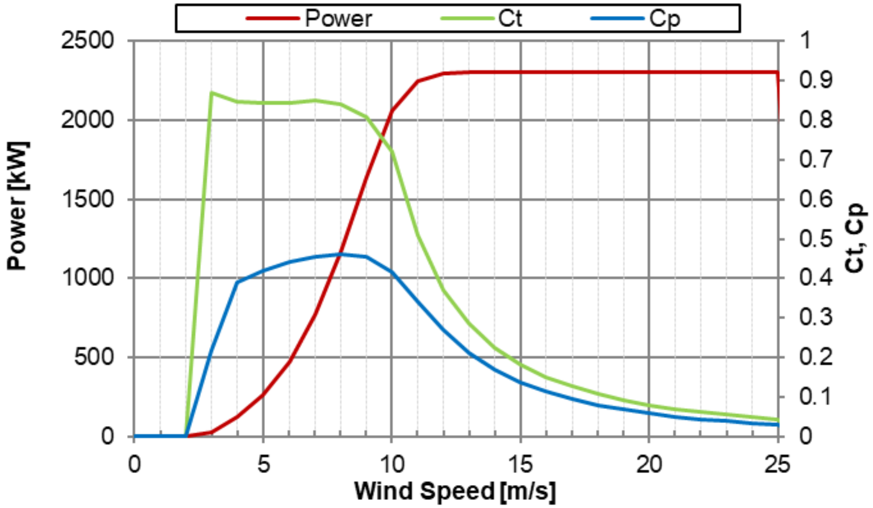
Manufacturer	Vestas	Hub height wind speed [m/s]	Electrical power [kW]	Thrust coefficient [Ct]
Turbine	N163 5.7	1	0	0.000
Power Control	Pitch	2	0	0.000
Rated power	5700 kW	3	34	0.875
Diameter	163 m	4	254	0.847
Hub height	118 m	5	594	0.819
Rotor speed	6.0 – 11.8 rpm	6	1075	0.809
Air Density	1.075 kg/m³	7	1739	0.806
Turbulence intensity	0 - 0%	8	2615	0.775
Peak C_p	0.46	9	3614	0.709
Cut-out ten-minute mean wind speed	26 m/s	10	4564	0.621
Restart ten-minute mean wind speed	25.5 m/s	11	5238	0.523
Operational temperature range	unknown	12	5580	0.427
		13	5697	0.345
		14	5700	0.279
		15	5700	0.226
		16	5700	0.183
		17	5700	0.153
		18	5700	0.131
		19	5700	0.116
		20	5700	0.105
		21	5455	0.088
		22	5153	0.073
		23	4856	0.062
		24	4560	0.051
		25	4269	0.044
		26	3973	0.038



Source:
F008_276_A12_EN_R01_Nordex_N163_5.X.pdf

Table B-2 Turbine data for the Siemens SWT 2.3-108

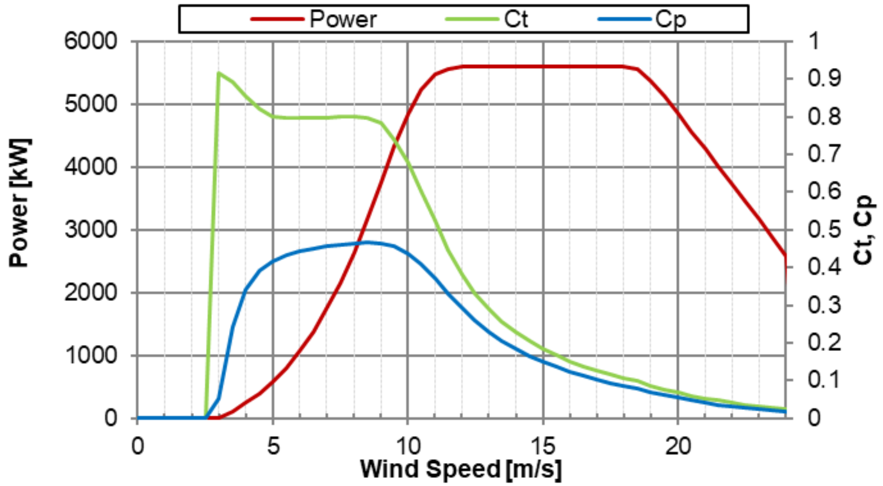
Manufacturer	Siemens	Hub height wind speed [m/s]	Electrical power [kW]	Thrust coefficient [Ct]
Turbine	N163 5.7	1	0	0.000
Power Control	Pitch	2	0	0.000
Rated power	2300 kW	3	29	0.871
Diameter	105 m	4	123	0.848
Hub height	99 m	5	259	0.844
Rotor speed	6.0 – 16 rpm	6	472	0.845
Air Density	1.080 kg/m³	7	771	0.85
Turbulence intensity	unknown	8	1166	0.841
Peak C_p	0.46	9	1643	0.807
Cut-out ten-minute mean wind speed	25 m/s	10	2060	0.72
Restart ten-minute mean wind speed	20 m/s	11	2251	0.511
Operational temperature range	unknown	12	2295	0.371
		13	2300	0.286
		14	2300	0.226
		15	2300	0.182
		16	2300	0.15
		17	2300	0.126
		18	2300	0.107
		19	2300	0.091
		20	2300	0.079
		21	2300	0.07
		22	2300	0.062
		23	2300	0.055
		24	2300	0.048
		25	2300	0.044



Source:
Siemens SWT-2.3-108 2300 108.0 !O!.wtg

Table B-3 Turbine data for the Vestas V162 5.6 MW

Manufacturer	Vestas	Hub height wind speed [m/s]	Electrical power [kW]	Thrust coefficient [Ct]
Turbine	V162 5.6	1	0	0.000
Power Control	Pitch	2	0	0.000
Rated power	5600 kW	3	16	0.915
Diameter	162 m	4	243	0.854
Hub height	120 m	5	578	0.801
Rotor speed	4.3 – 12.1 rpm	6	1059	0.797
Air Density	1.075 kg/m³	7	1737	0.796
Turbulence intensity	6 - 12%	8	2634	0.799
Peak C_p	0.47	9	3751	0.783
Cut-out ten-minute mean wind speed	24 m/s	10	4846	0.678
Restart ten-minute mean wind speed	22 m/s	11	5483	0.525
Operational temperature range	unknown	12	5591	0.383
		13	5600	0.290
		14	5600	0.228
		15	5600	0.183
		16	5600	0.151
		17	5600	0.126
		18	5598	0.107
		19	5374	0.087
		20	4837	0.068
		21	4280	0.053
		22	3722	0.041
		23	3164	0.032
		24	2579	0.024



Source:
0081-5098_V05 - Performance Specification V162-5.6 MW.pdf

APPENDIX C: WIND DATA

C-1. Mast M1

C-2. Reference wind data

C-1 Mast M1

Table C-9 Mast M1 configuration

Site name	Botterblom	Elevation [m]	Eastings [m]	Northings [m]	Coordinate system	Datum	Zone
Mast name	M1		360977	6628106	UTM	WGS84	34S
Installation date	2020-09-04						

Anemometer description

Channel no.	Anemometer model	Serial no.	Start date	End date	Instrument height [m]	Boom orientation [degrees]	Slope applied by data logger [m]	Offset applied by data logger [m/s]	Slope desired [m]	Offset desired [m/s]	Boom length [Dm][1]	Height above boom [Db][1]
1	Thies FCA II	03206126	2020-09-05	2021-12-31	124	Top	0.045870	0.236333	0.045870	0.236333	6.4[2]	-
2	Thies FCA II	03206127	2020-09-05	2021-12-31	120	134	0.045795	0.240954	0.045795	0.240954	5.8	2.5
3	Thies FCA II	03206128	2020-09-05	2021-12-31	100	135	0.045737	0.255168	0.045737	0.255168	5.8	2.5
4	Thies FCA II	03206129	2020-09-05	2021-12-31	80	137	0.045645	0.272412	0.045645	0.272412	5.8	2.5
5	Thies FCA II	03206130	2020-09-05	2021-12-31	60	135	0.045781	0.242171	0.045781	0.242171	5.8	2.5
6	Thies FCA II	03206131	2020-09-05	2021-12-31	40	133	0.045706	0.254386	0.045706	0.254386	5.8	2.5

Channel no.	Wind vane model	Serial no.	Start date	End date	Instrument height [m]	Boom orientation [degrees]	Offset desired [degrees]	Boom length [Dm][1]	Height above boom [Db][1]
7	Thies Compact	01200513	2020-09-05	2021-12-31	120	315	135	5.8	2.5
8	Thies Compact	01200511	2020-09-05	2021-12-31	100	314	134	5.8	2.5

Notes:
1. Dm = Mast Diameters; Db = Boom Diameters
2. Top-mounted sensor on vertical boom

Logger description	
M40	Campbell CR1000X
Serial number	16548
Installation date	2020-09-04
Averaging period	10 minutes
Sample frequency	1 Hz

Figure C-1   Panoramic view from location of Mast M1 (provided by the Customer)

Figure C-2 Mast M1 photographs (provided by the Customer)

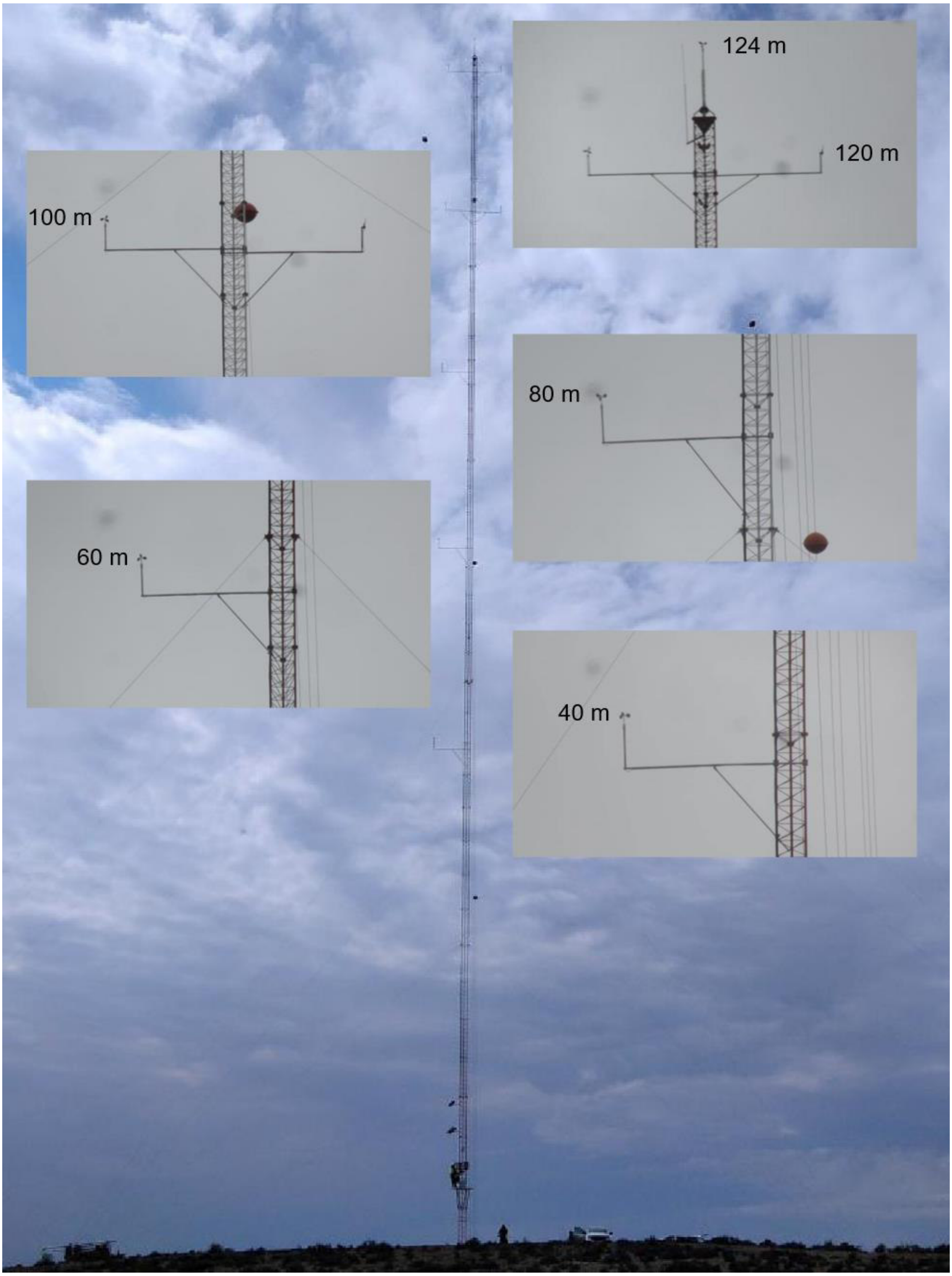


Table C-10 Mast M1 data summary

Month	Mean wind speed [m/s]						Wind speed data coverage [%]						Wind direction data coverage [%]	
	124 m[1]	120 m[2]	100 m[2]	80 m[2]	60 m[2]	40 m[2]	124 m[1]	120 m[2]	100 m[2]	80 m[2]	60 m[2]	40 m[2]	120 m[3]	100 m[3]
Sep-2020	7.6	7.5	7.4	7.2	7.0	6.7	86	86	84	85	85	85	85	85
Oct-2020	7.4	7.3	7.2	7.0	6.8	6.4	100	100	98	96	97	99	100	100
Nov-2020	8.3	8.3	8.1	8.0	7.8	7.5	98	98	98	98	98	98	98	98
Dec-2020	8.3	8.3	8.2	8.1	7.8	7.6	100	100	98	99	99	99	100	100
Jan-2021	8.3	8.3	8.2	8.0	7.8	7.5	100	100	99	100	100	100	98	98
Feb-2021	8.4	8.3	8.2	8.0	7.8	7.5	100	99	100	100	100	100	100	100
Mar-2021	7.1	7.1	6.9	6.8	6.6	6.3	100	100	100	100	100	100	99	99
Apr-2021	6.3	6.3	6.2	6.0	5.8	5.6	100	99	100	100	100	100	100	100
May-2021	7.3	7.2	7.1	6.9	6.7	6.4	100	99	100	100	99	100	100	100
Jun-2021	9.1	9.1	8.9	8.5	8.1	7.7	99	100	99	99	100	100	99	100
Jul-2021	8.9	7.7	8.6	8.3	8.0	7.7	100	39	99	100	99	99	99	100
Aug-2021	8.0	_	7.7	7.5	7.3	6.9	100	0	100	100	99	100	99	99
Sep-2021	8.2	_	8.0	7.8	7.6	7.3	100	0	100	100	100	100	95	95
Oct-2021	8.4	8.2	8.2	8.0	7.8	7.4	100	82	100	100	100	100	98	98
Nov-2021	8.3	8.2	8.1	7.9	7.7	7.4	100	100	99	99	99	99	100	100
Dec-2021	8.2	8.1	8.0	7.8	7.6	7.4	100	99	99	99	99	99	96	96

1. Instrument top-mounted
2. Instrument mounted on boom oriented to the southeast
3. Instrument mounted on boom oriented to the northwest

Table C-11 Mast M1 data filtering and quality control

The wind data have been subject to a quality checking procedure by DNV to identify records which were affected by equipment malfunction and other anomalies. The main periods for which valid wind data were not available are summarised below, together with details of the errors identified. • 2021-07-23 to 2021-10-06: Sensor offline due to faulty wiring, Anemometer at 120 m.

C-2 Reference wind data

Table C-12 ERA5 Grid Cell at 30.6°S 19.5°E at 100 m above ground summary statistics

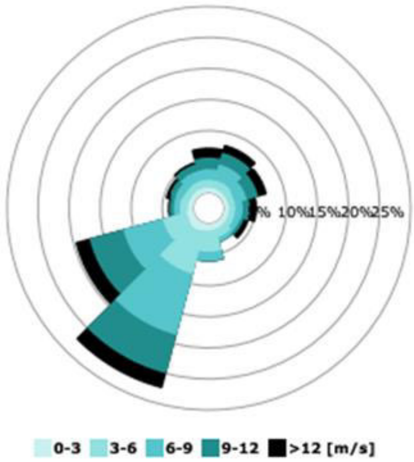
Month	Mean wind speed [m/s]																			
	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
Jan	6.2	6.7	6.1	6.5	5.6	6.4	6.3	6.3	6.0	6.3	6.3	6.8	6.2	6.3	6.0	6.8	6.5	6.8	6.2	6.5
Feb	6.3	5.6	6.0	6.1	5.5	6.2	5.7	6.2	5.8	4.6	5.5	6.5	6.1	6.3	6.3	6.0	6.3	6.0	6.5	6.5
Mar	5.0	6.3	6.2	5.6	6.6	6.0	5.4	4.9	5.2	5.0	5.6	6.1	5.5	5.4	5.6	5.6	5.6	5.6	4.8	5.4
Apr	5.3	5.0	6.3	6.0	6.0	5.3	5.3	6.0	5.5	6.1	6.3	6.0	5.7	5.6	6.6	6.7	5.2	5.5	5.5	4.8
May	5.2	5.8	5.4	5.9	6.2	6.3	5.9	5.4	6.0	5.4	5.3	6.4	6.2	4.5	7.0	6.1	5.6	5.3	5.2	5.6
Jun	6.4	5.9	6.5	5.8	7.5	7.1	6.5	7.3	7.1	6.4	6.5	6.9	7.2	6.4	6.5	6.8	5.8	6.3	7.4	7.0
Jul	6.9	6.6	6.4	6.2	6.0	7.0	6.8	7.3	7.4	7.0	6.0	5.9	6.8	5.7	6.8	5.9	8.4	5.9	7.3	6.9
Aug	6.5	6.2	5.7	5.7	6.9	6.5	5.9	5.9	7.4	7.5	6.4	6.5	6.2	6.1	6.7	5.6	5.8	5.5	6.2	6.2
Sep	6.5	5.7	5.9	5.3	6.4	5.4	6.6	5.9	6.1	5.6	6.0	5.6	5.6	6.2	5.9	5.8	5.8	6.7	5.9	6.3
Oct	6.3	6.0	6.1	6.2	6.2	6.9	6.1	6.1	6.1	6.2	6.5	6.4	6.7	5.9	6.2	6.8	7.4	6.2	5.8	6.7
Nov	6.9	6.5	6.3	6.7	6.9	6.7	6.6	6.8	6.5	6.7	6.7	6.4	6.1	7.3	6.4	6.5	6.5	6.2	6.8	-
Dec	6.4	6.6	6.8	6.6	6.8	6.1	6.6	6.3	6.5	6.7	5.6	6.5	6.7	6.0	6.6	6.7	6.3	6.7	6.6	-
Annual	**6.2**	**6.1**	**6.1**	**6.1**	**6.4**	**6.3**	**6.1**	**6.2**	**6.3**	**6.1**	**6.1**	**6.3**	**6.3**	**6.0**	**6.4**	**6.3**	**6.3**	**6.1**	**6.2**	**-**

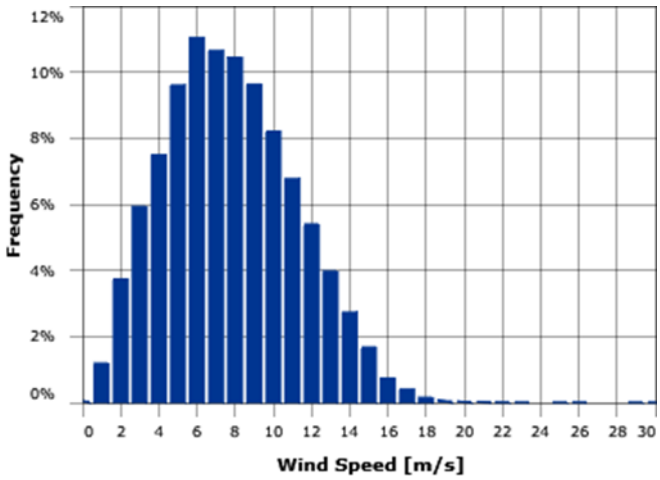
APPENDIX D: MAST LONG-TERM WIND REGIME

Table D-1 Mast M1 long-term wind speed frequency distribution at 99 m

Monthly mean wind speeds

Monthly	Wind speed [m/s]	Valid wind speed data [months]	Valid direction data [months]
January	8.1	1.0	1.0
February	8.2	1.0	1.0
March	6.9	1.0	1.0
April	6.2	1.0	1.0
May	7.1	1.0	1.0
June	8.9	1.0	1.0
July	8.6	1.0	1.0
August	7.7	1.0	1.0
September	7.7	1.9	1.8
October	7.7	2.0	2.0
November	8.1	2.0	2.0
December	8.1	2.0	2.0
Annual	7.8		





Wind speed and direction frequency distribution — Period: January 2002 to December 2021

Wind Speed [m/s]	0	30	60	90	120	150	180	210	240	270	300	330	No Direction	Total [%]
0	+	+	+	+	+	+	+	+	+	+	+	+	0.05	0.06
1	0.07	0.06	0.07	0.06	0.10	0.13	0.10	0.09	0.11	0.06	0.08	0.09	0.18	1.19
2	0.24	0.19	0.20	0.26	0.28	0.34	0.39	0.50	0.37	0.27	0.26	0.26	0.19	3.74
3	0.37	0.32	0.29	0.32	0.36	0.45	0.74	1.08	0.68	0.44	0.35	0.39	0.15	5.93
4	0.43	0.36	0.28	0.31	0.34	0.51	1.05	1.83	1.01	0.43	0.34	0.47	0.13	7.49
5	0.46	0.54	0.39	0.36	0.35	0.46	1.24	2.81	1.64	0.46	0.43	0.38	0.09	9.60
6	0.43	0.73	0.53	0.34	0.31	0.43	1.42	3.50	2.02	0.44	0.42	0.44	0.03	11.04
7	0.57	0.82	0.66	0.35	0.29	0.33	0.57	3.70	2.07	0.30	0.44	0.52	0.02	10.65
8	0.63	1.01	0.68	0.51	0.35	0.19	0.18	3.26	2.26	0.30	0.47	0.60	+	10.44
9	0.66	0.86	0.75	0.37	0.30	0.06	0.09	2.93	2.41	0.24	0.36	0.60	+	9.63
10	0.68	0.69	0.66	0.40	0.20	0.04	0.03	2.34	2.13	0.26	0.32	0.45	+	8.21
11	0.59	0.63	0.64	0.36	0.15	0.01	0.01	1.86	1.69	0.24	0.31	0.29	+	6.77
12	0.52	0.44	0.51	0.36	0.15	+	+	1.54	1.27	0.17	0.20	0.25	+	5.40
13	0.45	0.50	0.43	0.32	0.18		0.01	0.97	0.76	0.09	0.14	0.12		3.98
14	0.43	0.30	0.26	0.27	0.24		+	0.49	0.52	0.04	0.11	0.07		2.73
15	0.24	0.15	0.28	0.20	0.19		+	0.21	0.28	0.03	0.06	0.05		1.68
16	0.11	0.07	0.11	0.10	0.12		+	0.07	0.11	0.01	0.03	0.02		0.74
17	0.09	0.04	0.09	0.08	0.03			0.02	0.02	0.01	0.02	+		0.40
18	0.04	0.02	0.02	0.02	0.01			+	0.01	0.01	0.01	+		0.16
19	0.01	0.02	0.02	0.01	+				0.01	+	0.01	+		0.07
20		0.02	+	+	+			+	+	+	+	+		0.04
21		0.02	+					+	+		+	+		0.03
22											+	+		0.01
23											+			+
24														
25											+	+		+
26											+	+		+
27														
28														
29												+		+
30												+		+
30+														
Total [%]	7.00	7.76	6.88	5.01	3.97	2.93	5.83	27.19	19.39	3.82	4.35	5.01	0.85	100.00
Mean Speed	8.89	8.57	8.98	8.66	7.86	4.74	4.95	7.77	8.28	6.63	7.43	7.30	2.88	7.77

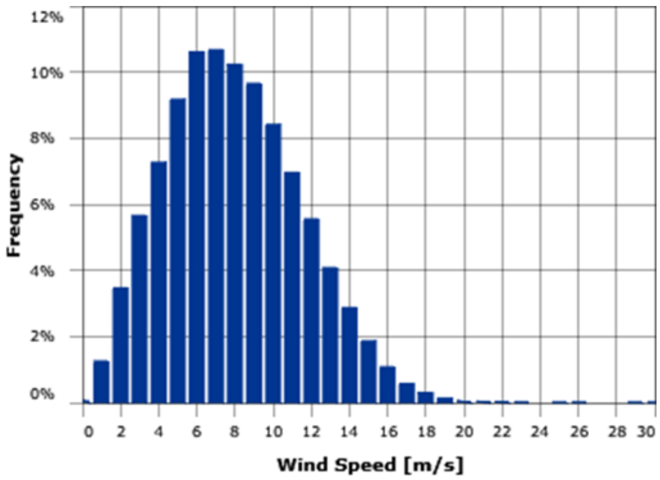
Note: '+' indicates non-zero percentage <0.005%, blank indicates zero percentage

DNV

Table D-2 Mast M1 long-term wind speed frequency distribution at 118 m

Monthly mean wind speeds

Monthly	Wind speed [m/s]	Valid wind speed data [months]	Valid direction data [months]
January	8.3	1.0	1.0
February	8.3	1.0	1.0
March	7.1	1.0	1.0
April	6.3	1.0	1.0
May	7.3	1.0	1.0
June	9.1	1.0	1.0
July	8.8	1.0	1.0
August	7.9	1.0	1.0
September	7.9	1.9	1.8
October	7.8	2.0	2.0
November	8.3	2.0	2.0
December	8.2	2.0	2.0
Annual	7.9		



Wind speed and direction frequency distribution — Period: January 2002 to December 2021

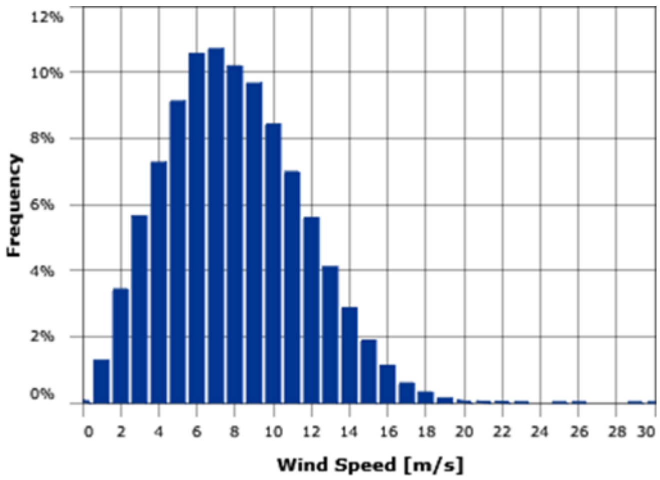
Wind Speed [m/s]	0	30	60	90	120	150	180	210	240	270	300	330	No Direction	Total [%]
0	+	+	+	+	+	+	+	+	+	+	+	+	0.05	0.07
1	0.07	0.07	0.07	0.07	0.12	0.13	0.10	0.09	0.12	0.07	0.09	0.09	0.19	1.25
2	0.23	0.19	0.20	0.25	0.26	0.28	0.34	0.47	0.34	0.25	0.24	0.25	0.17	3.47
3	0.36	0.31	0.29	0.28	0.32	0.41	0.65	1.07	0.65	0.44	0.34	0.39	0.15	5.66
4	0.43	0.38	0.29	0.32	0.32	0.46	0.98	1.72	1.01	0.41	0.35	0.46	0.14	7.26
5	0.45	0.52	0.40	0.37	0.32	0.43	1.12	2.69	1.56	0.46	0.39	0.39	0.07	9.17
6	0.41	0.71	0.49	0.33	0.26	0.40	1.38	3.35	1.97	0.44	0.43	0.42	0.04	10.61
7	0.55	0.76	0.63	0.33	0.29	0.37	0.79	3.69	2.01	0.32	0.42	0.49	0.02	10.68
8	0.59	0.97	0.64	0.43	0.27	0.26	0.26	3.27	2.19	0.29	0.45	0.60	0.01	10.23
9	0.66	0.87	0.72	0.38	0.29	0.12	0.13	2.93	2.38	0.24	0.36	0.57	+	9.65
10	0.65	0.73	0.61	0.39	0.24	0.05	0.03	2.49	2.17	0.24	0.33	0.49	+	8.41
11	0.60	0.59	0.65	0.34	0.23	0.02	0.02	1.88	1.73	0.27	0.30	0.32	+	6.96
12	0.49	0.45	0.51	0.30	0.17	+	+	1.63	1.37	0.18	0.22	0.23	+	5.56
13	0.44	0.43	0.43	0.27	0.18	+	+	1.05	0.86	0.12	0.16	0.13		4.08
14	0.41	0.37	0.29	0.34	0.18		0.01	0.53	0.53	0.04	0.09	0.08		2.87
15	0.30	0.20	0.22	0.22	0.21		+	0.23	0.32	0.03	0.08	0.06		1.86
16	0.16	0.08	0.21	0.16	0.17		+	0.08	0.14	0.02	0.04	0.03		1.08
17	0.09	0.04	0.13	0.12	0.11			0.02	0.03	0.01	0.02	+		0.57
18	0.07	0.02	0.08	0.06	0.03			+	0.01	0.01	0.01	0.01		0.30
19	0.03	0.02	0.03	0.02	0.01				0.01	+	0.01	+		0.13
20	0.01	0.01	0.01	0.01	+			+	+	+	+	+		0.05
21		0.02	+		+			+	+		+	+		0.04
22		0.02	+								+	+		0.03
23											+	+		0.01
24														
25											+	+		+
26											+	+		+
27														
28														
29												+		+
30												+		+
30+														
Total [%]	7.00	7.76	6.88	5.01	3.97	2.93	5.83	27.19	19.39	3.82	4.35	5.01	0.85	100.00
Mean Speed	9.07	8.70	9.21	8.99	8.34	5.05	5.17	7.88	8.40	6.78	7.54	7.41	2.92	7.93

Note: '+' indicates non-zero percentage <0.005%, blank indicates zero percentage

Table D-3 Mast M1 long-term wind speed frequency distribution at 120 m

Monthly mean wind speeds

Monthly	Wind speed [m/s]	Valid wind speed data [months]	Valid direction data [months]
January	8.3	1.0	1.0
February	8.4	1.0	1.0
March	7.1	1.0	1.0
April	6.3	1.0	1.0
May	7.3	1.0	1.0
June	9.1	1.0	1.0
July	8.8	1.0	1.0
August	7.9	1.0	1.0
September	7.9	1.9	1.8
October	7.9	2.0	2.0
November	8.3	2.0	2.0
December	8.2	2.0	2.0
Annual	7.9		



Wind speed and direction frequency distribution — Period: January 2002 to December 2021

Wind Speed [m/s]	0	30	60	90	120	150	180	210	240	270	300	330	No Direction	Total [%]
0	+	+	+	+	+	+	+	+	+	+	+	+	0.05	0.07
1	0.07	0.07	0.07	0.07	0.12	0.13	0.10	0.09	0.12	0.07	0.09	0.09	0.19	1.27
2	0.23	0.19	0.20	0.24	0.25	0.28	0.35	0.47	0.34	0.25	0.24	0.24	0.16	3.43
3	0.36	0.31	0.29	0.28	0.33	0.41	0.63	1.06	0.65	0.44	0.34	0.40	0.15	5.64
4	0.43	0.38	0.30	0.32	0.32	0.45	0.98	1.73	1.02	0.41	0.35	0.45	0.13	7.26
5	0.45	0.52	0.39	0.37	0.32	0.42	1.10	2.68	1.55	0.46	0.39	0.39	0.08	9.11
6	0.42	0.71	0.48	0.33	0.24	0.41	1.35	3.32	1.97	0.43	0.43	0.42	0.04	10.56
7	0.55	0.75	0.63	0.33	0.29	0.36	0.83	3.69	2.00	0.33	0.42	0.49	0.03	10.70
8	0.58	0.96	0.64	0.43	0.26	0.27	0.28	3.25	2.18	0.29	0.45	0.59	0.01	10.18
9	0.67	0.88	0.70	0.38	0.29	0.12	0.13	2.96	2.35	0.23	0.36	0.58	+	9.65
10	0.64	0.72	0.61	0.38	0.24	0.05	0.04	2.49	2.18	0.24	0.32	0.48	+	8.42
11	0.60	0.61	0.64	0.35	0.22	0.02	0.02	1.88	1.75	0.27	0.30	0.33	+	6.98
12	0.48	0.44	0.52	0.28	0.19	+	+	1.65	1.38	0.18	0.23	0.23	+	5.59
13	0.46	0.42	0.41	0.30	0.18	+	+	1.05	0.87	0.12	0.16	0.13		4.10
14	0.41	0.38	0.29	0.33	0.17		0.01	0.54	0.54	0.04	0.08	0.08		2.86
15	0.30	0.20	0.22	0.22	0.22		+	0.23	0.31	0.03	0.09	0.06		1.88
16	0.16	0.08	0.21	0.17	0.18		+	0.08	0.14	0.02	0.04	0.03		1.12
17	0.10	0.04	0.13	0.13	0.11			0.02	0.03	0.01	0.02	+		0.59
18	0.07	0.02	0.08	0.07	0.03			+	0.01	0.01	0.01	0.01		0.31
19	0.03	0.01	0.03	0.02	0.01				0.01	+	0.01	+		0.13
20	0.01	0.01	0.02	0.01	+			+	+	+	+	+		0.06
21		0.02	+		+			+	+		+	+		0.04
22		0.03	+								+	+		0.03
23											+	+		0.01
24														
25											+	+		+
26											+	+		+
27														
28														
29												+		+
30												+		+
30+														
Total [%]	7.00	7.76	6.88	5.01	3.97	2.93	5.83	27.19	19.39	3.82	4.35	5.01	0.85	100.00
Mean Speed	9.09	8.71	9.23	9.02	8.39	5.07	5.20	7.89	8.42	6.79	7.56	7.42	2.93	7.95

Note: '+' indicates non-zero percentage <0.005%, blank indicates zero percentage

APPENDIX E: ANALYSIS METHODOLOGY

E-1 Wind data analysis process overview

The analysis of the wind data involves several steps, which are summarised below:

1. The raw wind speed data from the site are processed and evaluated to identify periods with missing or erroneous data due to instrument failures, icing, or other factors.
2. Missing wind speed and direction data at the primary anemometer and wind vane at each site mast are synthesized from data recorded at the same mast where available, or from others on-site masts, to create a full record for the site period (site period wind speed and direction).
3. The on-site measurements are correlated with the sources of long-term reference wind data, and the results evaluated, to develop an estimate of reference period wind speeds at measurement height.
4. Uncertainties in the site period wind speeds and reference period wind speeds, as well as the relationships between the two are analysed to ascertain which methodology results in the best estimate of the true long-term wind speeds with the lowest bias and uncertainty.
5. The measurement height estimate of long-term wind speeds is extrapolated to hub height using power law wind shear exponent and the associated uncertainties are assessed.
6. Long-term hub-height wind speed and direction frequency distribution estimates at each measurement location are derived from the measured and synthesized data.
7. The wind regime at the proposed turbine locations is assessed using wind flow models and DNV experience and judgment.
8. The uncertainties in the resulting hub-height wind speeds at the turbine locations are assessed.

E-2 Met mast data processing and validation

Meteorological data should be provided in a raw form, preferably encrypted. Sufficient documentation should be provided to ensure the data integrity.

When calibration certificates from a Measnet-accredited facility have been supplied, DNV applies these in order to convert the raw data into wind speeds. For anemometers where calibration data are not provided, DNV applies a model-specific calibration.

Meteorological data are subject to a quality checking procedure by DNV to identify records which were affected by equipment malfunction, icing, and other anomalies. These records are considered invalid and excluded from the analysis.

All data from NRG #40 anemometers manufactured between mid-2006 and January 2009 are evaluated for evidence of a problem described in a technical note from NRG issued in spring 2008 /E1/. In this technical note, NRG described the problem, which manifests itself as intermittent under-speeding or dragging. After investigation, NRG concluded that the degrading and under-speeding was due to a phenomenon known as "dry friction whip". All anemometers manufactured by NRG after 1 January 2009 featured modifications aimed at reducing or eliminating the occurrence of this behaviour. The conclusions of NRG's investigation and the subsequent design changes are discussed in more detail in /E2/, presented by NRG at the AWEA annual conference in early May 2009. DNV examines potentially affected wind data to identify and remove periods affected by this issue. Any periods which are clearly affected are removed from the analysis and the additional uncertainty associated with either data removal or the inclusion of suspect data in the wind analysis is estimated.

To minimise the impact of the mast structure on the measured wind speed data, data recorded at levels with redundant instruments are “selectively averaged”. In direction sectors where an anemometer is affected by the wake of the mast, the unaffected anemometer is selected; in direction sectors where both anemometers are valid, the measurements are averaged.

E-3 Remote sensing data processing and validation

In order to evaluate the quality of a remote sensing device, several parameters may be reviewed. These include:

- Carrier-to-noise ratio (CNR)
- Signal-to-noise ratio (SNR)
- Wiper count
- Availability
- Amplitude signal
- Signal level
- Noise
- Echo suppression
- Valid count or recovery rate
- Standard deviation
- Turbulence intensity
- Beam component wind speed

Of these the CNR or SNR provides vital information about the quality of the beam propagation. The CNR or SNR generally decreases with height. If a significant number of points deviate from this, it can indicate signal noise contamination.

The first order quality control is generally an automatic procedure that is carried out by the manufacturer's online software program. Data are then filtered with in-house software using following data quality tests:

- Data with poor reliability, quality, or availability are removed;
- Horizontal wind speed (0 to 60 m/s) and direction validation (0 to 360°);
- Vertical wind speed validation (between -2 and 2 m/s); and
- Horizontal and vertical standard deviation validation (<5 m/s).

Following automated data processing, all remote sensing datasets are checked manually to ensure that the results are sensible. This includes an assessment of the consistency between measurement heights and consistency relative to the associated met mast anemometry, if possible.

E-4 Data correlation and prediction

The period of data available at the site masts can be extended through establishing relationships between two data sets, using correlations to synthesize the missing data at the site. In this procedure, concurrent wind data from a "target" sensor and a "reference" sensor are compared. The reference sensor may be on the same mast or at a different measurement location. The reference sensor is chosen to be one for which wind records are available for the period being synthesized. The concurrent measured wind data are then used to establish the correlation between the winds at the two locations. This correlation is then used to synthesize data at the "target" location from the "reference" location.

The following methods are used to extend the period of record available at a mast.

E-4.1 Ten-minute or hourly synthesis method

In the correlation of 10-minute or hourly data, the concurrent data are correlated by comparing wind speeds at the two locations for each of twelve 30° direction sectors, based on the wind direction recorded at the "reference" location. This correlation involves two steps:

- Wind directions recorded at the two locations are compared to determine whether there are any local features influencing the directional results. Typically, only those records with speeds in excess of 5 m/s at both locations are used.
- Wind speed relationships are determined for each of the direction sectors using a principal component analysis.

The result of the analysis described above is a series of wind speed relationships, "speed-up ratios", each corresponding to one of twelve direction sectors. These relationships are used to factor the wind data measured at the "reference" mast location, thereby obtaining synthesised wind data for the period of missing data at the "target" mast location.

In order to retain as much measured data at the target location as possible, the synthesized wind data are only used to fill in gaps in the measured data series.

E-4.1.1 Correlation check

To check the quality of a correlation between the reference and target, the concurrent measured and synthesized wind data at the target are compared. If the energy content of the synthesized time series is within acceptable bounds, the data are considered well correlated.

E-4.2 Daily synthesis method

In the correlation of daily wind speeds, the concurrent daily wind speeds are compared in one of two ways:

- If there is a seasonal trend between the target and reference, the daily correlation can be divided into 12 separate correlations, based on the calendar month. In this "Daily-by-Month" method, 12 separate correlations are established.
- If there is no seasonal trend, or less than a year of concurrent data, a single "all-data" daily correlation is derived.

The results of these analyses are either a single correlation slope and offset or a set of twelve correlation slope and offset values, each corresponding to one of twelve calendar months. These slope and offset values are applied to the wind data measured at the "reference" mast location, thereby obtaining synthesized daily wind data for the period of missing data at the "target" mast location.

The measured and synthesised daily wind speed time series are combined, with priority given to the measured data. The long-term wind speed is then derived from this combined measured and synthesised daily time series.

E-4.3 Monthly synthesis method

In the correlation of monthly wind speeds, the concurrent monthly wind speeds are compared to establish a single correlation slope and offset. The slope and offset values are applied to the wind data measured at the "reference" mast location, thereby obtaining synthesized monthly wind data for the period of missing data at the "target" mast location.

The measured and synthesised monthly wind speed time series are combined, with priority given to the measured data. The long-term wind speed is then derived from this combined measured and synthesised monthly time series.

E-4.4 Mean of monthly means

In order to avoid the introduction of seasonal bias into estimates of the annual wind speed as well as wind speed and direction distributions from seasonally uneven data coverage, the following procedure is followed:

- The wind speed or distribution for each month is determined from the average of all valid data recorded in that month over the period. This is taken as the monthly mean, thereby assuming that the valid data are representative of any missing data.
- The mean of the monthly means, weighted by the number of days in a month, is taken to determine the annual mean ("mean of means").

E-5 Hub-height wind speed and direction distributions

E-5.1 Shear power law

The boundary layer power law shear exponents at the site masts are derived from the available measurements. The power law relates the ratio of measured wind speeds, U_1/U_2, to the ratio of the measurement heights, z_1/z_2, using the wind shear exponent, α, as follows:

$$\frac{\bar{U}(z_1)}{\bar{U}(z_2)} = \left(\frac{z_1 - d}{z_2 - d}\right)^{\alpha}$$

where
α is power law wind shear exponent,
$\bar{U}$ is the wind speed,
z is the height above ground level, and
d is the effective flow displacement height, if any.

The boundary-layer power law shear exponent was derived for each mast location using the ratios of measured concurrent wind speed data recorded at multiple measurement heights.

E-5.2 Directional shear method

The relationship between two or more heights on a mast is established for each of twelve 30° direction sectors, using the technique described in Section E-4.1. These relationships are used to derive the boundary-layer power law shear exponent in each of twelve direction sectors, which are then used to extrapolate data recorded at the upper measurement height to the target hub height, on a directional basis.

The annual average wind speed frequency and direction distributions at measurement height are determined from the site period wind speed data using the mean of monthly means approach described in Section E-4.4. The resulting distributions in each direction sector are then scaled to the predicted long-term hub height wind speed(s).

E-5.3 Time series method

The boundary-layer power law shear exponent is derived between two measurement heights for each 10-minute, or hourly, time step. A time series of wind speed at the target hub height is calculated by extrapolating the upper measurement height using the instantaneous boundary-layer power law shear exponent. The Mean of Monthly Means procedure is used to avoid the introduction of bias into the annual wind regime prediction from seasonally-uneven data coverage at each mast as discussed in Section E-4.4.

E-5.4 Annual shear method

The relationship between two, or more, heights on a mast is established using the concurrent mean of monthly means technique described in Section E-4.4. These relationships are used to derive the boundary-layer power law shear exponent, which is then used to extrapolate data recorded at the upper measurement height to the target hub height.

E-6 Wind flow modelling

The project wind speed is typically modelled using either the WAsP model or the DNV CFD model as described in the following sections. Other models may be applied in cases where significant errors are apparent or expected from these models. These models may be exposure-based models, experience-based models or other models that DNV expects to reduce uncertainty or bias in the results. Where multiple site masts are available, typically these models initially generate set of predictions initiated from each site mast. From any given site mast, the primary output from the models is a set of wind speed ratios for each of the twelve 30° direction sectors between the initiating mast and other locations, typically either mast or turbine locations, at the same height.

In order to validate the flow model, the following procedure is undertaken. For a given mast pair, a prediction error is determined for each direction sector by comparing the modelled wind speed ratio to the wind speed ratio derived from measurements. A root-mean-square (RMS) of the twelve prediction errors is performed, weighted by the directional frequency distribution, in order to calculate an overall directional speed-up error.

E-6.1 WAsP approach

To calculate the variation of wind speed over the site, the computer wind flow model, WAsP, is used. Details of the model and its validation are given by Troen and Petersen /E4/.

The inputs to the model are a map of the topography and surface roughness length of the terrain for the site and surrounding area. A digital map of an area extending at least 10 km from the site in all directions is normally used and the inputs for this project are listed in Section 2 of the main body of the report. Although the domain size is much larger than the area of the site itself, such an area is necessary because the flow at any point is dictated by the terrain several kilometres upwind.

Wind flow is affected by the roughness of the ground and, therefore, the surface roughness length of the site and surrounding area is estimated following the Davenport classification /E5/, as detailed in Section 2 of the main body of the report.

The wind flow calculations are carried out using the same 30-degree steps in wind direction for which the measured wind rose is defined, and results are produced as speed-up factors relative to the mast location for a grid encompassing the site area.

To determine the long-term wind speed at any location, the speed-up factor for each wind direction is weighted with the measured probability previously derived for the mast location. All directions are then summed to obtain the long-term wind speed at the required location.

E-6.1.1 Forestry representation within the WAsP approach

Where obstacles to the flow are present, such as trees in proximity to a mast or turbine, it is necessary to consider the effect of these on the wind flow model. When using the WAsP wind flow model, the following methodology is therefore adopted:

- Areas of forestry and land cover are analysed to establish both the location and height of trees.
- Forestry less than 5 m in height is assumed to not cause a flow displacement and is modelled as a terrain roughness only.
- For forestry, greater than 5 m of equal height, a flow displacement is assumed. To account for the influence of the trees as an obstacle to the wind flow at the mast and turbine locations an effective reduction in the hub height of each mast or turbine is estimated. The magnitude of each hub height reduction is based on the flow displacement height of the trees, the proximity of the mast or turbine to the trees, and the frequency of occurrence of the relevant wind directions. The following relationship /E6/ is used to calculate the effective flow displacement height for each direction sector at each mast and turbine location:

  $$d(\theta_i) = d(\theta_i)_{\text{tree}} - D(\theta_i)/50$$

  where *d* is the effective flow displacement height at the mast or turbine location;
  d_{tree} is the flow displacement height of the surrounding trees; and
  D is horizontal distance from surrounding trees.

- By weighting each sector's effective flow displacement height by the frequency of winds in that sector, a weighted displacement height is calculated for each individual site mast and turbine.

$$d = \sum_i f(\theta_i) d(\theta_i)$$

Where appropriate, an indicative energy loss factor profile is derived to account for the impacted of expected tree growth or felling over the operational period of the wind farm.

E-6.2 DNV CFD modelling

The DNV CFD methodology is based around STAR-CCM+, a commercial computational fluid dynamics (CFD) software package and produces simulations of the Atmospheric Boundary Layer (ABL) for wind power applications. The CFD software solves the time averaged equations of mass and momentum conservation. An energy conservation equation is also solved when modelling atmospheric stability. The DNV CFD methodology has been validated for a number of academic cases and well over 100 real wind farm sites /E7/. These studies show that on average the DNV CFD method offers substantially improved wind speed predictions as compared with WAsP.

The CFD approach requires significantly more computational resource than a classical WAsP analysis as the calculations are significantly more complex. A flow domain is created and defined by a set of boundary conditions which control the air flows in and out of the domain. A 3D mesh is created within the domain and the conservation and turbulence equations are solved at each discrete point on the mesh. Due to this construction, the model is subject to discretization errors and can only evaluate wind from a single direction at a time. Hence, a separate simulation is undertaken for all wind directions, typically at intervals of 6 to 25 degrees, depending on the wind direction and frequency at the site. The results are averaged to derive 30-degree direction sector speed-ups from the masts to the turbine locations. These speed-ups are then combined with the measurement-based wind resource at each mast to predict the wind resource at each turbine location.

The turbine and mast locations are at least 10 km away from the edge of the computational domain for each calculation. The horizontal spacing of the mesh near points of interest is 12.5 m to 50 m, depending upon the complexity of the local terrain. Mesh independence studies have shown that such tight mesh spacing is necessary to resolve flows at microscale.

For sites where atmospheric stability significantly affects wind speeds, DNV employs a stability-enabled CFD analysis. The spatial variation of wind speed over topography is often very different during stable atmospheric conditions as compared to unstable conditions. Traditional wind flow models that assume a neutral atmosphere can provide reasonable predictions of unstable and near-neutral flows, but the predictions of stably stratified flows are comparatively poor. Thus, the stability-enabled CFD analysis, includes two sets of CFD calculations: a neutral CFD analysis to represent unstable and near-neutral flows and a stable CFD analysis, which directly models buoyancy effects, to represent stable flows. The results from the two sets of calculations are combined to produce an overall wind flow model for the site. Extensive validation has demonstrated that the stability-enabled CFD analysis provides significantly improved wind speed predictions at sites where stability effects are important /E8//E9/.

E-6.2.1 Forestry representation within the DNV CFD approach

Where appropriate, the CFD model used by DNV includes a canopy model designed to reproduce within the Reynolds-averaged Navier-Stokes (RANS) simulations the turbulence generation and aerodynamic drag associated with forestry and can therefore model the resulting flow perturbation /E10/. Canopy model source terms are added to the governing equations within the volume occupied by the forestry, i.e. between ground level and the approximate height of the canopy, as described in /E12/ and /E13/. Inputs to the canopy model include tree height, coefficient of drag, and foliage density of the forestry.

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About DNV

DNV is the independent expert in risk management and assurance, operating in more than 100 countries. Through its broad experience and deep expertise DNV advances safety and sustainable performance, sets industry benchmarks, and inspires and invents solutions.

Whether assessing a new ship design, optimizing the performance of a wind farm, analyzing sensor data from a gas pipeline or certifying a food company's supply chain, DNV enables its customers and their stakeholders to make critical decisions with confidence.

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