Netherlands Enterprise Agency

Site Studies Wind Farm Zone Borssele

Wind Resource Assessment

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SOC Zone Borssele Wind Resource

This Letter provides the outcome of DNV GL's review of the Ecofys Report 'Site Studies Wind Farm Zone Borssele 'Wind Resource Assessment' rev 4 issued 2015-09-17.

DNV GL certifies that the Wind Resource conditions presented in the report

- are made according to DNV-OS-J101, IEC 61400-1 and IEC61400-3
- are appropriate to be applied as background for making energy production estimates for the future Zone Borssele wind farms

The Lower bound long term wind distribution (Conservative parameters) can be applied directly for energy assessment without further justification.

Sincerely
for Det Norske Veritas, Danmark A/S

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Borssele Offshore Wind Farm Zone

Wind Resource Assessment

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Wind Resource Assessment

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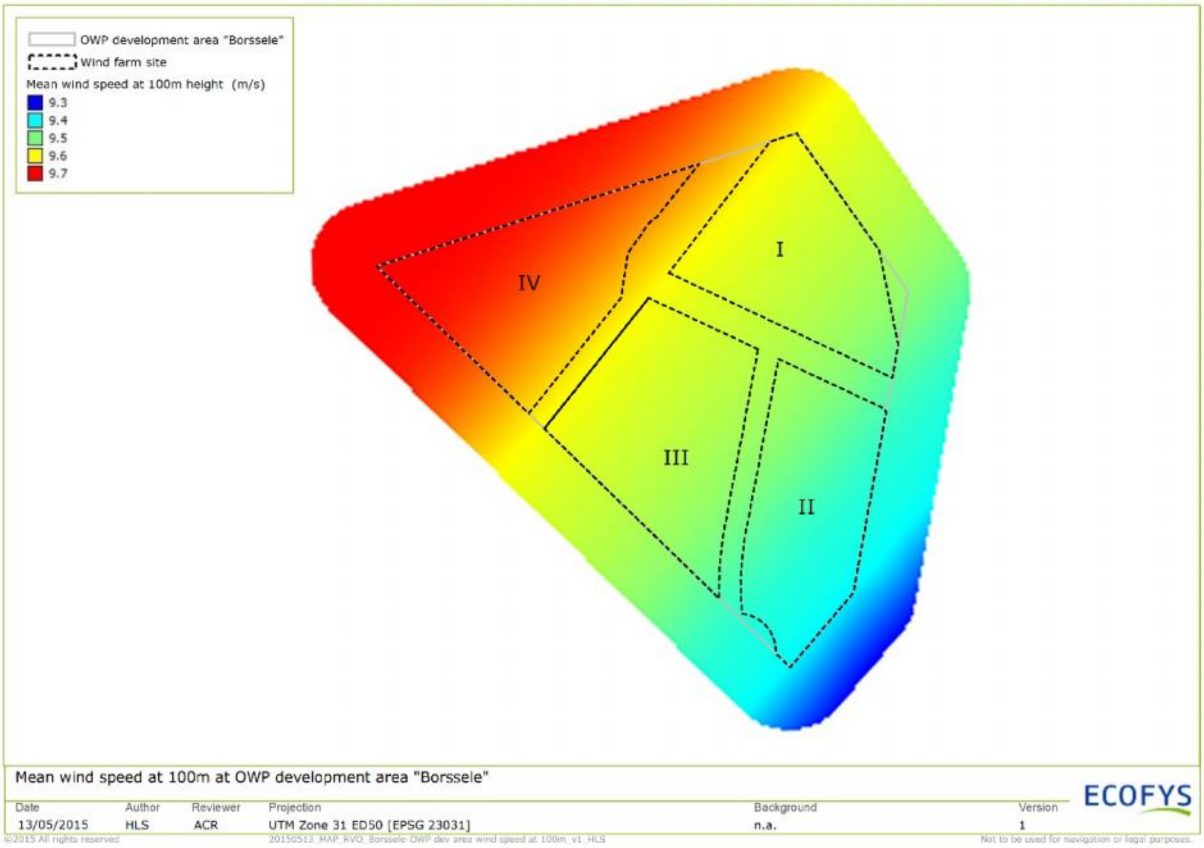
Samenvatting

Dit rapport beschrijft een wind klimaat onderzoek voor de geplande Borssele offshore wind park zone. Deze opdracht is gebaseerd op het gecombineerde gebruik van offshore wind meetcampagnes en mesoschaal model data. Er zijn in deze studie geen specifieke windmetingen op de locatie zelf gebruikt.

De offshore meetmast IJmuiden vormt de basis van dit onderzoek, gebaseerd op de laagste onzekerheid in de windmetingen, inclusief horizontale extrapolatie naar de Borssele site. De extrapolatie is gedaan op basis van het KNMI KNW mesoschaal model, welke was geselecteerd na validatie tegen vier offshore meetmast datasets. Gedetailleerde analyses van het windklimaat zijn uitgevoerd, die laten zien dat alle karakteristieken van het nieuwe windklimaat redelijk zijn voor een locatie in de Nederlandse Noordzee en dat ze consistent zijn op alle gemodelleerde hoogtes.

De gemiddelde lange termijn windsnelheid op ashoogte van 100m MSL in het centrum van de Borssele site is 9.6 ± 0.5 m/s (± standaard deviatie). De variatie over de site is ongeveer 0.3 m/s, zoals is weergegeven in de figuur op de volgende bladzijde.

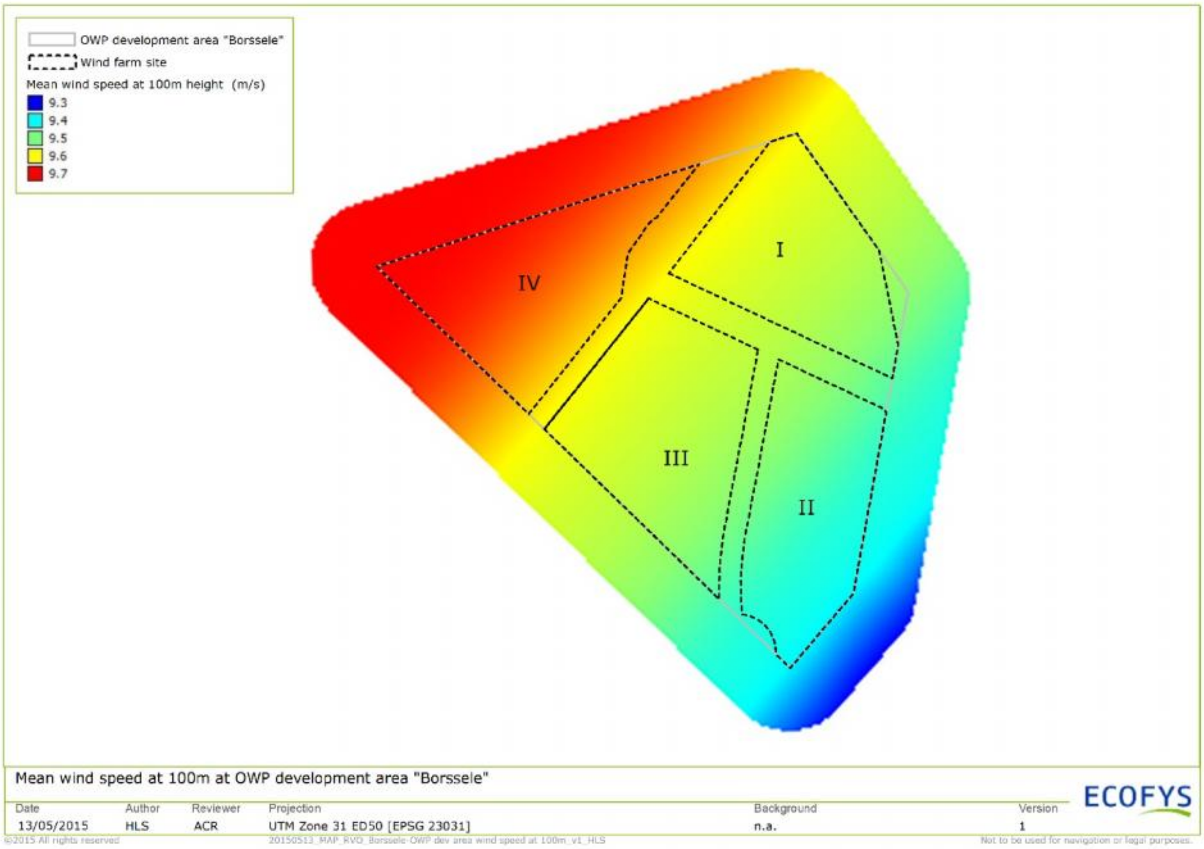


Executive Summary

This report describes a wind climate assessment for the planned Borssele offshore wind farm zone. This assessment is based on the combined use of offshore wind measurement campaigns and mesoscale model data. No specific on-site measurement records were used for this study.

The Meteomast IJmuiden offshore mast data forms the primary basis of this wind resource assessment, based on the overall low uncertainty of the wind measurements, including the horizontal extrapolation to the Borssele zone. The extrapolation is based on the KNMI KNW mesoscale model, which was selected based on a validation using four offshore met mast datasets. Detailed analyses of the calculated wind climate were carried out, showing that all of the analysed trends are reasonable for an offshore site in the Dutch North Sea and consistent across the modelled heights.

The long-term mean wind speed at a hub height of 100 m MSL at the Borssele zone centre is 9.6 ± 0.5 m/s (± standard deviation). The variation across the site is about 0.3 m/s, as seen in the map below.



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1 Introduction

1.1 Goal of the study

The Dutch Government has defined three offshore wind farm zones for the planned deployment of 3,500 MW new offshore wind power, as agreed upon in the Energy Agreement. The first zone to be tendered (in two phases) is Borssele, with an expected capacity of 1,400 MW. The zone will be divided into four sites.

RVO commissioned this preliminary independent wind resource assessment for the Borssele Wind Farm Zone and its four sites (project reference WOZ1500020). This information can be used as input for wind farm modelling, yield assessments and business case calculations for offshore wind farms to be developed in the Borssele wind farm area.

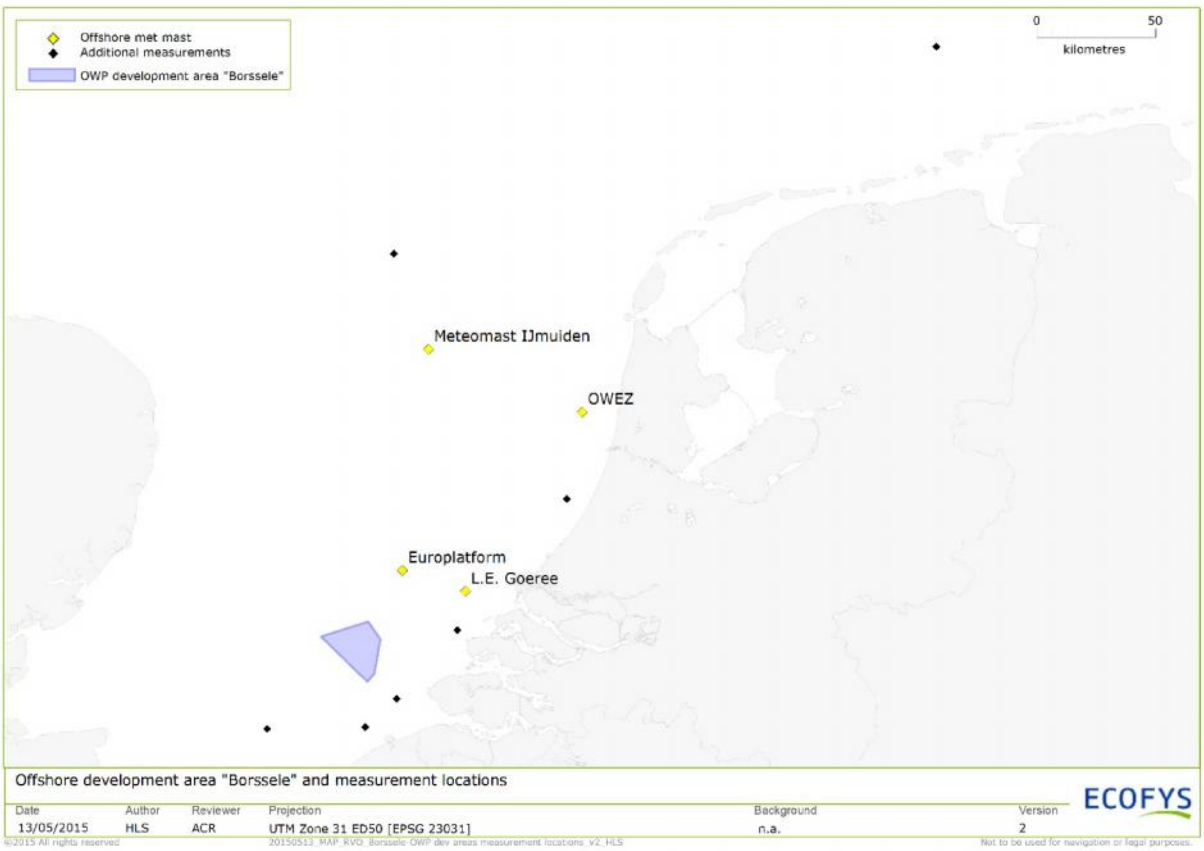


Figure 1 – Map of Borssele offshore wind farm zone with offshore wind measurement locations.

1.2 Methodology

There are four offshore wind measurement masts in the Dutch North Sea, which are suitable for this wind resource assessment. There are two wind-energy-specific offshore meteorological masts (met masts): Offshore Windpark Egmond aan Zee (OWEZ) and Meteomast IJmuiden. Closer to the Borssele zone, there are also two offshore platforms with met masts: Europlatform and Lichteiland Goeree. There are also co-located LiDARs at two of the locations.

Since there are no on-site wind measurements, a mesoscale model is used to quantify the gradient between the measurement locations and the wind farm site. As mesoscale model accuracy varies, a number of models and input datasets are compared.

The following approach has been followed:

1. A detailed analysis of datasets from the four offshore measurement locations identifies the highest quality data sources.
2. Several mesoscale models are compared and the most accurate model and input source for this assignment is selected; this is reported separately and summarised in Appendix D.
3. The wind farm wind climate is calculated based on a combination of the best available data sources, presenting the long-term wind farm wind climate across the wind farm zone. The analysis includes variations with height, time and distance, as well as a comprehensive uncertainty assessment.
4. The wind climate is compared to previous metocean analyses of the Borssele zone, commissioned by RVO, and three public offshore wind atlases.

1.3 Structure of the report

Chapter 2 presents the wind measurement datasets from the offshore met masts and compares relevant trends. The wind climate calculation is described in Chapter 3, with a detailed assessment of the wind speed uncertainty, and a verification against other sources. Chapter 4 describes trends in the wind climate at the Borssele wind farm zone. Conclusions are presented in Chapter 5.

2 Wind Measurements

Ecofys has analysed wind measurement data from four offshore met masts and two co-located LiDARs. These measurements are used together with mesoscale model data to characterise the wind climate for the Borssele wind farm zone. The measured datasets are described in detail, including all data processing, and their suitability is assessed as a primary data source and for use in the validation of different mesoscale models, as detailed Appendix D.

Of the measurement locations shown in Figure 1, four were selected based on the measurement setup, data availability and relative proximity to the Borssele wind farm zone. The measurement campaigns are summarised in Table 1. The datasets were thoroughly analysed to verify the data quality. Further details are provided in the following sections.

Table 1 – Characteristics of wind measurement locations

Measurement location	Distance offshore [km]	Measurement type	Measurement duration	Height [m]
Europlatform	42	Mast	12 years	29.1 m MSL
Lichteiland Goeree	17	Mast	12 years	38.3 m MSL
		LiDAR	5.5 months	62, 90-290 m MSL (every 25 m)
Offshore Windpark Egmond aan Zee (OWEZ)	15	Mast	1 year	21, 70, 116 m MSL
Meteomast IJmuiden (MMIJ)	82	Mast	3.3 years	27, 58, 85, 92 m LAT
		LiDAR	3.3 years	90-315 m LAT (every 25 m)

2.1 Europlatform

Europlatform is located 42 km due west of the port of Rotterdam. Two anemometers are mounted atop a 10 m met mast at the eastern edge of a helicopter landing pad, as seen in Figure 2. The measurement height is 29.1 m above sea level. The mast setup and measurement protocols are well documented [1] [2], with key details summarised below.

Figure 2 – Europlatform [source: Schero, 2013]

The cup anemometers are presumed to be Mierij Meteo 018, manufactured for Koninklijk Nederlands Meteorologish Instituut (KNMI, Royal Netherlands Meteorological Institute). KNMI is responsible for calibrations and quality control. Rijkswaterstaat (RWS, Dutch Ministry of Infrastructure and the Environment) is responsible for operations and data collection, as part of the Meetnet Noordzee programme since the early 1980s. RWS is also responsible for initial processing before data is sent to KNMI for further processing and storage. The raw measurement data has been stored by KNMI since April 2003. This raw data has been acquired by Ecofys for this analysis. It was received by email as a text file.

Erroneous data is marked as -999 by KNMI and was excluded from the analysis. In addition, Ecofys filtered the wind speed and direction data for frozen measurements and other visible errors. In particular, there were repeated wind vane issues, especially before May 2003, and a few month-long periods of missing data in 2014 and 2015. The filtered data periods are shown in Appendix B. The overall data availability of wind speed records is over 95%.

Since the measurement height is only 10 m above the platform, it is likely that the wind flow is disturbed and that the measurements are affected. The magnitude of these effects cannot be quantified based on the available data.

The Europlatform dataset is summarised in Table 2.

Table 2 – Europlatform dataset

	Europlatform
Measurement type	29.1 m offshore mast
Location [Latitude, longitude WGS84]	51°59'56.4" N / 3°16'33.6" E
Distance from coast	42 km
Measurement period	04/2003 - 03/2015 (12 years)
Documentation	General description, 2001 [1] Mast drawings [2]
Traceable instruments?	No details of calibration or maintenance
Availability of valid wind speed data	95.7%

2.2 Lichteiland Goeree

Lichteiland Goeree is an offshore platform that is also located west of the port of Rotterdam. Two anemometers and two wind vanes are at the top of a 16 m met mast, located at the northern corner of a platform 22.5 m above sea level (for a total measurement height of 38.3 m), as shown in Figure 3.

Figure 3 – Lichteiland Goeree [sources: Vem Bouwkundig en Civieltechnisch Adviesbureau, left; NAPNAM Publishing & Consulting, 2012, right]

The Lichteiland Goeree met mast measurement campaign is also part of the Meetnet Noordzee network, so mast setup, data acquisition and processing is similar to Europlatform. Raw measurement data from 2003 to 2015 was received from KNMI and filtered for frozen measurements and other visible errors.

Data availability is high, with only 1.3% rejected data. The filtered data periods are shown in Appendix B. The Lichteiland Goeree met mast dataset is summarised in Table 3.

Table 3 – Lichteiland Goeree mast dataset

	Lichteiland Goeree mast
Measurement type	38.3 m offshore mast
Location [Latitude, longitude WGS84]	51°55'1.6" N / 3°40'1.3" E
Distance from coast	17 km
Measurement period	04/2003 - 03/2015 (12 years)
Documentation	General description, 2001 [1] Mast drawings [3]
Traceable instruments?	No details of calibration or maintenance
Availability of valid wind speed data	98.7%

As part of a separate wind measurement campaign, managed by ECN, a Windcube V2 LiDAR was installed on the Lichteiland Goeree platform in October 2014. The wind speed and direction is recorded at 40 m above the platform height (equivalent to 62 m above sea level) and at nine heights every 25 m from 68 to 268 m (equivalent to 90-290 m above sea level).

Raw data was received from ECN, as a CSV file, and filtered for a minimum 80% data availability per 10-minute period (based on the LiDAR manufacturer's recommendations for data quality control). Data availability decreases with measurement height, with 1-3% excluded data for heights up to 165 m, then significant increases up to 32% excluded data at 290 m. There are also several days of missing data in April 2015. The filtered data periods are shown in Appendix B. The Lichteiland Goeree LiDAR dataset is summarised in Table 4.

Table 4 – Lichteiland Goeree LiDAR dataset

	Lichteiland Goeree LiDAR
Measurement type	Windcube V2 LiDAR
Location [Latitude, longitude WGS84]	51°55'1.6" N / 3°40'1.3" E
Distance from coast	17 km
Measurement period	11/2014 - 05/2015 (5.5 months)
Documentation	None
Traceable instruments?	No details of validation or maintenance
Availability of valid wind speed data	81% at 62 & 90 m; 80% at 115 m; 79% at 140 m; decreasing to 37% at 290 m

The availability of concurrent wind measurements from the mast and LiDAR allows for a cross-validation of the two independent data sources. There is no common measurement height, but it is possible to extrapolate the LiDAR wind measurements to the met mast height of 38 m, using the measured shear profile (hourly power law exponents). The two datasets show excellent correlation over the common 4.4 month period (R^2=0.98) and a linear relationship (slope = 1.00), as shown in the scatter plot in Figure 4. This gives a good indication that the cup anemometry measurements are accurate, without significant flow distortions due to the platform.

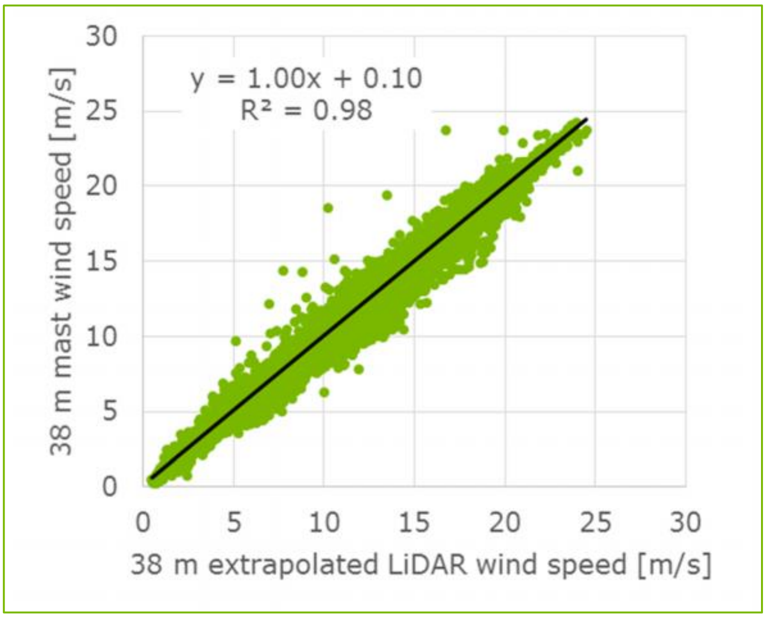


Figure 4 – Comparison of 38 m mast and 38 m extrapolated LiDAR wind speeds at Lichteiland Goeree

The quality of the LiDAR data is high, although it is only considered as a secondary source for this analysis due to the relatively short measurement period and the lack of documentation.

2.3 OWEZ

A 116 m met mast was erected in mid-2005 at the site of the OWEZ wind farm, one year prior to its construction. The met mast has measurement levels of 21, 70 and 116 m (MSL); it is shown in Figure 5. Data from the first year of operation is considered, since in later years, the measurements are disturbed by the constructed wind farm.

Figure 5 - OWEZ mast [source: Noordzeewind]

The measurement campaign is managed by ECN, which has extensively documented the met mast, datasets and processing details in publicly available documents [4] [5]. The data processing for OWEZ was done by Mierij Meteo. In the context of the Monitoring and Evaluation Programme connected to the wind farm, the measurement datasets are publicly available. The data is provided as CSV files.

The OWEZ met mast is a fully dedicated met mast for the purpose of performing accurate wind speed measurements in close alignment to IEC standards. There are three booms with Mierij Meteo 018 cup anemometers at each height, allowing for the selection of relatively undisturbed instruments. However, comparisons between the instruments has shown that there remains tower shadow effects, particularly at lower heights. All sensors were calibrated in accordance with MEASNET; with calibration certificates available upon request. ECN states that accuracy of the data should be within 95% [5].

The data is manually checked by ECN for consistency, quality and out of range numbers. Missing or corrupt data are subsequently reported in the raw data files as -99999 error code. This dataset is provided, along with a processed time series of wind speed and direction, created by directional filtering and selection between the multiple instruments at each height. All processing is described in two 6-month reports.

Ecofys reproduced the single processed time series for each measurement height, with minor adjustments to the ECN filters, in order to increase the data availability, as explained in Appendix B. The OWEZ mast dataset is summarised in Table 5.

Table 5 – OWEZ mast dataset

	OWEZ
Measurement type	116 m offshore mast
Location [Latitude, longitude WGS84]	52°36'22.9'' N / 4°23'22.7'' E
Distance from coast	15 km
Measurement period	07/2005 - 06/2006 (1.0 year)
Documentation	Mast design and data manual [4] Data filtering manual [5]
Traceable instruments?	MEASNET calibrated anemometers; other instruments also calibrated; regular maintenance by ECN
Availability of valid data	85.7% at 116 m and 95.7% at 70 m

2.4 Meteomast IJmuiden

ECN is also carrying out a four-year wind measurement campaign at Meteomast IJmuiden, an offshore met mast built in 2011, approximately 82 km west of the coast of IJmuiden. The mast is shown in Figure 6. Thies First Class Advanced cup anemometers are mounted at heights of 21 m, 58 m and 92 m LAT, with Metek USA-1 sonic anemometers at 85 m [6].

Figure 6 – MMIJ mast (the floating LiDAR next to the mast is being tested and is not included in this study) [source: RWE Innogy]

The design of the met mast and data processing techniques ensure high data quality. Flow distortion due to the tower is minimised by installing anemometers on three different booms at each height (two at the mast top). Each boom is pointing in another wind direction, so that data can be selected only from relatively undisturbed sensors.

ECN verifies the data quality in several ways. The measurement computer checks sensor connection and if recordings exceed minimum and maximum thresholds. Subsequently the data is checked manually. Only valid data is kept in the provided raw data files. Missing values are indicated with blanks.

Although derived wind speed and wind direction are calculated by ECN, based on similar directional selection as for OWEZ, Ecofys recalculated these values using modified filters, as explained in Appendix B. Ecofys also defined its own filters for the top measurement height, to average the two anemometers, as the ECN procedure only details filters for levels with three anemometers. The met mast dataset from Meteomast IJmuiden is summarised in Table 6.

Table 6 – Meteomast IJmuiden met mast dataset

	Meteomast IJmuiden
Measurement type	92 m mast
Location [Latitude, longitude WGS84]	52.85° N / 3.44° E
Distance from coast	82 km
Measurement period	11/2011 – 02/2015 (3.3 years)
Documentation	Mast setup and data manual [6]
Traceable instruments?	All instruments are calibrated according to ISO 17025
Availability of valid data	98.7% at 92 m

A ZephIR ZP300 LiDAR is also installed on the mast platform, inside the mast, as shown in Figure 7. It measures the wind at heights from 90 to 315 m LAT [6]. Although the ZephIR beam might be disturbed by the met mast structure, disturbed data will be automatically filtered out of the dataset. No documentation is available regarding data quality and data processing.

Figure 7 - LiDAR located within the lattice structure of the Meteomast IJmuiden offshore met mast [source: ECN]

ECN provided the raw LiDAR data as CSV files. Ecofys filtered the data, according to standard practices for a ZephIR LiDAR, as described in Appendix B. An additional filter was implemented for periods with high turbulence intensity, as measured by the met mast, since significant deviations were found between the met mast and LiDAR wind speeds during those periods, but affecting only a small amount of data. The Meteomast IJmuiden LiDAR dataset is summarised in Table 7.

Table 7 – Meteomast IJmuiden LiDAR dataset

	Meteomast IJmuiden
Measurement type	ZephIR ZP300 LiDAR
Location [Latitude, longitude WGS84]	52.85° N / 3.44° E
Distance from coast	82 km
Measurement period	11/2011 – 02/2015 (3.3 years)
Documentation	Mast setup and data manual [6]
Traceable instruments?	No details of validation or maintenance
Availability of valid data	84.5% at 90 m to 84.2% at 165 m

An intercomparison of the wind speed measurements of the LiDAR at 90 m and the met mast at 92 m showed excellent correlation (R^2 = 1) and a linear relationship (slope = 1.00), as shown in Figure 8, indicating that overall there is no significant issue with either the top anemometry or the LiDAR. There do remain some data points with significant deviation between the LiDAR and met mast anemometry, but this affects only an estimated 0.1% of available data.

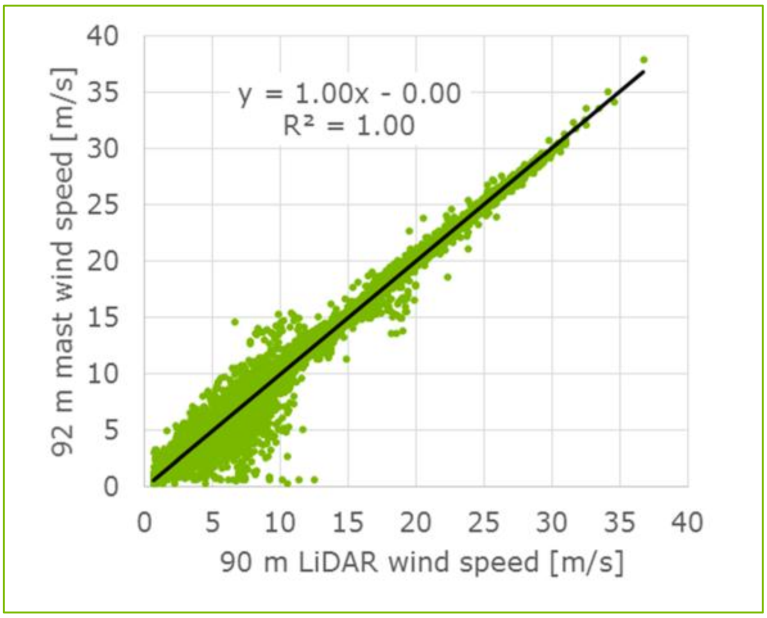


Figure 8 – Comparison of 92 m mast and 90 m LiDAR wind speeds at Meteomast IJmuiden

2.5 Uncertainty in wind speed measurements

The uncertainty in measurement accuracy have been assessed for each of the four met mast datasets, in terms of instrument accuracy and mounting, as well as data quality and processing (see Table 8). The LiDARs at Lichteiland Goeree and Meteomast IJmuiden are considered as secondary sources, providing independent validations of the mast measurements.

General descriptions of each source of uncertainty are given in Appendix F. More detailed descriptions of the uncertainties are provided after the table. Each uncertainty is assumed to be independent of the others and represented as a Gaussian distribution, so the total uncertainty is calculated as the root-sum-square of all uncertainties.

Table 8 –Uncertainties relating to wind speed measurements for four offshore met masts

Uncertainty description	Europlatform	Lichteiland Goeree	OWEZ	Meteomast IJmuiden
- Instrument accuracy	5.6%	5.6%	2.0%	2.0%
- Instrument mounting	2.0%	2.0%	2.5%	1.5%
- Data quality	1.0%	1.0%	0.5%	0.5%
- Data processing	5.0%	5.0%	1.0%	1.0%
Total	7.8%	7.8%	3.4%	2.7%

The accuracy of KNMI cup anemometers is within ±0.5 m/s [1], which equates to about 5.6% uncertainty for the wind climate at Europlatform and Lichteiland Goeree. The instrument accuracy is higher for OWEZ and Meteomast IJmuiden since the instruments are calibrated and monitored by a MEASNET institute.

The KNMI masts may experience flow distortions due to the platforms, but the instruments are mounted at the top of masts, so there will be little tower shadow. The effects of tower shadow at the OWEZ mast have been quantified in an ECN report [5]. There is a relatively large uncertainty due to instrument mounting, since the booms are relatively short for the size of the mast, although effects are mitigated by the use of a filtering protocol to select the least disturbed instruments. The uncertainty is lower for Meteomast IJmuiden, since the top measurement height is taken as the primary reference, which is relatively unaffected by tower effects.

The data availability of all datasets is high. However, a large uncertainty is attributed to data processing for the KNMI masts, as no documentation is available regarding the measurement campaigns and data is provided in a processed form that cannot be independently verified. The data provided by ECN for OWEZ and Meteomast IJmuiden merits a lower uncertainty, since the masts are well documented and all processing steps can be independently repeated by Ecofys. The data is not available in its raw format, but is processed or checked by a MEASNET institute (Meteomast IJmuiden and OWEZ respectively).

2.6 Data selection

The quality of the datasets from all four masts is sufficient for use in the mesoscale model validation described in Appendix D.

As a result of the lowest wind measurement uncertainty, shown in Table 8, the Meteomast IJmuiden mast data will form the primary basis of this wind resource assessment. The wind speed measurements at the mast top are extrapolated to hub height, then corrected to the long-term and extrapolated horizontally to the Borssele zone, based on mesoscale reference data. This procedure is described in the next chapter. Additional details of the measurement campaign are provided in Appendix A, including any deviations from best-practice.

2.7 KNMI KNW mesoscale model

In addition to the measured wind data, a mesoscale model is used in the calculation of the Borssele wind climate. Several different models were validated by comparing modelled time series with wind measurements from the four offshore masts (as explained in detail in Appendix D). Based on this validation exercise, the KNMI KNW mesoscale model was selected for use in this wind resource assessment. The characteristics of the mesoscale model time series are presented in Table 9.

Table 9 – Characteristics of mesoscale model time series

Mesoscale Model	Parameters	Measurement Period (Duration)	Heights [m]
KNMI KNW, based on European joint HARMONIE project	Wind speed, wind direction, temperature, humidity	01/1979 - 12/2014 (35 years)	10, 20, 40, 60, 80, 100, 120, 140, 160, 180, 200 m (MSL)

An hourly time series of wind data was acquired from KNMI for the four measurement mast locations, as well as six available grid points covering the Borssele offshore wind farm zone, as shown in Figure 9 (coordinates in Table 10).

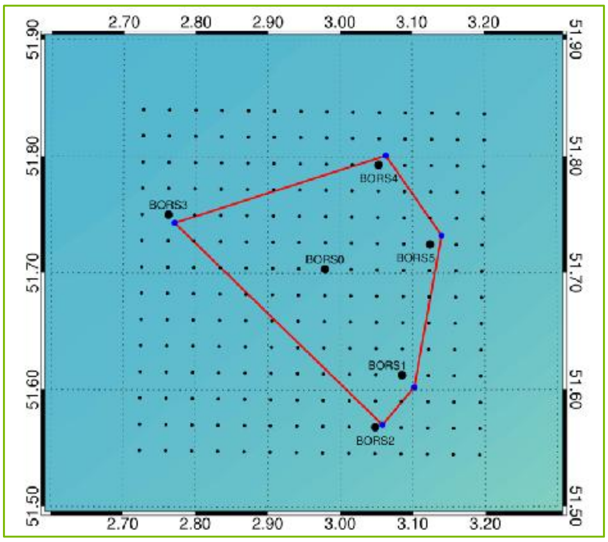


Figure 9 – KNMI KNW mesoscale grid points within Borssele zone [source: KNMI]

Table 10 – Grid point coordinates for KNW grid points

KNW grid points	Geographical coordinates [Latitude, Longitude WGS84]	Cartesian coordinates [Easting, Northing ETRS89 zone 31]
BORS0	51°42’13"N / 2°58’52" E	498,699 m E / 5,728,071 m N
BORS1	51°36’48"N / 3°05’14" E	506,044 m E / 5,718,038 m N
BORS2	51°34’07"N / 3°02’58" E	503,426 m E / 5,713,053 m N
BORS3	51°44’58"N / 2°45’56" E	483,808 m E / 5,733,184 m N
BORS4	51°47’37"N / 3°03’17" E	503,780 m E / 5,738,094 m N
BORS5	51°43’32"N / 3°07’29" E	508,608 m E / 5,730,525 m N

3 Wind Climate Calculation

The preceding analysis of offshore measurement datasets identified that the Meteomast IJmuiden offshore met masts represents the most suitable primary source for this wind resource assessment. In order to quantify the on-site wind climate at the Borssele zone, several calculations are necessary:

1. Extrapolation from measurement height to hub-height
2. Long-term correction from 3 years of measurements to a 10-year period
3. Extrapolation from the measurement location to the Borssele zone.

These calculations are described in the next sections, with the results and estimated uncertainty of each step.

3.1 Hub-height wind speed

First, the measured wind speeds are extrapolated to a height of 100 m (approximately hub height). The quality-controlled measurement dataset from the top measurement height of 92 m are extrapolated using Windographer, based on a matrix of average power law exponents per hour and wind direction bin.

The uncertainty in vertical extrapolation is estimated based on sensitivity tests of different shear profiles.

The calculated mean wind speed at 100 m height, and the associated uncertainty in vertical extrapolation is shown in Table 11.

Table 11 – Extrapolation of wind speed measurements to height of 100 m

	Meteomast IJmuiden
Selected measurement period	01/01/2012 – 31/12/2014
Measurement height	92 m
Data availability [%]	98.8%
Measured mean wind speed at measurement height [m/s]	9.88
Resulting mean wind speed at 100 m [m/s]	9.95
Estimated uncertainty in vertical extrapolation [%]	0.3%

3.2 Long-term mean wind speed

The dataset covers a period of three years. In order to represent the long-term wind climate, the data is compared to a long-term reference, by means of a Measure-Correlate-Predict (MCP) procedure. The

MCP method analyses the relationship between the short-term measured wind speed and direction data and concurrent data from a nearby reference (in this case the KNW mesoscale data from the co-located grid point). This statistical relationship is then used to predict and synthesise site data from the reference data. The synthesised data extends the time series and fills gaps, but does not replace measured data.

An extension of the 3-year dataset to cover a 10-year period (2004-2013), using MCP and the KNW mesoscale model, would result in a minor decrease in mean wind speed of -0.2%. Since this comparison shows that there is minimal variation between the short-term measurements and long-term mean, it is decided to use the 3-year dataset without long-term correction. The uncertainty due to a shorter time series (3.5%, see Appendix F for details) is lower than the uncertainty relating to the MCP procedure, so this choice results in a lower overall uncertainty.

3.3 Extrapolation to Borssele zone

The KNW mesoscale data also shows the horizontal gradient between the Meteomast IJmuiden measurement location and the Borssele zone. A correction factor is derived between the relative difference in mean wind speeds between the mesoscale modelled wind speeds at the Borssele zone centre grid point (BORS0) and the grid point nearest to the measurement location. This factor is used to extrapolate the long-term hub-height wind climate to the Borssele zone, as shown in Table 12.

The uncertainty in horizontal extrapolation is estimated by means of a cross-prediction exercise between the four measurement locations (see Appendix E).

Table 12 – Horizontal extrapolation of wind speed measurements

	Meteomast IJmuiden
Long-term mean wind speed at measurement location [m/s]	9.95
Relative difference of mean wind speeds in mesoscale model, between Borssele zone centre and measurement location	-3.8%
Calculated long-term hub-height mean wind speed at Borssele zone centre [m/s]	9.57
Estimated uncertainty in horizontal extrapolation [%]	3.6%

A similar horizontal extrapolation calculation was repeated for each of the KNW mesoscale grid points within the Borssele zone, in order to determine the variation in wind speed across the zone. These results are presented in Figure 15 in the next chapter.

3.4 Comparisons

The calculated wind climate at Borssele is compared to several other sources. A number of independent scientific studies of the Dutch offshore wind climate has previously been performed. Moreover, the results are compared with a previously RVO-commissioned metocean analyses of the Borssele zone.

3.4.1 Other wind measurements

As described in Appendix E, the wind climate at the Borssele zone is also calculated using the wind measurements from Europlatform, Lichteiland Goeree and OWEZ, as shown in Table 13. These results can be directly compared to the results from Meteomast IJmuiden (explained in more detail in Table 15 and Table 16). While the uncertainty in these other estimates is higher, the calculated mean wind speeds are similar, with three of the four independent results showing 9.5-9.6 m/s.

Table 13 – Calculated mean wind speed at Borssele wind farm zone and the associated uncertainty, using the other wind measurements as the primary source.

	Europlatform	Lichteiland Goeree	OWEZ	Meteomast IJmuiden
Calculated mean wind speed at at 100 m at the Borssele wind farm zone and the associated uncertainty [m/s]	9.6 ± 0.9	9.8 ± 0.9	9.5 ± 0.6	9.6 ± 0.5

3.4.2 Offshore wind atlases

First, the results have been compared to the ECN offshore wind atlas for the Dutch North Sea [7] which was calculated in 2005 and 2011. The primary differences between the two datasets are the different reference periods (1997-2002 and 2003-2009) and a different estimation of sea surface roughness (dependent on wind-speed only in 2004 and including also waves in 2011). The estimated standard deviation in the modelled wind speeds is 0.20 m/s and 0.42 m/s for 2005 and 2011 respectively, according to ECN [7].

According to the ECN wind atlases, the average wind speed at 90 m at the centre of the Borssele zone is about 10.0 m/s (2004 version) and 9.0 m/s (2011 version), as shown in Figure 10 and Figure 11 respectively. The two ECN wind atlas estimates differ by 1 m/s, so it is difficult to compare directly with the calculated wind climate.

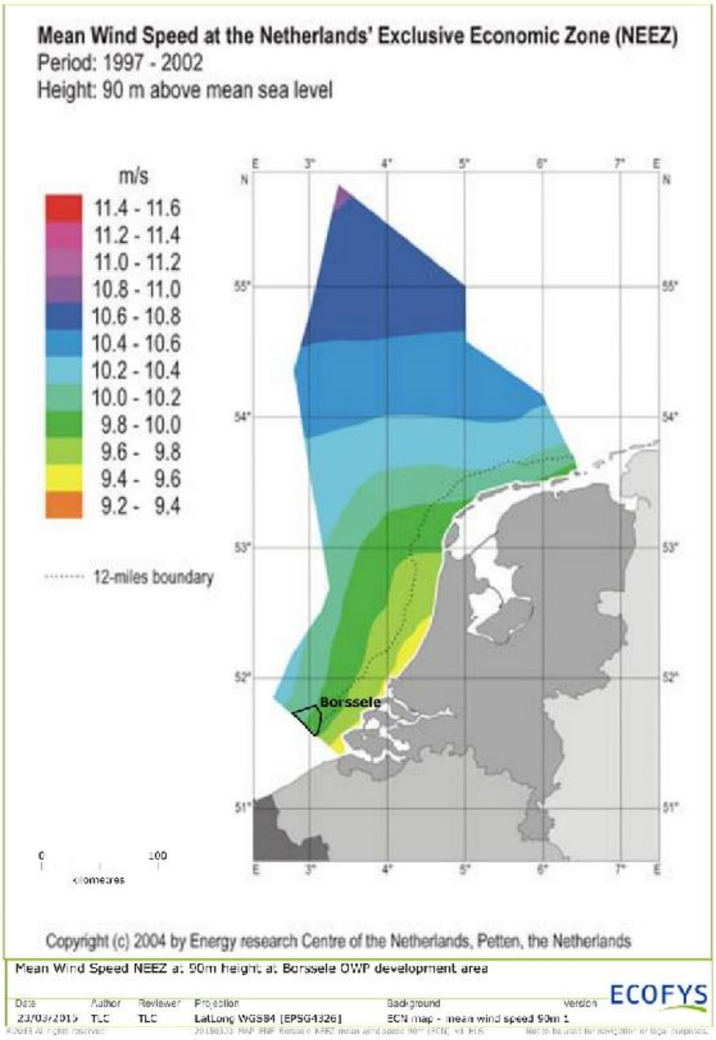


Figure 10 – Borssele zone and the ECN offshore wind atlas (2004 version)

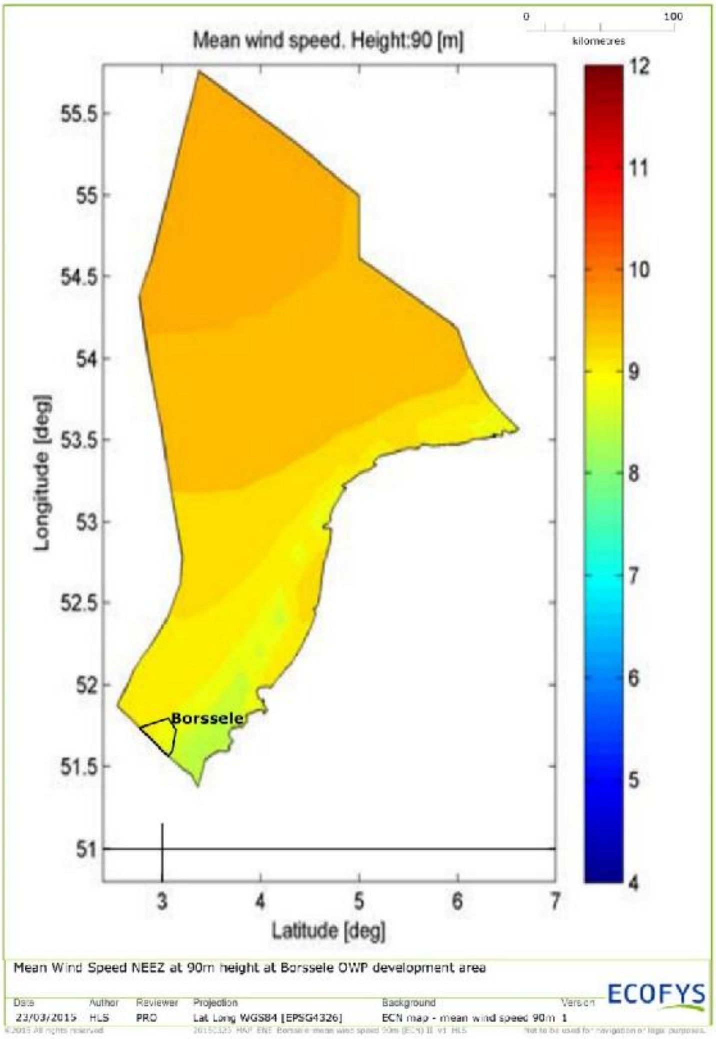


Figure 11 – Borssele zone and the ECN offshore wind atlas (2011 version)

Another offshore wind atlas was prepared by NORSEWInD, an EU project which combined offshore LiDAR measurements, mesoscale model data and satellite-derived wind speeds into a GIS-enabled wind atlas. The wind atlas shows a 100 m mean wind speed of about 9.3 m/s at the Borssele zone centre, as shown in Figure 12, with a reported uncertainty of -0.25 m/s. The mean wind speed calculated by Ecofys in this current study is about 0.3 m/s higher than this NORSEWInD estimate. The wind atlas was validated against the FINO met masts in Germany and an offshore LiDAR in Belgium, but it is not known whether any Dutch datasets were included.

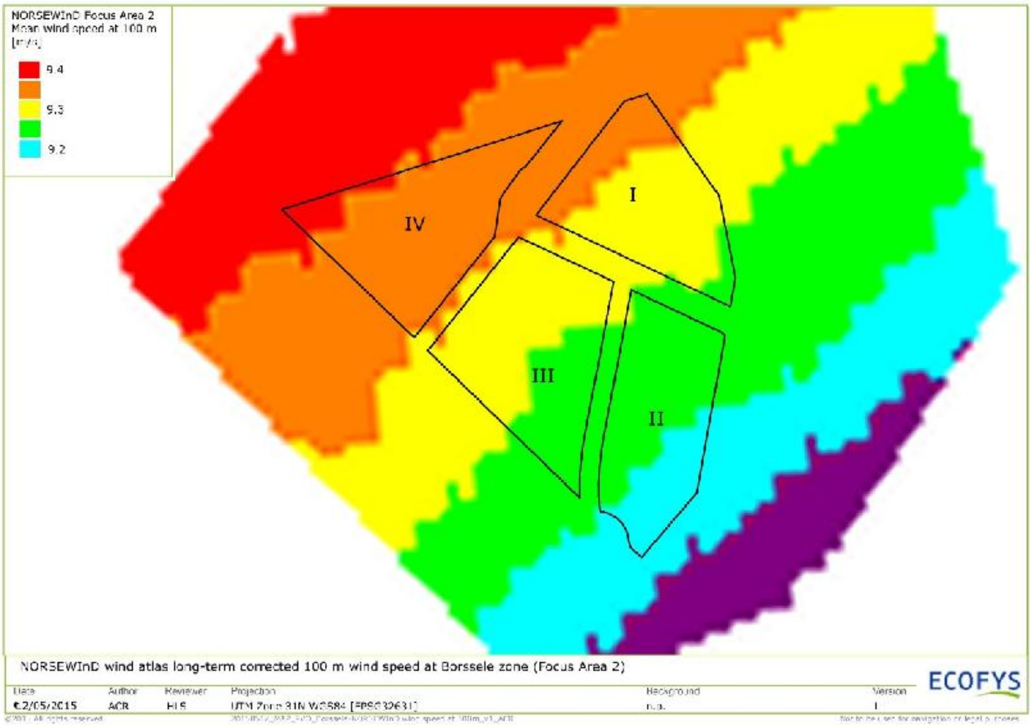


Figure 12 – Long-term corrected mean wind speed at 100 m for the Borssele zone, as calculated by the EU project NORSEWInD, Focus Area 2

Although the reported uncertainty for each wind atlas is relatively low, it should be noted that the predicted wind speeds at the Borssele zone differ by more than 1 m/s, and that mesoscale model results alone are not considered as bankable sources for wind farm yield calculations. While there is variation between the wind atlases, they are roughly in line with the Ecofys calculated wind climate at the Borssele zone, within the current uncertainty margin.

3.4.3 RVO metocean studies

RVO has also commissioned metocean studies of each Borssele wind farm site, which were performed by Deltares [8] [9] [10] [11]. These studies present wind conditions for the sites, which can be directly compared with the results of this wind resource assessment. The wind conditions in the metocean reports are based on the KNMI KNW mesoscale model (referred to as the HARMONIE model in the reports). KNMI has informed Ecofys that the KNW model was updated after data was supplied to Deltares, so the results in those reports cannot directly be traced to the KNW mesoscale data used in this assessment.

For all four sites, Deltares evaluated the wind conditions for a single KNW mesoscale grid point, which is similarly located to the point BORS0 shown in Figure 9. In general, the Deltares metocean analysis shows similar results and trends as this wind resource assessment, although the wind speeds are lower. The mean wind speed at 100 m is found by Deltares to be 9.26 m/s (Table 3.6 in [8] [9] [10] [11]), which is 0.3 m/s lower than the wind speed found in this assessment. It is expected that this difference is due to two factors:

1. The KNW model dataset used by Deltares was supplied by KNMI prior to full validations and a subsequent increase in the wind speeds. The Deltares dataset shows a mean wind speed of 9.26 m/s, whereas the KNW dataset provided by KNMI for this analysis shows a mean wind speed of 9.5 m/s, as illustrated in the wind atlas map from KNMI in Figure 13.
2. The validation of mesoscale models, detailed in Appendix D, shows a negative bias of about 0.15 m/s in the KNW wind atlas at Europlatform, Meteomast IJmuiden and OWEZ (see Figure 38), indicating a likely under prediction at Borssele as well.

The Deltares reports also shows the upper bounds of the wind speed estimate at 100 m to be 10.04 m/s (Table 3.7 in [8] [9] [10] [11]), which can be seen as 95% upper bounds estimates given in Table 3.6. Within this context, the wind speed found in this assessment is below this upper bound.

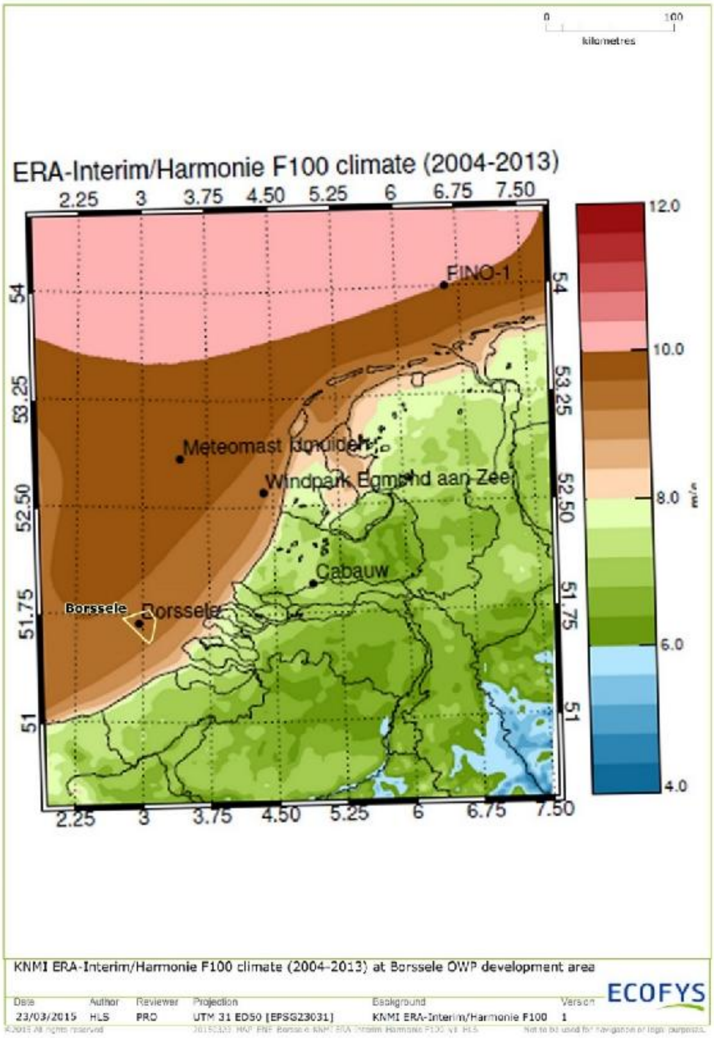


Figure 13 – Borssele zone and the KNMI NoordzeeWind (KNW) offshore wind atlas

In addition to the mean wind speed, the Deltares reports analyse several other trends in the wind climate, which can be compared to this wind resource assessment. Most of these trends are investigated in more detail in the next chapter, but a summary comparison is provided below in Table 14. The Deltares results are similar, especially in terms of wind shear and wind rose, although the mean and extreme wind speeds are lower. The difference in extreme wind speeds can be partially due to the overall lower wind speeds in the earlier KNW model, and also to the hourly averaging period, as compared to the 10-minute averaging periods in this study.

The Deltares reports serve as an independent analysis of the KNW mesoscale data (although an earlier version) and do not indicate any significant differences with the present study.

Table 14 – Calculated mean wind speed at Borssele wind farm zone and the associated uncertainty, using the other wind measurements as the primary source.

	Ecofys (this study)	Deltares [8] [9] [10] [11]	Deltares 95% upper bound [8] [9] [10] [11]
Mean wind speed at 100 m at zone centre [m/s]	9.6 (Table 12)	9.26	10.04
Extreme wind speed (50-year return) at 100 m at zone centre [m/s]	43-46 (10-minute) (Table 19)	36 (hourly) 40 (10-minute)*	45 (hourly) 49 (10-minute)*
Weibull scale factor (k)	2.19 (Figure 27)	2.09	2.09
Power law exponent	0.085 ± 0.03 (Figure 17)	0.08 ± 0.03	0.11
Dominant wind direction	SW (Figure 29)	SW	n/a

3.5 Borssele wind climate

The detailed analysis of four offshore wind measurement datasets has shown that speeds based on the Meteomast IJmuiden data have the lowest uncertainty. The measured wind speed at 92 m is 9.9 m/s, with an uncertainty in the measurements of 2.7% (see Table 8 and 10).

This wind speed is extrapolated to a height of 100 m, based on the measured wind shear. The mean wind speed in the 3-year dataset is found to closely represent the long-term mean wind speed, based on an MCP analysis using a 10-year period of the KNW mesoscale model. Since there is no bias, it is decided not to make any corrections to the long-term, considering that this process would add a larger uncertainty.

* 20150216_SDB_Deltares_Metocean study for the Borssele Wind Farm Zone Site I_Tables_F.xls; Sheet 'Extreme Wind Speeds'; cell S80 (Extreme 600s mean wind speed, U100, OMNI direction)

Finally, the wind speeds at Meteomast IJmuiden are horizontally extrapolated to the Borssele zone, according to the mean wind speed difference in the KNW mesoscale model between the two locations. This leads to a reduction of about 4% to 9.6 m/s.

The combined uncertainty in the calculated Borssele wind climate is shown in Table 15. The uncertainty definitions are given in Appendix F, and explained in Sections 3.1, 3.2 and 3.3. The calculated long-term mean wind speed at the Borssele zone is shown in Table 16, along with the associated uncertainty in terms of wind speed.

Table 15 –Combined uncertainties relating to the long-term 100 m wind speed at the Borssele zone

Uncertainty description	Meteomast IJmuiden
- Instrument accuracy	2.0%
- Instrument mounting	1.5%
- Data quality	0.5%
- Data processing	1.0%
- Vertical extrapolation	0.3%
- Horizontal extrapolation	3.6%
- Long term representation	3.5%
Total	5.7%

Table 16 – Calculated mean wind speed at Borssele wind farm zone and the associated uncertainty

	Meteomast IJmuiden
Calculated mean wind speed at Borssele wind farm zone at 100 m and the associated uncertainty [m/s]	9.6 ± 0.5

For symmetrical distributions, the mean wind speed can be expressed as the P_{50} value (the value that will be exceeded with a probability of 50%). It is also common to use the P_{90} value (the value that will be exceeded with a probability of 90%), or other exceedance probabilities (Pxx). Assuming a Gaussian distribution of the results, the different exceedance probabilities can be calculated as a function of the uncertainty calculated above, as shown in Table 17.

Table 17 – Mean wind speed at 100 m at the Borssele wind farm zone centre, for different probability levels

Exceedance probability	Mean wind speed at 100 m [m/s]
P90	8.9
P80	9.1
P70	9.3
P60	9.4
P50	9.6
P40	9.7
P30	9.9
P20	10.0
P10	10.3

4 Wind Farm Wind Climate

The analysis in the sections below is based on the calculated long-term time series of wind speed at a grid-point within the Borssele zone.

A number of data checks were performed with Windographer software, in order to validate general trends and identify outliers (if any). The analysis in the sections below will primarily show results from the central grid point, with reference when relevant to the four wind measurement locations. Trends are also noted across the zone, between the modelled grid points.

4.1 Mean wind speed

As described in the previous chapter, the mean wind speed at 100 m at the central Borssele grid point is 9.6 m/s. The wind climate is also calculated, using the same methodology, at three other KNW model grid points, in order to approximate the wind resource of each of the planned wind farms within the site, as illustrated in Figure 14. The wind speeds are also extrapolated from 92 m to several heights, between 10 and 150 m MSL, based on the measured shear profile at Meteomast IJmuiden, using mast and LiDAR measurements up to 165 m. The mean wind speeds are shown in Table 18.

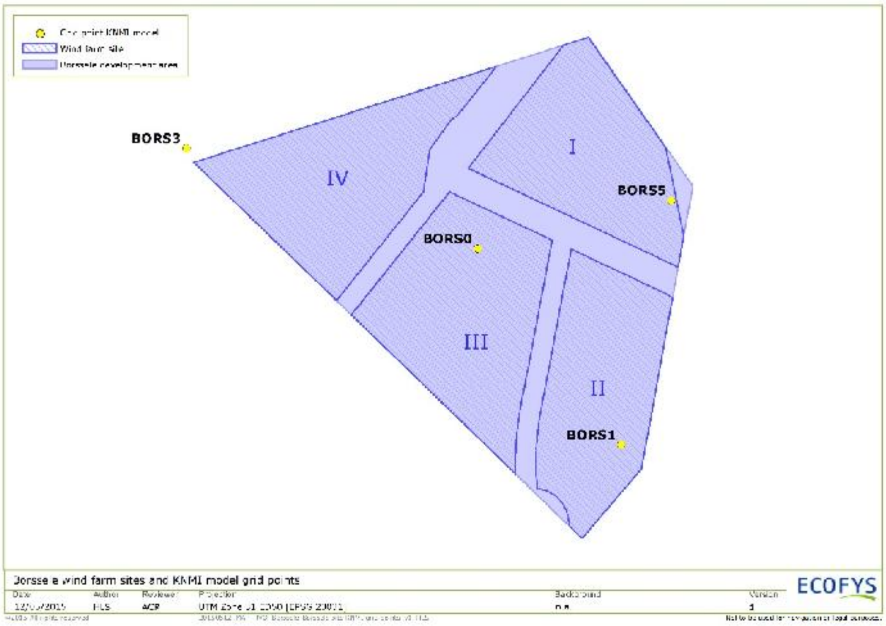


Figure 14 – Borssele wind farms and neared KNW model grid points.

Table 18 – Mean wind speeds at various locations and heights within the Borssele zone.

Height [m MSL]	Mean wind speed [m/s] Borssele I	Mean wind speed [m/s] Borssele II	Mean wind speed [m/s] Borssele III	Mean wind speed [m/s] Borssele IV
150	9.9	9.8	9.9	10.0
100	9.5	9.4	9.6	9.7
90	9.4	9.3	9.5	9.6
80	9.3	9.2	9.4	9.5
70	9.2	9.1	9.3	9.4
10	7.8	7.7	7.9	8.0

The calculated variation in wind speed across the site is about 0.3 m/s; the wind speed is lower closer to shore at the site of Borssele II, and highest further from shore, at Borssele IV. The horizontal variation is shown in Figure 15.

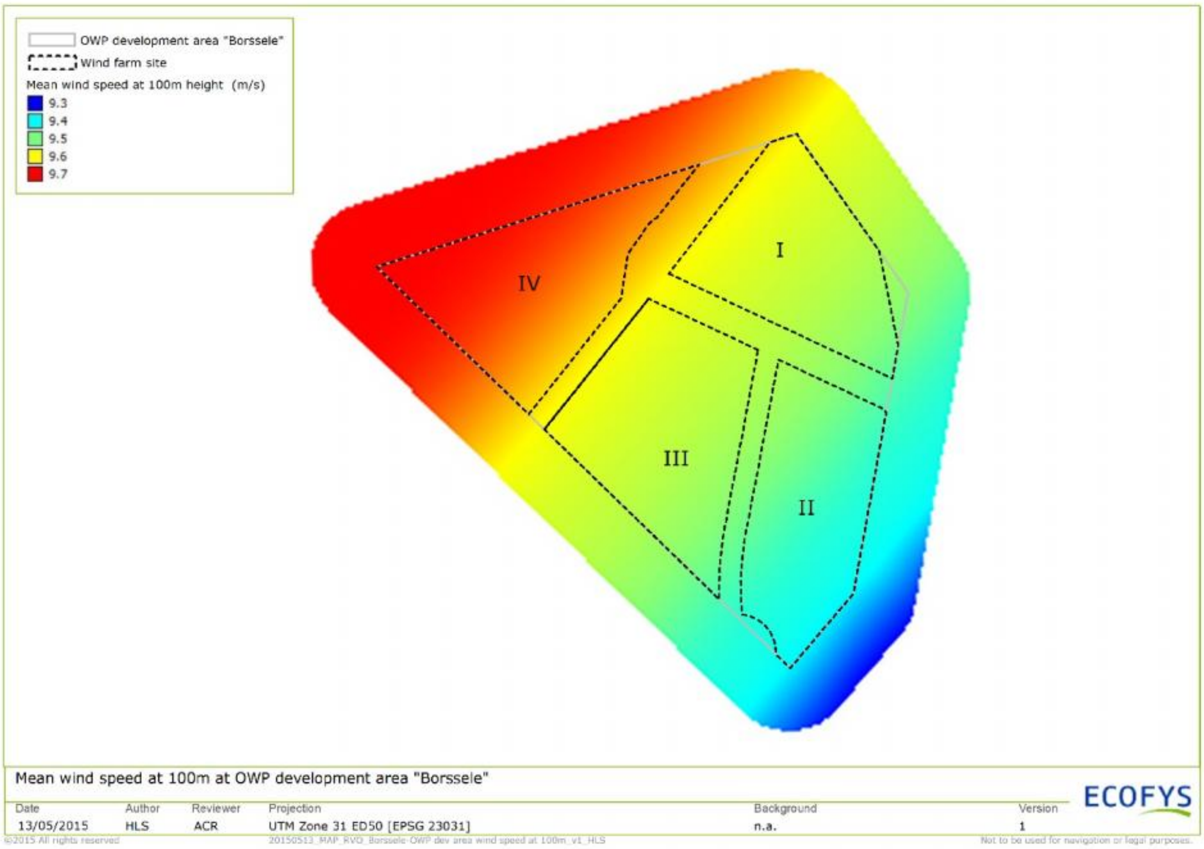


Figure 15 – 100 m mean wind speed map over Borssele wind farm zone.

The mean wind speed decreases by about 0.1 m/s per 10 m decrease in height, down from 100 m to 70 m, as shown in Figure 16.

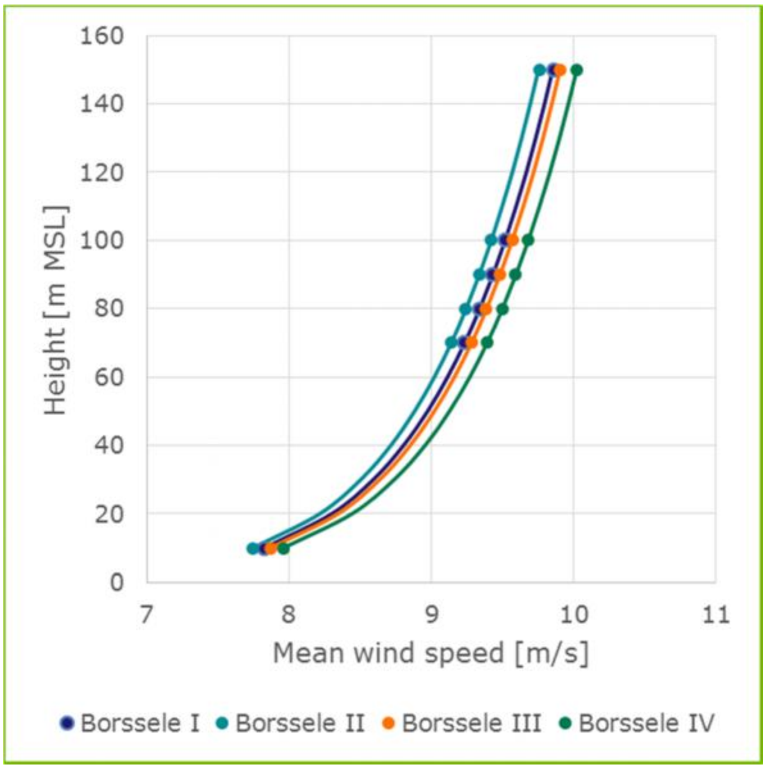


Figure 16 – Mean wind speed profiles at Borssele wind farm zone

4.2 Wind shear

The wind shear shown in Figure 16 can be characterised by the power law exponent in the power law equation:

$$U_2 = U_1 \times \left(\frac{z_2}{z_1}\right)^{\alpha}$$

Where U is wind speed (in m/s), z is height (in m) and α is the power law exponent.

The power law exponent is calculated to represent the best-fit of the vertical wind speed profile using all measurement heights, up to 150 m, if available. Windographer uses linear least squares regression to find the best-fit value of the power law exponent.

The calculated power law exponents for 12 wind direction sectors are shown in a radar plot in Figure 17. The measured wind shear at Meteomast IJmuiden and OWEZ is shown in Figure 18, for comparison (note: not concurrent periods). The extrapolation to other heights is based on the Meteomast IJmuiden mast and LiDAR data, so it is logical that they are closely related; the shear also aligns very well with the measured wind shear at OWEZ. Point of attentions is, that the measured shear at OWEZ is highest in the south eastern sectors, likely due to effects of the coast at a distance of 15 km. By contrast, Meteomast IJmuiden, at 80 km from shore has lower shear to the southeast. It is expected that the Borssele zone, with its distance of 30-50 km to shore will adhere mostly to the IJmuiden profile.

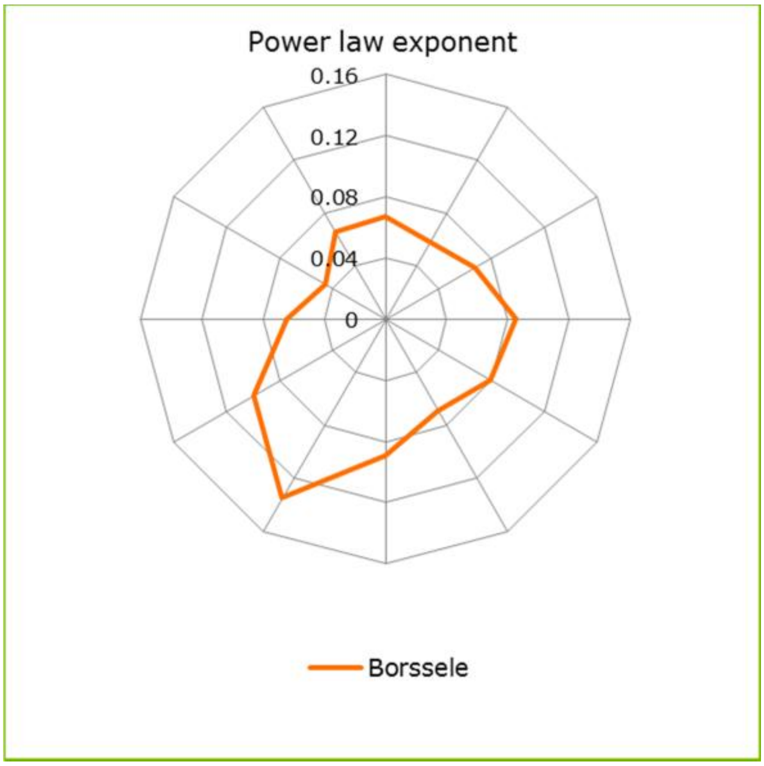


Figure 17 – Power law exponents by wind direction sector for Borssele zone centre

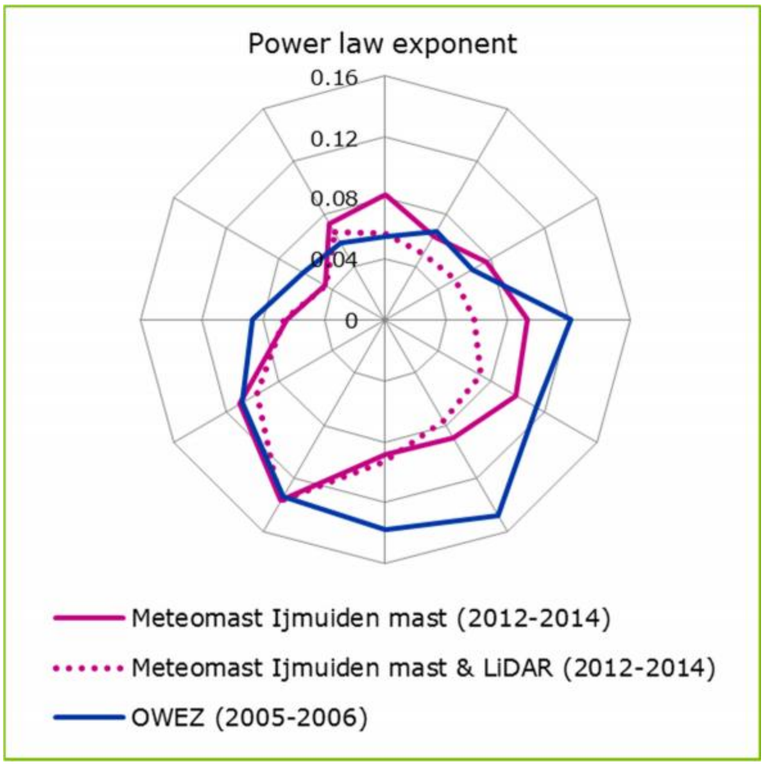


Figure 18 – Power law exponents by wind direction sector for offshore measurement locations

4.3 Diurnal Variation

Figure 19 shows the diurnal variations in the calculated mean wind speed for the Borssele zone, based on the wind climate described in Chapter 3. The patterns are quite similar at all heights with generally little variation throughout the day. At the upper heights, there is a slight increase of about 0.4 m/s in wind speeds in the evening, while at lower heights the slight peak is earlier in the day. The same general trends can be seen at the four offshore met masts, as shown in Figure 20, with a small peak of about 0.3 m/s in the evenings. In general, given the method applied, the pattern is close to identical to that of Meteomast IJmuiden itself.

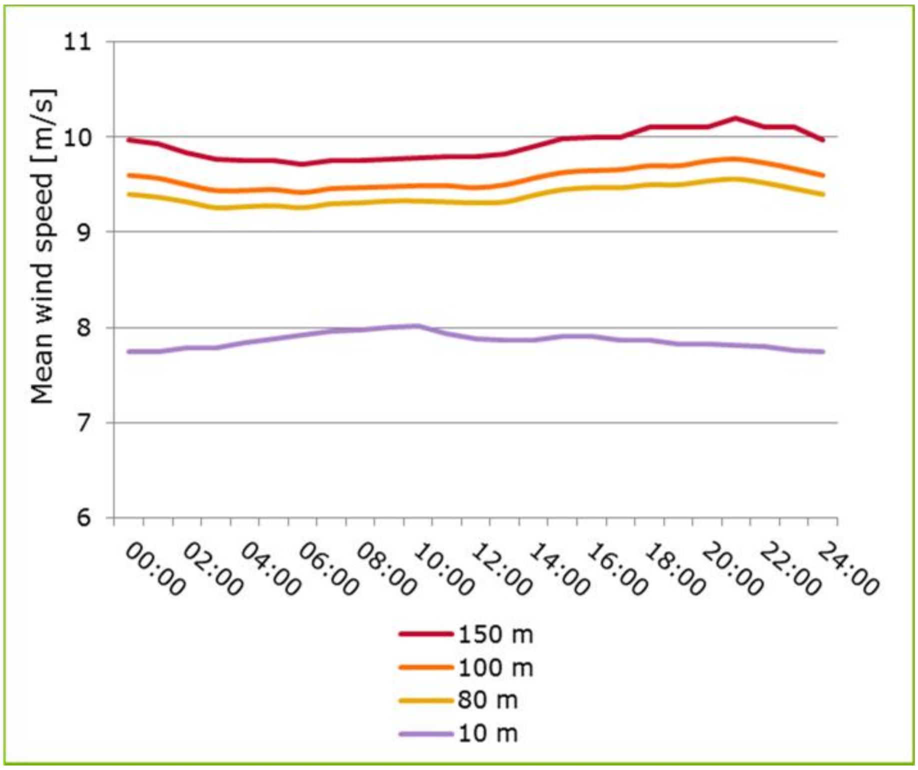


Figure 19 – Mean diurnal profile of wind speed, at the centre of the Borssele zone

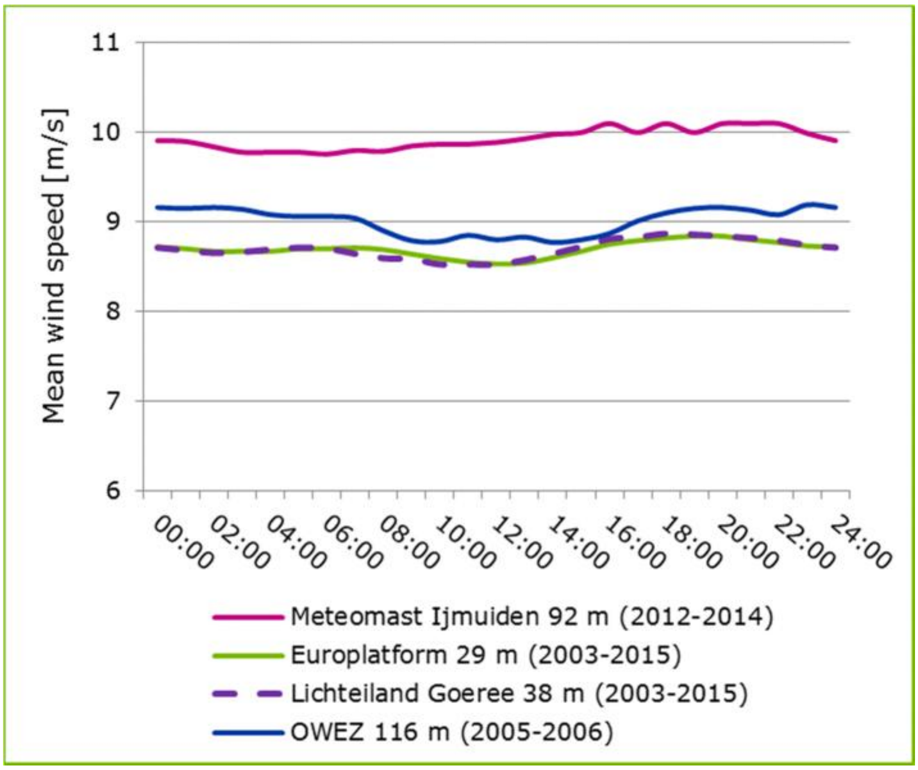


Figure 20 – Mean diurnal profile of wind speed for four measurement locations. The top measurement heights show very little diurnal variation, as is typical offshore.

The vertical wind shear also exhibits a diurnal pattern, with lower shear during the day than at night, although the change is relatively small. This is shown in Figure 21 and Figure 22 for the calculated Borssele wind climate and the offshore measurement locations respectively.

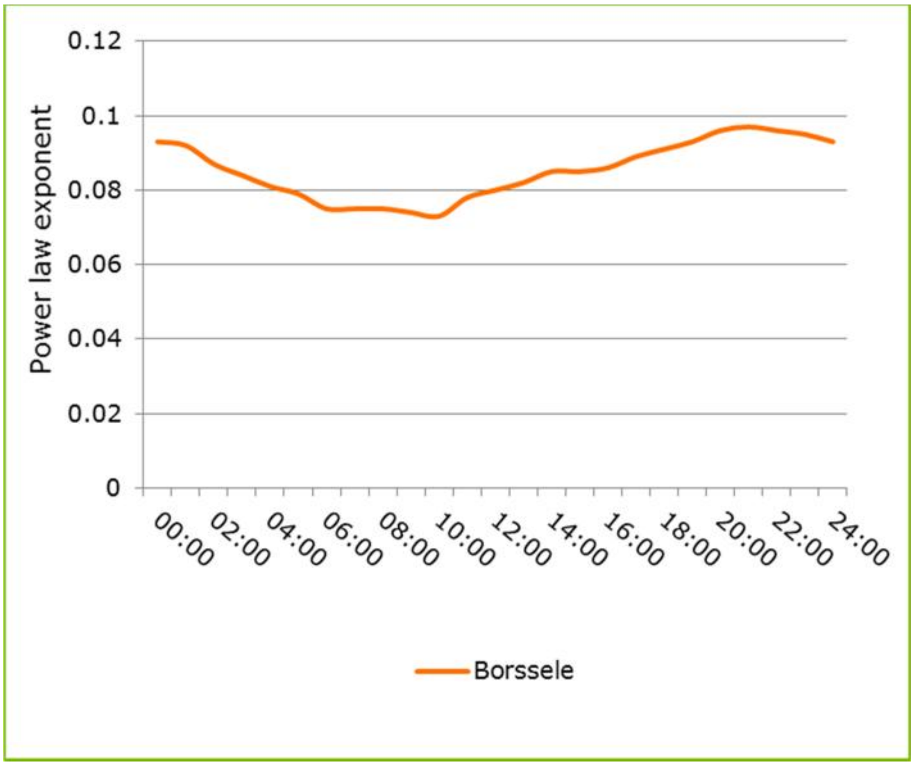


Figure 21 – Mean diurnal profile of power law exponents for Borssele zone.

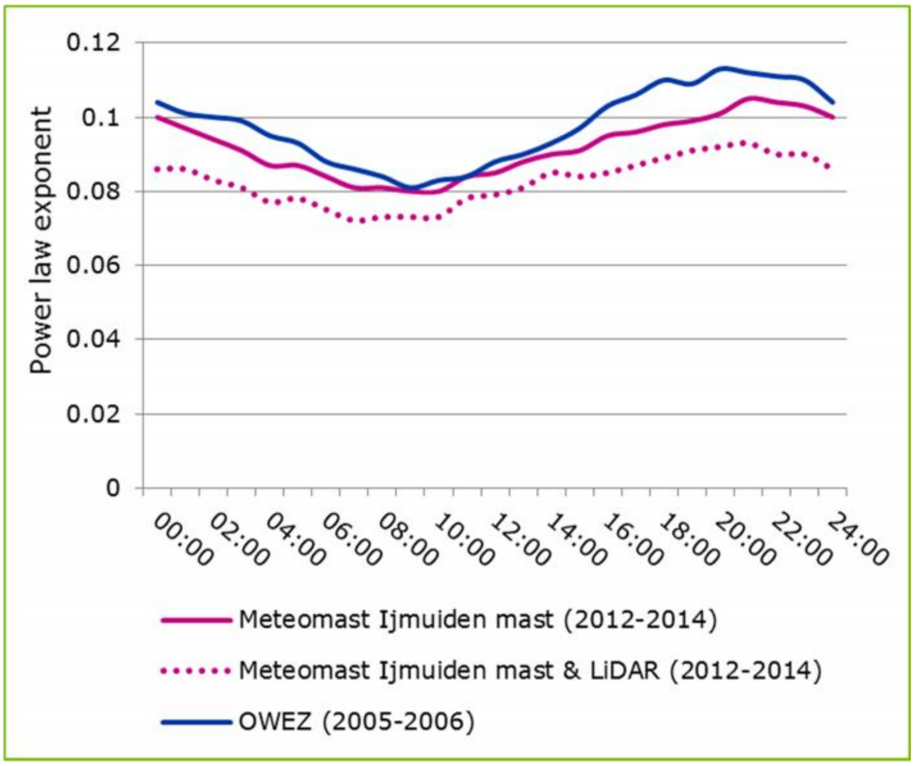


Figure 22 – Mean diurnal profile of power law exponents for four measurement locations.

4.4 Monthly Variation

The trends in mean monthly wind speed are similar at all heights, as seen in Figure 23. There is a significant difference between the high mean wind speeds in winter compared to summer, which is typical for the offshore wind climate in Northern Europe and is also seen in the mast measurements (in Figure 24). It shall be noted that the measurements compared in the second graph are of non-concurrent periods but still showcase a higher level of similarity, which indicates an overall consistent regional wind climate.

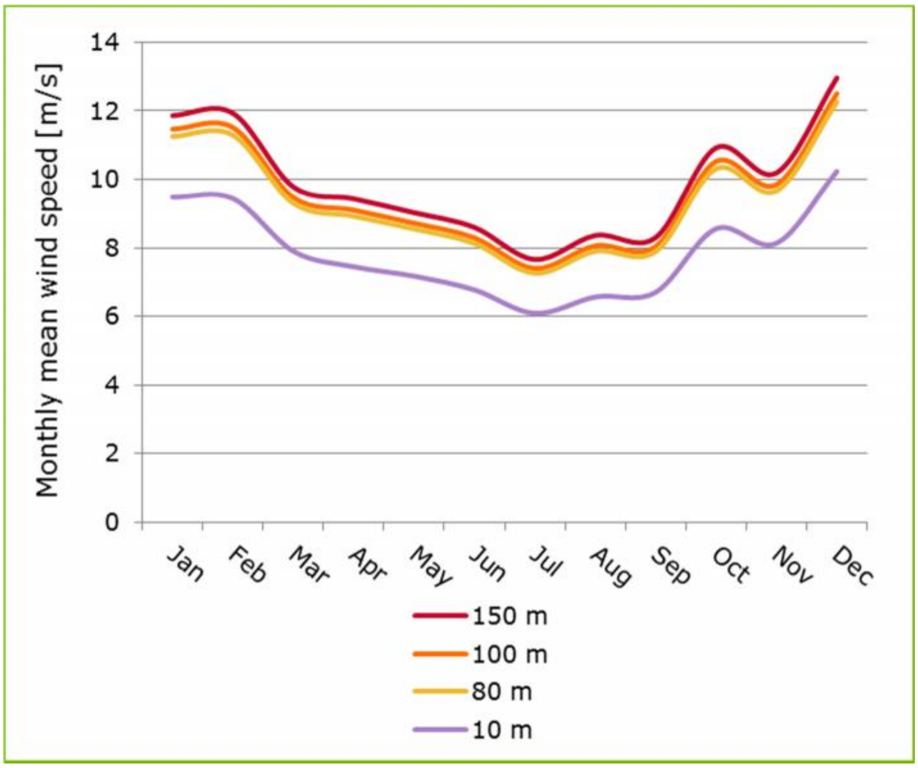


Figure 23 – Monthly mean wind speeds at the centre of Borssele zone. Monthly mean wind speeds are over 50% higher in the winter than summer.

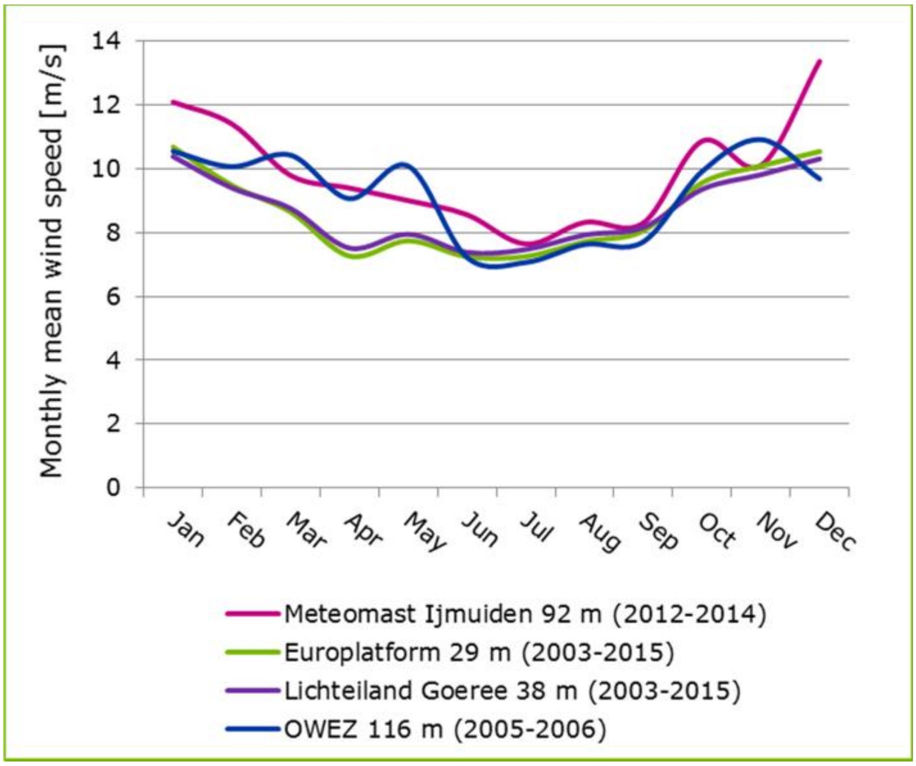


Figure 24 – Monthly mean wind speeds for the top measurement heights of the four mast locations. A similar pattern of lower wind speeds in summer is seen in these datasets. Note the different reference periods of each dataset.

4.5 Inter-annual Variation

The wind climate at Borssele is based on the 3-years of wind measurements from Meteomast IJmuiden, without long-term correction (as explained in Section 3.2). Thus, the graph of annual mean wind speeds in Figure 25 only shows those same three years. The mean wind speeds from the KNW model, at 100 m for the centre grid point at Borssele, are also shown to further confirm that the 3-year dataset is generally representative of the long-term mean. The short-term period can also be compared to the 10-year measurement period of the Europlatform and Lichteiland Goeree datasets, as in Figure 26, which exhibit the same trends as the KNW model.

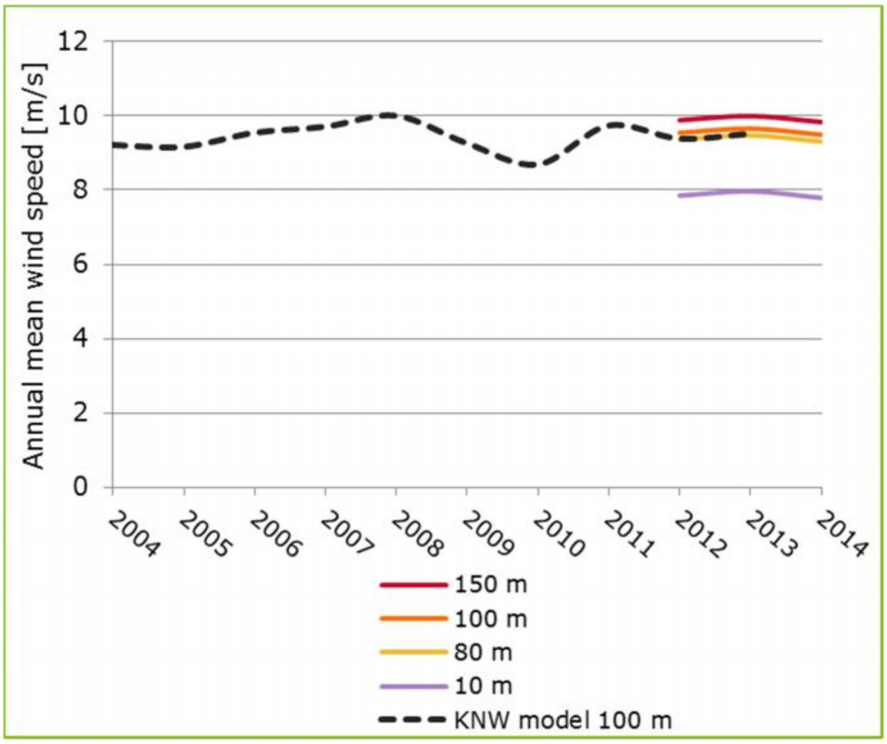


Figure 25 - Annual mean wind speeds at the centre of the Borssele zone.

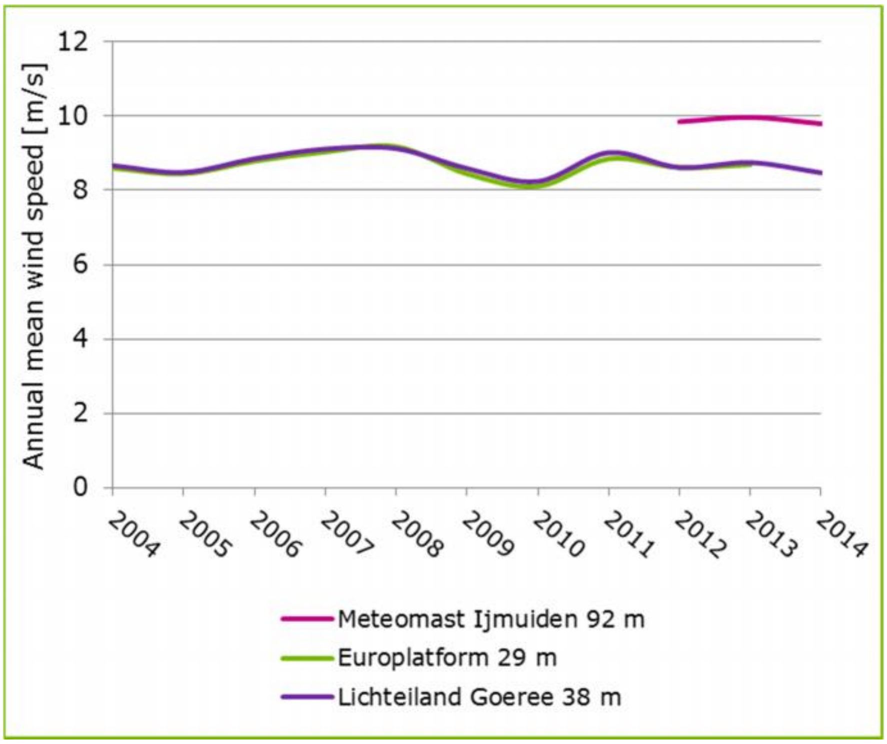


Figure 26 - Annual mean wind speeds for offshore met masts, showing that 2012-2014 period is generally representative of the long-term mean. Note: Europlatform 2014 data excluded due to low data availability.

4.6 Frequency distribution

The frequency distribution of the calculated wind speed is shown in Figure 27 for the Borssele zone centre at a height of 100 m. A Weibull curve is fitted to the data, with a good representation of the actual distribution. The Weibull shape factor (k = 2.18) is in good agreement with the range of factors found for the mast measurements, 2.16 to 2.19, as illustrated in Figure 28.

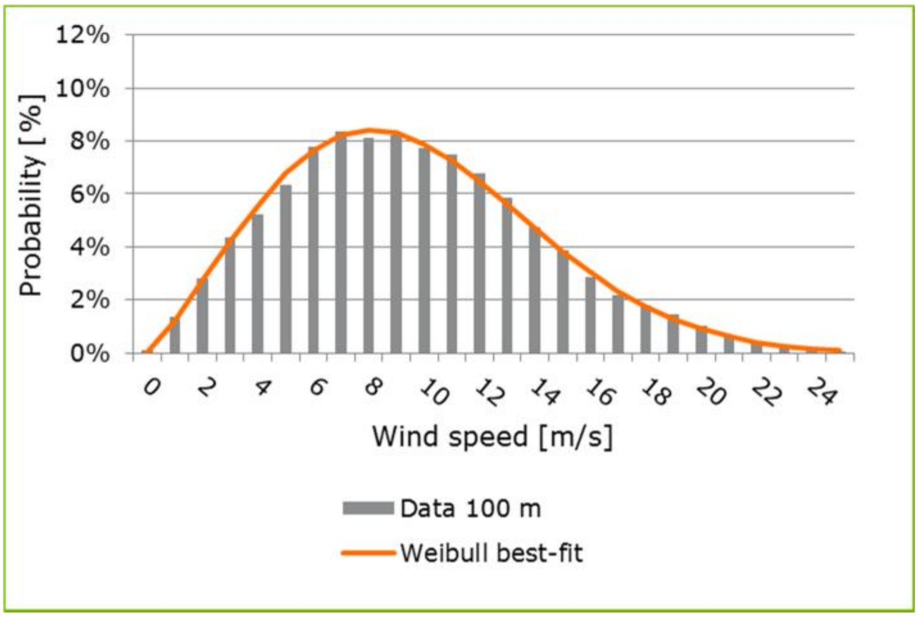


Figure 27 – Probability plot of the calculated wind speed at 100 m at the centre of the Borssele zone, with the fitted Weibull curve.

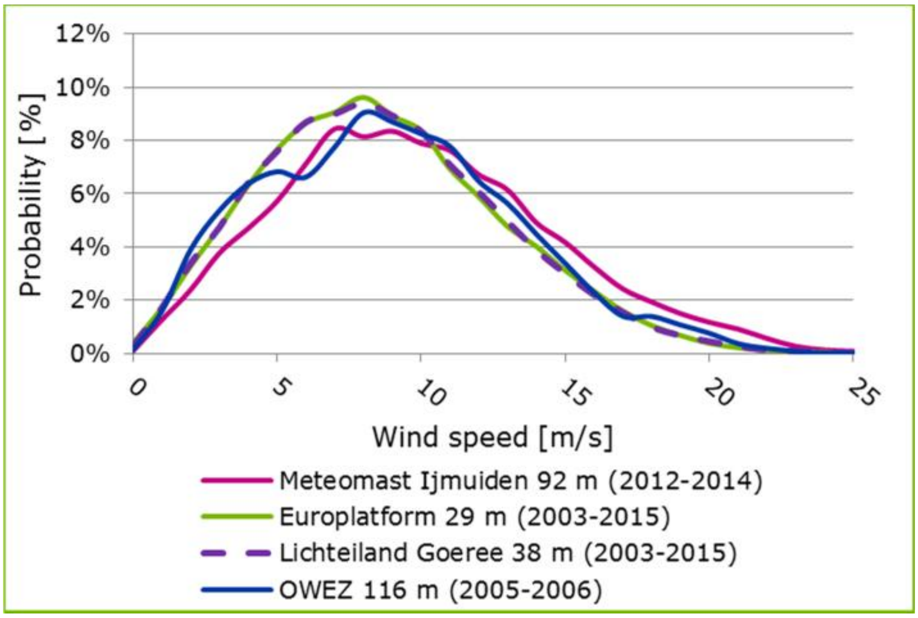


Figure 28 – Probability plot of the mast-top measurements at the offshore masts.

4.7 Wind rose

The wind rose in Figure 29 indicates the relative frequency of occurrence for each wind direction sector. A second comparison is made in terms of energy content of the wind in each sector, based on wind speed and air density, as shown in Figure 30. The most frequent and strongest winds are from the southwest. The Borssele wind roses show close agreement with the mast measurements, although there are indications that the fit is not perfect. The calculated data is based on wind measurements from Meteomast IJmuiden, at a location further north than the other locations, and it experiences most frequently SSW winds, while WSW winds dominate slightly more at the other sites. This effect is worth considering when designing offshore wind farm layouts, as the true wind rose may have slightly more WSW winds than modelled in this assessment.

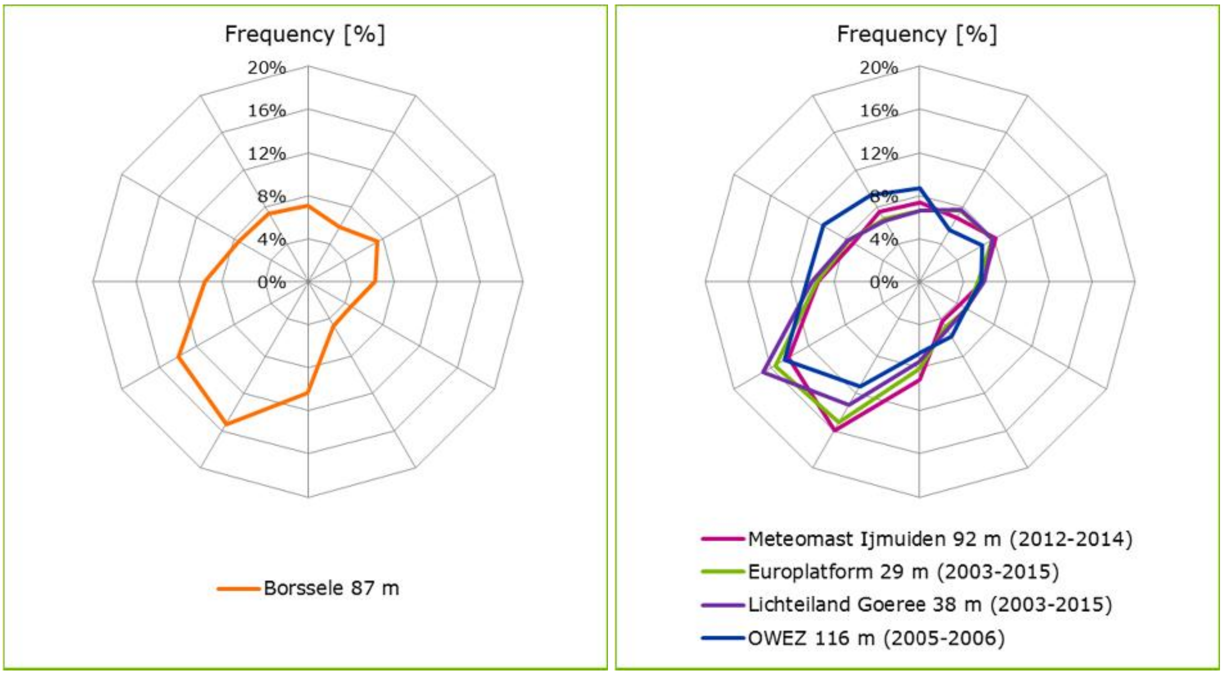


Figure 29 - Wind rose at 100 m at the centre of the Borssele zone (left), with comparison to mast-top measurements at the masts (right): wind direction frequency per sector. The predominant winds are from the southwest.

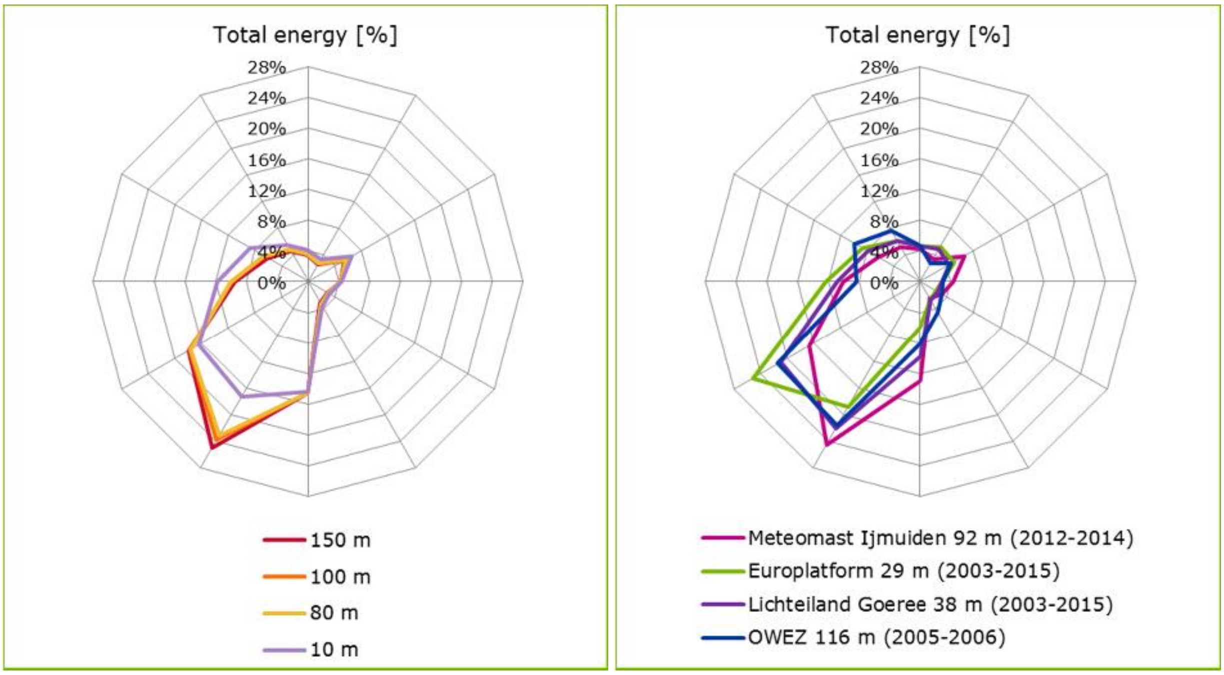


Figure 30 - Wind rose at 100 m at the centre of the Borssele zone (left), with comparison to mast-top measurements at the masts (right): energy density per sector. The strongest winds are also from the southwest.

4.8 Turbulence intensity

The ambient turbulence intensity should be considered as a function of wind speed. Ambient turbulence intensity levels are not modelled accurately by mesoscale models, thus it is not possible to validate the extrapolation from the measurement locations to the Borssele zone. In the absence of on-site measurements, it is acceptable to model the ambient turbulence intensity for the site according to the Charnock equation, which relates turbulence intensity to the roughness of the sea at different wind speeds [13].

The resulting calculated ambient turbulence intensity is low, as shown in Figure 31. The measured turbulence intensity levels at Meteomast IJmuiden and OWEZ are shown for comparison, demonstrating that the calculated levels are reasonable for offshore conditions. These turbulence intensity levels are well below the limits for Category A or B wind turbines [13], although it should be noted that wake-added turbulence intensity must also be included for in assessing the site-suitability for a particular wind turbine type. This component will depend primarily on the spacing of the wind farm layout.

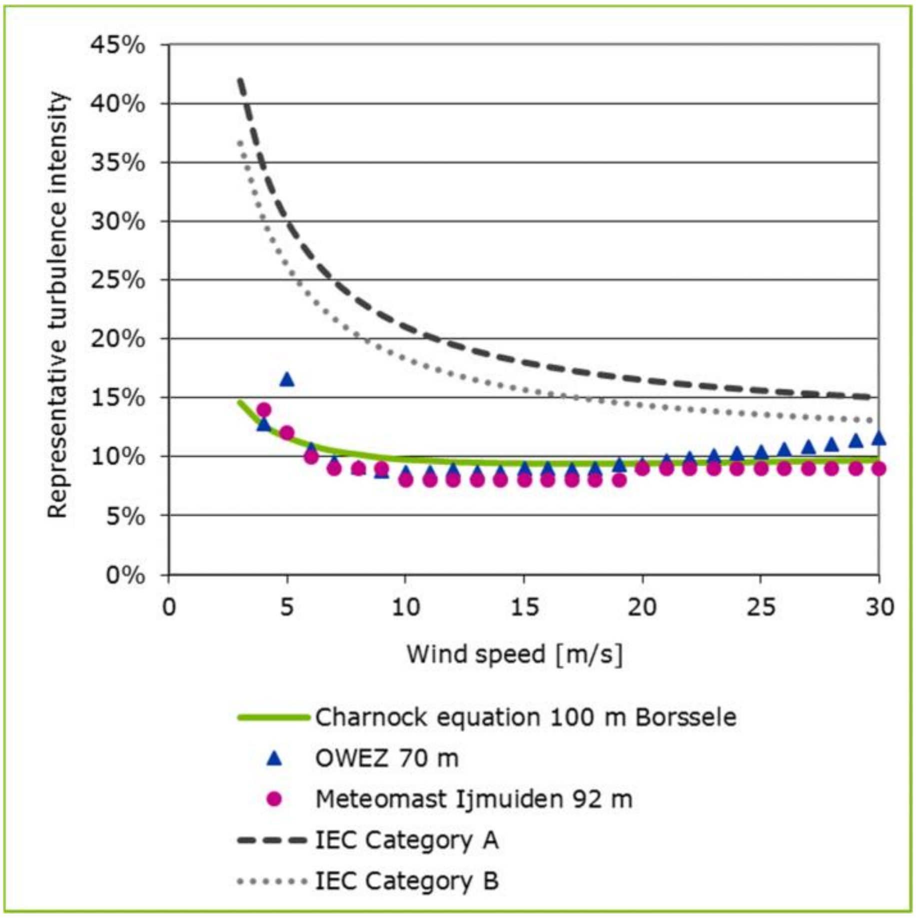
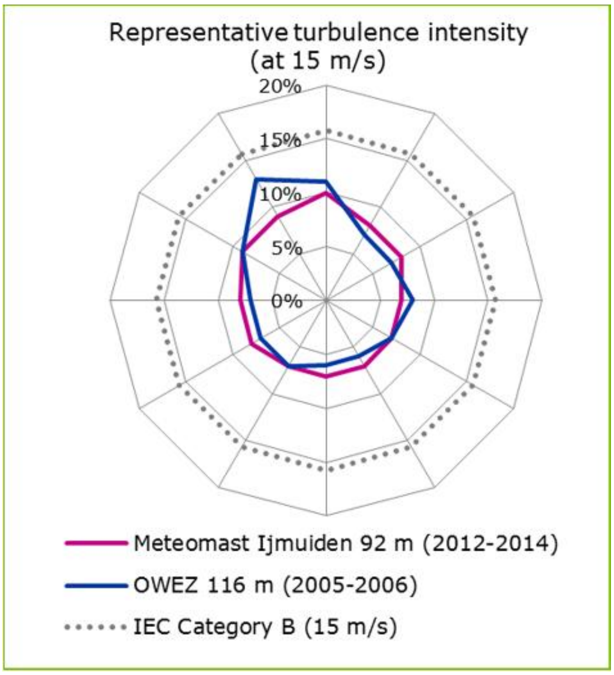


Figure 31 – Calculated offshore turbulence intensity for hub height of 100 m, according to Charnock equation. The model shows close agreement with measured turbulence intensity at OWEZ and Meteomast IJmuiden.

Direction plots of the measured representative turbulence intensity at Meteomast IJmuiden and OWEZ are shown in Figure 32, for wind speeds of 15 m/s and 5 m/s. The turbulence intensity levels are generally similar in all directions and across both datasets. At wind speeds of 15 m/s, the representative turbulence intensity levels are within 7-10% in all directions, except for a single sector with higher turbulence at OWEZ (13% in the NNW). Similarly, the representative turbulence intensity levels are similar at wind speeds of 5 m/s, within 10-13%, except for the eastern sectors at Meteomast IJmuiden (up to 14% in the SSW). These small deviations cannot be fully explained by the expected meteorological conditions, although they could be due to the different measurement periods or some effects of tower shadow. In any case, the overall conclusion is that the turbulence intensity levels are significantly below the IEC limits for Category B wind turbines and generally independent of wind direction.



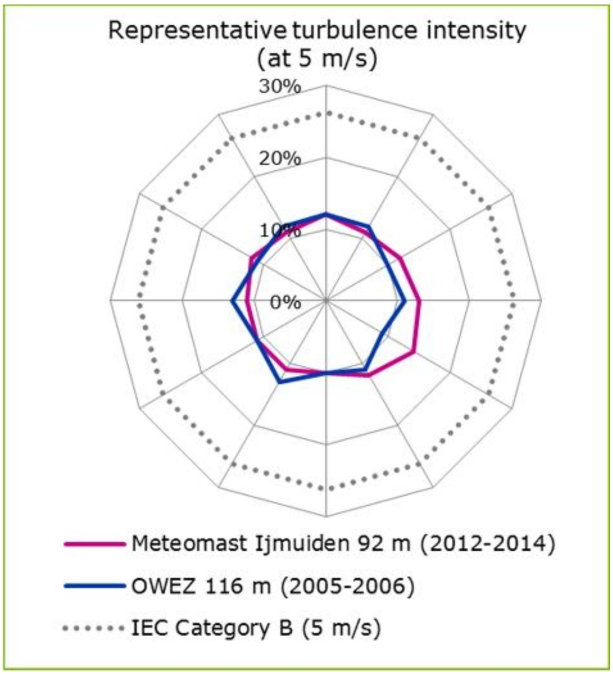


Figure 32 – Measured representative turbulence intensity at OWEZ and Meteomast IJmuiden, for wind speeds of 15 m/s (left) and 5 m/s (right). The IEC limits for Category B wind turbines are also shown.

4.9 Extreme Wind Speeds

Ideally, the extreme wind speeds are calculated based on long-term on-site measurements. For the Borssele zone, two data sources provide alternative estimates: 1) the wind climate calculated above, based on Meteomast IJmuiden 10-minute wind speed measurements for three years; and 2) the 35-year KNW mesoscale model hourly dataset for the grid point at the centre of the Borssele zone.

To calculate the extreme wind speed on-site, a Gumbel analysis is performed using two methods within the Windographer Extreme Wind Analysis Tool [12]. The period maxima method considers the peak wind speeds within a given period. The method of independent storms evaluates all storms with wind speeds greater than a given limit, and separation between storms of more than 48 hours. For both methods, the settings are based on best-practice to provide a suitable number of data points for the extrapolation.

The extreme wind speeds at 100 m MSL for different return periods are shown in Table 19, based on the wind climate assessment described in Chapter 3. The method of independent storms yields higher extreme wind speeds, of about 46 m/s for the 50-year return period.

Table 19 – Extreme wind speed at 100 m MSL at centre of Borssele offshore wind farm zone, using calculated wind climate based on 3-years of Meteomast IJmuiden 10-minute wind measurements

Return period [years]	Extreme 10-minute wind speed [m/s] Period Maxima method	Extreme 10-minute wind speed [m/s]: Method of Independent Storms
10	37	39
25	41	43
50	43	46

The extreme wind speed estimates based on the 35-year KNW mesoscale model data are shown in Table 20. The mesoscale model data is hourly; the estimated extreme winds for a 10-minute averaging period are based on the conversion factors given in the GL Guidelines for Certification of Wind Turbines [14]. The two extreme wind calculation methods yield similar results, with an extreme wind speed of 41 m/s for the 50-year return period.

Table 20 – Extreme wind speed at 100 m MSL at centre of Borssele offshore wind farm zone, using 35-years of KNW mesoscale model hourly wind data, corrected to 10-minutes

Return period [years]	Extreme 10-minute wind speed [m/s] Period Maxima method	Extreme 10-minute wind speed [m/s]: Method of Independent Storms
10	37	37
25	39	39
50	41	41

These estimates can be compared to the detailed extreme wind climate estimates in the Deltares reports ([8] [9] [10] [11]) and accompanying Excel tables. The primary comparisons show that the estimates in this report are below the upper bounds found by Deltares (see Table 14).

The 50-year extreme 10-minute wind speed can be directly compared to the IEC design class of the wind turbine [13]. The estimates based on the KNW mesoscale data (41 m/s) are slightly below the extreme wind speed limit for Class II wind turbines (V_{ref} = 42.5 m/s), whereas the estimates derived from the Meteomast IJmuiden measurements (43-46 m/s) are above this limit and below the extreme wind speed threshold for a Class I wind turbine (V_{ref} = 50 m/s). The accuracy of the estimates from both data sources is unknown, as both involve assumptions regarding the suitability of off-site or modelled data.

It should be noted that, in order to obtain a project specific approval, it has to be shown that the rotor nacelle assembly loads due to wind & waves do not exceed type approved loads.

4.10 Air temperature

The KNW mesoscale dataset also includes modelled air temperature at 100 m. The normal and extreme temperature ranges for the grid point at the centre of the Borssele zone are shown in the table below, with comparison to measurements from Meteomast IJmuiden and OWEZ. The three datasets show similar results, with a mean air temperature of about 11°C at 100 m.

Table 21 – Normal and extreme air temperature ranges in KNW mesoscale model and at measurement locations

Dataset	Mean air temperature [°C]	Maximum air temperature [°C]	Minimum air temperature [°C]
100 m KNW BORS0	10.7	30.6	-5.8
116 m OWEZ	10.7	27.2	-3.3
90 m Meteomast IJmuiden	9.8	28.7	-5.9

4.11 Air pressure

The air pressure is shown in Table 22 for the measurement locations at OWEZ and Meteomast IJmuiden, since it is not part of the KNW mesoscale dataset. The mean air pressure at Meteomast IJmuiden is 1,004 hPa at 90 m, which is roughly in-line with the OWEZ measurements at a lower height. This closely approximates the International Standard Atmosphere, calculated to be 1,001 hPa at 100 m above sea level [12] and it is expected that these results are generally applicable to the Borssele zone. The OWEZ and Meteomast IJmuiden datasets have different measurement periods, so it is not possible to directly compare the maximum or minimum values since these could be caused by different storms or other meteorological conditions.

Table 22 – Normal and extreme air pressure ranges at offshore measurement locations

Dataset	Mean air pressure [hPa]	Maximum air pressure [hPa]	Minimum air pressure [hPa]
100 m KNW BORS0	n/a	n/a	n/a
100 m International Standard Atmosphere	1,001	n/a	n/a
20 m OWEZ	1,015	1,040	974
90 m Meteomast IJmuiden	1,004	1,034	965

4.12 Relative humidity

The KNW mesoscale dataset includes modelled specific humidity at 100 m (in kg/kg) which is converted to relative humidity based on the air temperature and an assumed constant air pressure of 1,001 hPa. The normal and extreme relative humidity ranges are shown in Table 23 for the grid point at the centre of the Borssele zone, with comparison to measurements from Meteomast IJmuiden and OWEZ. The three datasets all show mean relative humidity levels of 79% at about 100 m.

Table 23 – Normal and extreme relative humidity ranges in KNW mesoscale model and at measurement locations

Dataset	Mean relative humidity [%]	Maximum relative humidity [%]	Minimum relative humidity [%]
100 m KNW BORS0	78.6%	102.6%	20.4%
116 m OWEZ	78.9%	99.7%	22.1%
90 m Meteomast IJmuiden	78.9%	101.1%	15.4%

4.13 Air density

The air density is calculated for each time step of each data series, based on the air temperature, pressure and relative humidity. The air density is shown in Table 24 for the KNW mesoscale model at the centre grid point of the Borssele zone and for the measurement datasets from OWEZ and Meteomast IJmuiden as a comparison. The annual average air density is 1.22 kg/m³ at 100 m at the Borssele zone, comparing well with similar values at the measurement masts. The monthly mean air density varies by ±3% throughout the year, with lower density in the summer months, as shown in Figure 33.

Table 24 – Normal and extreme air density ranges in KNW mesoscale model and at measurement locations

Dataset	Mean air density [kg/m³]	Maximum air density [kg/m³]	Minimum air density [kg/m³]
100 m KNW BORS0	1.22	1.30	1.14
116 m OWEZ	1.23	1.32	1.16
90 m Meteomast IJmuiden	1.24	1.35	1.15

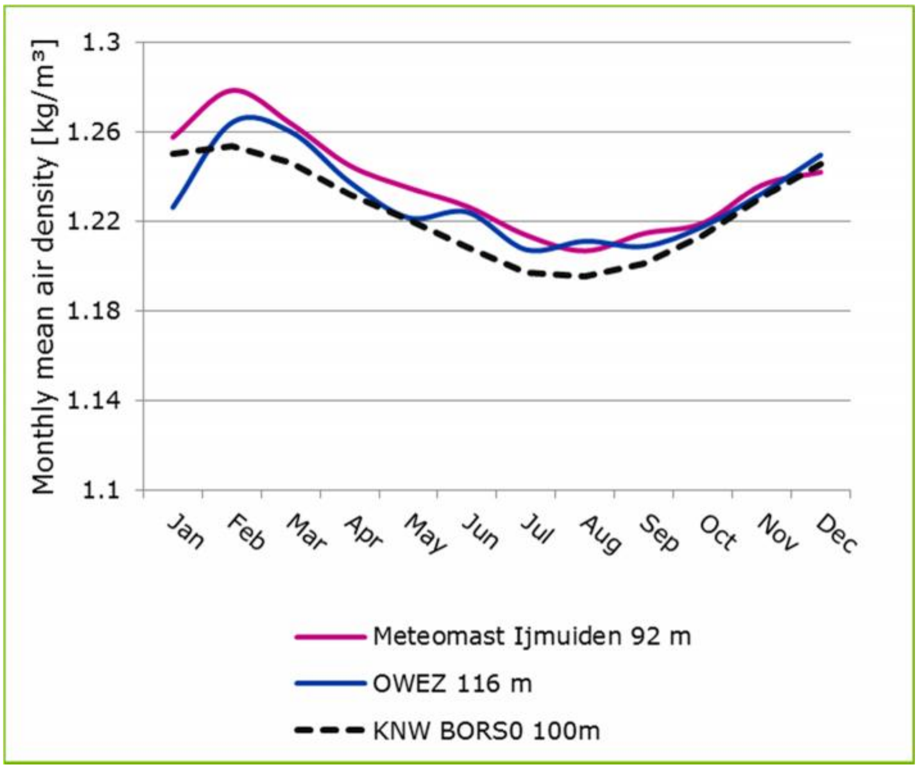


Figure 33 – Monthly mean air density for KNW mesoscale model and at measurement locations

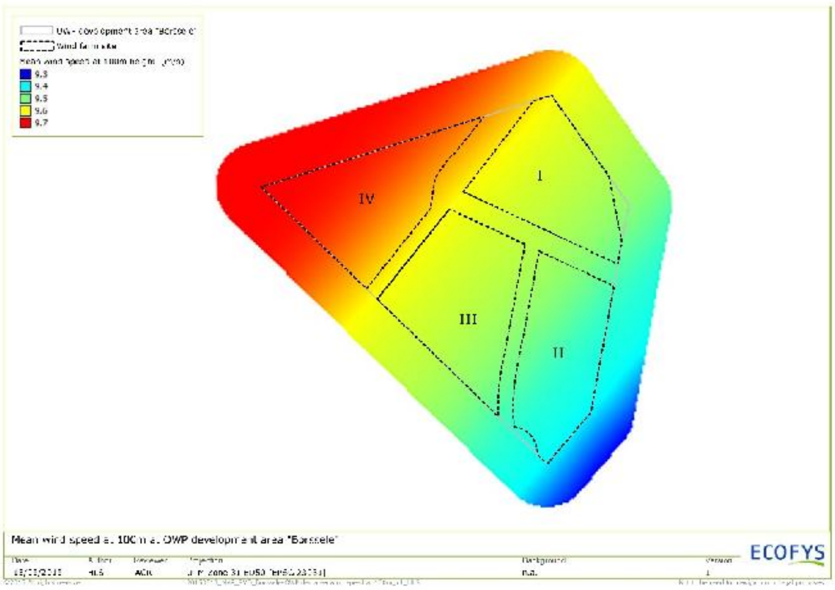
5 Conclusions

The offshore wind climate was assessed for the Borssele offshore wind farm zone in the Dutch North Sea. This assessment is based on the combined use of offshore wind measurements and mesoscale model data. No on-site offshore measurement records were used for this study.

Wind measurements from four offshore met masts were analysed and considered appropriate for the mesoscale model validation. Four different mesoscale model datasets were compared to the measurements, and the KNW mesoscale model was selected as the most representative modelled dataset for this region.

The detailed analysis of the offshore wind measurement datasets shows that speeds based on the Meteomast IJmuiden data have the lowest uncertainty. The measured wind speed at 92 m is 9.9 m/s, which is then extrapolated to a height of 100 m based on the measured shear profile and to the wind farm zone based on the KNW mesoscale model. No long-term correction is necessary since the measurement period of 3-years is found to closely represent the long-term. The calculated long-term mean wind speed at 100 m at the Borssele wind farm zone centre is 9.6 ± 0.5 m/s (± standard deviation).

Detailed analyses of the wind climate were carried out, showing that all of the analysed trends are reasonable for an offshore site and consistent across modelled heights from 10 to 150 m. The calculated variation in mean wind speed across the wind farm zone is shown below.



According to the extreme winds and turbulence intensity analysis, the site is suitable for IEC Class 1B (or better) wind turbines, assuming wake-added turbulence is correctly considered.

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- Rein de Wolff, BLIX

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Appendix A Measurement Documentation

This appendix contains details of the measurement campaign, which are additional to the descriptions and comments in the body of the report. Typically, this includes site photos, descriptions of the meteorological mast(s) and instruments, and documentation the measurement procedure. As well, any deviations from measurement best-practice (for instance, the MEASNET Guideline "Evaluation of Site Specific Wind Conditions") are documented.

Description of Site

The wind farm site and all measurement stations are located offshore, and terrain conditions are described in the report. For the wind farm site, there are no site photos, nor are any necessary, because of the homogeneous sea surroundings. For the measurement masts, site photos are given in the report.

Description of Measurement System

Ecofys did not perform the wind measurement campaigns described in this report. Thus, calibration certificates and other specifications of the instrumentation are not available. Within the report, references are made to detailed description of the Meteomast IJmuiden measurement system [6], as well as the other met masts [1] [2] [3] [5]. These references have been extensively examined during the quality control and uncertainty analyses. These references are considered sufficient documentation and it is not deemed necessary to reproduce more details here.

Description of Measurement Procedures

The report contains details of the measurement procedures and data processing, with sufficient references to more detailed studies.

Deviations to Best-Practice

Ecofys analysed in detail the datasets from the Europlatform, Lichteiland Goeree, OWEZ and Meteomast IJmuiden met masts and concludes that they provide sufficient basis for an accurate preliminary wind resource assessment for the Borssele wind farm zone. However, these wind measurements do differ from industry best-practice in a number of ways, as addressed here:

1. Meteomast IJmuiden is located over 125 km from the wind farm zone. This is much further than 10 km, which is a typical maximum distance for simple terrain [15]. However, offshore conditions should generally be similar between the Meteomast IJmuiden and Borssele sites, and the use of a validated mesoscale model dataset reduces the uncertainty in horizontal extrapolation.
2. It cannot be confirmed that the layout of the Meteomast IJmuiden mast is fully designed in compliance to IEC 61400-12-1. Especially, the instruments are sometime affected by significant tower shadow effects. Through a filtering scheme that selects the least-disturbed instruments,

these obstacle effects can be minimised. These flow effects are considered in the uncertainty analysis.

3. The accuracy of extreme wind conditions is unknown, as it is difficult to quantify the uncertainty of horizontal extrapolation with regards to wind speed peaks. In addition, the turbulence intensity levels are assessed based on a calculated model, rather than on-site measurements.

Appendix B Filtering of Measurement Data

Europlatform

The filtered data for the Europlatform dataset is summarised in Table 25.

Table 25 – Data filtering for Europlatform data

Period	Note
Entire period	All missing data or values of -999 were excluded. This affects approximately 1.2% of data.
Entire period	Sudden drops in wind direction (to a value around 10°) were removed. This affects approximately 0.7% of data, mostly before May 2003.
07/10/2003 to 27/10/2003	Wind direction frozen below 10°.
16/11/2010 11:40	Wind speed spike to 40 m/s.
02/05/2014 to 06/05/2014	Wind speed frozen at 0 m/s.
06/05/2014 to 31/07/2014	Missing wind speed.
18/01/2015 to 22/01/2015	Missing wind speed and direction.
22/01/2015 to 02/02/2015	Wind speed frozen at 0 m/s.
02/02/2015 to 10/02/2015	Missing wind speed and direction.

Lichteiland Goeree

The filtered data from the Lichteiland Goeree mast is summarised in Table 26.

Table 26 – Data filtering for Lichteiland Goeree mast data

Period	Note
Entire period	All missing data or values of -999 were excluded. This affects approximately 1.2% of data.
Entire period	Sudden drops in wind direction (to a value around 10°) were removed. This affects approximately 0.1% of data.

The filtered data from the LiDAR at Lichteiland Goeree is summarised in Table 27.

Table 27 – Data filtering for Lichteiland Goeree LiDAR data

Period	Note
Entire period	Data filtered for 'data availability' (self-defined quality signal) below 80%, in accordance with LiDAR manufacturer recommendation
Entire period	Wind direction offset corrected by +30°
15/12/2014	Missing data at all heights
26/12/2014	Missing data at all heights
07/01/2015	Missing data at all heights
16/01/2015	Missing data at all heights
19/01/2015 to 20/01/2015	Missing data at all heights
23/01/2015	Missing data at all heights
05/03/2015 to 06/03/2015	Missing data at all heights
02/04/2015	Missing data at all heights
04/04/2015	Missing data at all heights
08/04/2015	Missing data at all heights
10/04/2015 to 24/04/2015	Missing data at all heights
29/04/2015 to 30/04/2015	Missing data at all heights

Offshore Windpark Egmond aan Zee (OWEZ)

Wind speed and wind direction was recorded at three heights (21, 70 and 116 m MSL). Each 10-minute period mean values are recorded, as well as the maximum, minimum and standard deviations over the same period. In addition, temperature and relative humidity are recorded at 70 m and 116 m. A pressure sensor is installed at 20 m. Finally a rain sensor can be found at 70 m.

There are three cup anemometers and three wind vanes at each measurement height, attached to booms oriented NW, NE and S. There is also a sonic anemometer at each level on the NW boom. ECN has described a directional selection process to derive a single undisturbed wind speed from the three measurements at each height, as illustrated in Figure 34. Ecofys has reproduced this process, with some modifications to increase data availability. The ECN process would calculate the wind direction based on the average of two wind vanes and exclude wind speeds if data from either wind vane was missing. This leads to the exclusion of otherwise valid data.

	Wind direction	Selected sensors
Derived wind direction	(1) 330 to 30 degree	average of wind vanes NW and NE boom
	(2) 30 to 90 degree	average of wind vanes S and NW boom
	(3) 90 to 150 degree	average of wind vanes S and NE boom
	(4) 150 to 210 degree	average of wind vanes NW and NE boom
	(5) 210 to 270 degree	average of wind vanes NW and S boom
	(6) 270 to 330 degree	average of wind vanes NE and S boom
Derived wind speed	0 to 120 degree	cup anemometer in NE boom
	120 to 240 degree	cup anemometer in S boom
	240 to 360 degree	cup anemometer in NW boom

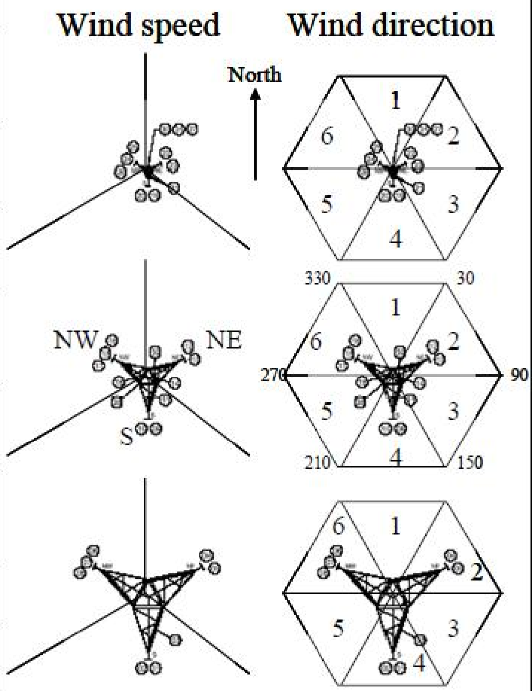

Figure 34 - Overview of ECN data processing rules for the OWEZ mast data to obtain derived wind speed and wind direction from undisturbed sensors only.

The Ecofys directional filters and selection process includes recordings even if only one of the two undisturbed wind vanes is available. This increases the overall data coverage at the expense of the accuracy in (some of) the wind direction recordings. In addition, sonic anemometer data is used in case all cup anemometer data is missing, under the condition of that the wind direction sector is undisturbed for the sonic anemometer. In this way, data availability increased to 86% at 116 m and 96% at 70 m. All data filtering is summarised in Table 28

Table 28 – Data processing for OWEZ met mast

Period	Change
25/11/2005 to 05/12/2014	Extended period of missing data of the Final mean wind speed at 116 m [derived wind speed of all cup and sonic anemometers at 116 m]
25/11/2005 to 05/12/2006	Extended period of missing data of the Final mean wind speed at 70 m [derived wind speed of all cup and sonic anemometers at 70 m]
25/11/2005 to 05/12/2005	Extended period of missing data of the Final air density at 70 m [calculated from 70 m temperature, pressure and relative humidity]
25/11/2005 to 05/12/2005	Extended period of missing data of the Final air density at 116 m [calculated from 116 m temperature, pressure and relative humidity]
19/12/2005 to 01/02/2006	Extended period of missing data of the Final mean wind speed at 116 m [derived wind speed of all cup and sonic anemometers at 116 m]
01/02/2006 12:10 to 12:20	RHTT 261/S/70/RH Mean has incomplete 10min interval after long period of missing data. Extremely low value disturbing air density
05/05/2006 11:40 to 11:50	RHTT 261/S/70/AT Mean has incomplete 10min interval after long period of missing data. Extremely low value disturbing air density
20/04/2006 to 05/05/2006	Extended period of missing data of the Final mean wind speed at 21 m [derived wind speed of all cup and sonic anemometers at 21 m]

Meteomast IJmuiden

Measurement heights are 21 m, 58 m, 85 m and 92 m LAT. The met mast is equipped with three cup-anemometers at 21 m and 58 m and two at 92 m. Three sonic-anemometers are installed at 85 m. Temperature, pressure and relative humidity are sampled at two heights: 21 m and 90 m. Finally, extensive measurements on rain, clouds, fog and visibility take place at 21 m.

The derived wind speed and direction were calculated according to the methods described by ECN for three anemometers at each height [6], modified by Ecofys to include periods with only a single undisturbed wind vane (as for the OWEZ mast).

No information is given regarding the recommended filters for the derived wind speed for the top measurement height where there are only two anemometers. Therefore, Ecofys designed its own interpolation method based on disturbed sectors. The location of the two anemometers was identified based on the instrumentation report [6] and the mast layout shown in Figure 35. The location of the lightning rod is also assumed. An intercomparison of the two measured wind speeds confirmed flow disturbances in the expected sectors, and the directional filters in Table 29 were defined.

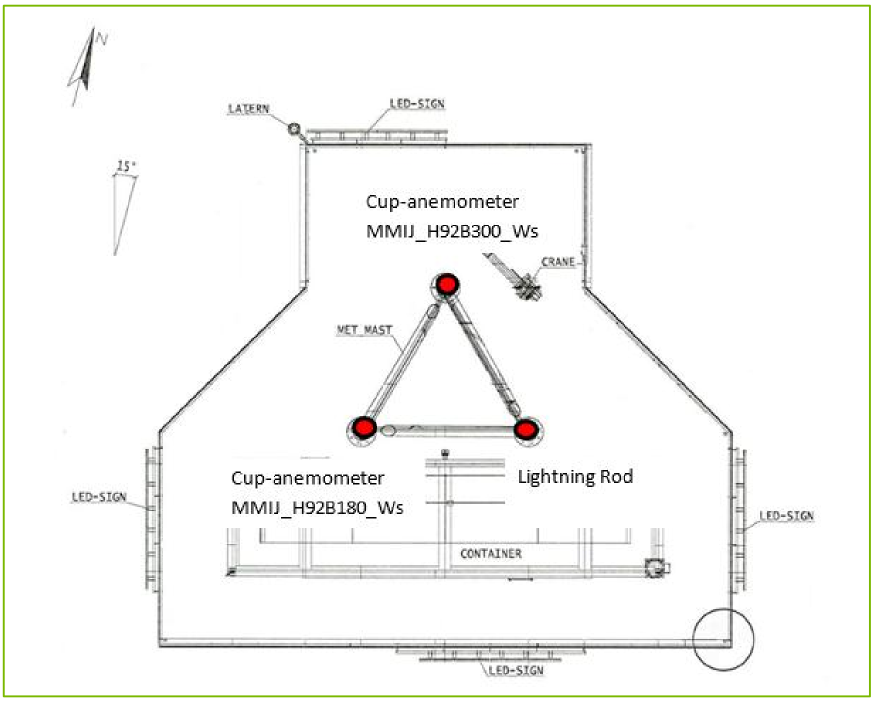

Figure 35 - Top view of 92 m top section of met mast IJmuiden (source: [6]) with the location of the two cup-anemometers and the lightning rod indicated.

Table 29- Summary of directional filters for 92 m measurement height

Disturbed sector [°]	Blockage effects	Valid data
10-30	MMIJ_H92B180_Ws affected by MMIJ_H92B300_Ws	MMIJ_H92B300_Ws
60-100	MMIJ_H92B180_Ws affected by Lightning rod	MMIJ_H92B300_Ws
125-160	MMIJ_H92B300_Ws affected by Lightning rod	MMIJ_H92B180_Ws
185-210	MMIJ_H92B300_Ws affected by MMIJ_H92B180_Ws	MMIJ_H92B180_Ws

The full list of filtered data for Meteomast IJmuiden is shown in Table 30.

Table 30 – Data processing for Meteomast IJmuiden met mast

Period	Change
Entire period	The first measurement before or after a period of missing data is often disabled, as it is based on less than 10 min of data. These data points are often spikes.
25/02/2012 to 05/03/2012	Missing data at all heights.
21/01/2013 15:30 to 22:10	Wind speed at 85 m: frozen constant values
21/08/2013 to 22/08/2013	Missing data at all heights
01/11/2013 to 10/12/2013	Wind direction at 21 m is frequently significantly offset from other two records
11/03/2014 to 31/03/2014	Wind direction at 21 m is frequently significantly offset from other two records

Ecofys also filtered the LiDAR data. A known issue with the ZephIR wind direction recording is that it can be reported with a ~180° offset due to flow distortion around the LiDAR. So, the LiDAR wind direction measurements were compared to the upper met mast wind direction and disabled if the deviation exceeded 60 degrees; this error would affect all measurement heights for the same time period.

Also, if a ZephIR LiDAR is only operational for part of a ten-minute interval, the data is not automatically disabled. To remove these partial records, all data with less than 30 packets (as a measure of sampling frequency) within a ten-minute interval is disabled.

The filtered data from the LiDAR at Meteomast IJmuiden is summarised in Table 31.

Table 31 – Data filtering for Meteomast IJmuiden LiDAR data

Period	Note
Entire period	Data filtered for 'number of packets' (self-defined quality signal) below 30
Entire period	Data filtered for periods where wind direction at 90 m deviates by more than 60° from the met mast wind direction at 85 m
07/11/2011 to 13/11/2011	Missing data at all heights
25/02/2012 to 03/03/2012	Missing data at all heights
10/02/2015 to 28/02/2015	Missing wind speed data at all heights

Appendix C Mesoscale model overview

This appendix gives an outline of the mesoscale models validated in this study, as described by the data providers themselves. All use state-of-the-art meteorological flow models, fed with high-quality reanalysis input source data (some from multiple sources), and high-resolution topography and roughness. The model providers each pride themselves on the extensive validations that have been performed which confirm the accuracy of their data.

EMD-ConWx

ConWx is a Danish-based company, supplying a wide variety of weather and energy related tools and our services include numerical weather models, offshore forecasts, wind power generation forecasts, energy trading services and energy consumption forecasts. A high resolution mesoscale dataset from ConWx (in collaboration with EMD) is available in the latest version of WindPro software.

Advantages and limitations of model

EMD-ConWx has a staff of highly experienced model engineers, programmers and meteorologists collaborating to bring the best ideas forward. They supply utilities, offshore companies and trading houses with wind turbine forecasts based on high-quality numerical weather models. The forecasts contain information about all parameters needed for precise wind turbine forecasting. Wind speeds can be extracted for any height assuring the highest amount of accuracy and model parameters like freezing rain can predict sudden drops in production. The development of the EMD-ConWx mesoscale dataset benefits from this wide experience.

Inputs used to force or calibrate the model

The EMD-ConWx model uses the WRF mesoscale model, with ERA-Interim as input boundary data. It is available as an hourly time series for 15+ years, with a 3km resolution.

Grid resolution and long-term time period

The mesoscale model is run at a high spatial resolution of 0.03° x 0.03° (approximately 3 x 3 km with hourly temporal resolution. The dataset covers Europe including larger parts of Turkey and Ukraine, excluding the northern extreme of Scandinavia. Timespan is at 15-20 years back, updated monthly with approximately 3 months delay defined by ERA-Interim availability

Validation of data

The EMD-ConWx mesoscale data has been validated against wind speed measurements at 116m at a site on the Danish west coast, showing high accuracy.

KNMI KNW wind atlas

The Royal Netherlands Meteorological Institute, KNMI, has recently developed an improved wind atlas for the Dutch North Sea. The wind atlas was specifically initiated to aid government plans to achieve part of the sustainability objective by building offshore wind farms, including the Borssele zone. KNMI has therefore compiled the KNW atlas (where KNW represents KNMI NoordzeeWind), on behalf of the Dutch government, in order to provide reliable wind climatology for wind energy applications at relevant heights offshore.

Advantages and limitations of model

This model is specifically targeted at the Borssele zone and Dutch North Sea. KNMI intends to make this wind atlas publicly available in 2015 in an effort to contribute to the government goal of 40% reduction of the cost of offshore wind energy. Unfortunately, it is not certain whether this model will be available for this project, due to potential delays in permissions and compilation.

Inputs used to force or calibrate the model

The input model data is 35 years of data from a reanalysis model (ERA-Interim at 80 km resolution). That data is re-calculated based on statistical methods to a finer resolution with the aid of the HARMONIE weather model that KNMI also used for making weather forecasts.

Grid resolution and long-term time period

In producing the KNW- atlas KNMI has made a detailed wind climatology at 2.5 x 2.5 km grid resolution for the North Sea; more specifically for the areas designated for offshore wind energy and for heights relevant for wind energy production. The KNW-atlas is based on 35 years of HARMONIE forecasts with boundary conditions provided by ERA interim.

Validation of data

KNMI has validated the KNW-atlas against publicly available wind measurements, such as provided by scatterometer and Cabauw [19].

EMD-WRF

In WindPro 3.0, EMD provides WRF model results, run on their Performance Cluster.

Advantages and limitations of model

The on-demand mesoscale calculations offers several advantages such as results at multiple heights, better background roughness model and better solar radiation results. It uses the newest version of the WRF model. Turbulence information for all years is included.

Inputs used to force or calibrate the model

The EMD-WRF model uses the WRF mesoscale model, with either ERA-Interim or MERRA datasets as input boundary data. It is available as an hourly time series with a 3km resolution.

Grid resolution and long-term time period

The mesoscale model is run at a high spatial resolution of 0.03° x 0.03° (approximately 3 x 3 km) with hourly temporal resolution. The dataset has global coverage and calculations can be made for any period from 1979 to present, updated monthly (with a delay defined by the availability of the input dataset)

Validation of data

There are not yet any published validations of the EMD-WRF mesoscale data.

Appendix D Validation of Mesoscale Models

Four different mesoscale models were analysed. The modelled time series were acquired from three different modellers:

- EMD-ConWx
  - with ERA-Interim
- KNMI KNW
  - with ERA-Interim
- EMD-WRF
  - with ERA-Interim
  - with MERRA

Time series were acquired for each model for the nearest grid point and for concurrent periods with the measurements.

The mesoscale model heights were interpolated to match the measurement heights as closely as possible, as shown in Table 32. Three measurement heights are compared for each mast. Time-series interpolation was performed using the Windographer software using the nearest modelled height and the average hourly shear profile. The shear matrix is based on all modelled heights from the same mesoscale model. The wind direction was taken from the nearest model height (without interpolation).

Table 32 – Measurement heights, compared to mesoscale model heights

	Measurement heights	EMD-ConWx / EMD-WRF	KNMI KNW
OWEZ	27, 70, 116 m	Interpolated 10, 25, 50, 75, 100, 150 m	Interpolated 10, 20, 40, 60, 80, 100, 120, 140, 160, 180, 200 m
Meteomast IJmuiden (MMIJ)	21, 58, 92 m		
Europlatform (EURO)	29 m		
Lichteiland Goeree (LEG)	38 m		

Appendix C contains detailed descriptions of the respective flow models, input data sources and relative merits (according to the modellers themselves).

Statistical tests

A number of statistical tests were performed, using Matlab software for the concurrent datasets. The first two tests evaluate the relationship between time series, in terms of wind speed and direction:

1. Wind speed correlation
   The correlation coefficient is a measure of the linear dependence between the measured and modelled wind speed. A correlation coefficient of +1 indicates that two wind speeds can be perfectly described by a linear equation. A high correlation in wind speeds indicates that two time series are largely in sync.

2. Wind direction correlation
   A circular correlation coefficient similarly evaluates the relationship between two variables – in this case angular wind directions. This methodology assures an accurate correlation between e.g. 359° and 1°. A high wind direction correlation shows that the modelled time series is closely synchronised with the measurements.

Two tests were then performed to evaluate any bias in the modelled data, and the magnitude of the difference:

3. Mean difference in wind speed
   Mean difference indicates the average direction of the deviation between modelled and measured wind speeds, but will not reflect the magnitude of the difference. It can indicate whether the modelled wind speed is biased (positively or negatively) as compared to the measured data.

4. Mean absolute difference in wind speed
   The mean absolute difference shows the variation from the mean difference. This statistical test can be used to estimate the confidence in correcting for bias.

Since the accuracy of a wind resource assessment is primarily concerned with the wind speed distribution rather than the time series, two further tests were performed:

5. Kolmogorov-Smirnov test statistic
   A two-sample Kolmogorov-Smirnov test compares the cumulative distribution of the two datasets. The Kolmogorov–Smirnov test statistic quantifies the largest distance between the empirical distribution functions of both samples. The test is sensitive to differences in both location and shape of the empirical cumulative distribution functions of the two samples, and thus can serve a goodness of fit curve. Two datasets with identical cumulative distributions will yield a test statistic of zero.

6. Difference in energy yield for representative wind turbine
   A time series of energy yield was calculated using each time series of wind speed, and the power curve a representative 6 MW wind turbine for this site. The difference in total energy yield was then compared. This allows for a test of the distribution of wind speeds, largely focusing on the range of 3 – 12 m/s as this is where power curves are most sensitive to wind speed variations.

All of the test results are presented in the same manner in the following graphs. The statistical test result is presented on the y-axis, with the eight measurement datasets on the x-axis. There are four results per site; one for each of the mesoscale models. The results are also presented in table form, with the best results highlighted in green for each comparison.

Correlation

The wind speed correlation is high for all datasets, achieving correlation coefficients of over 90% in almost all cases. The KNMI KNW results are consistently highest. The lowest correlation coefficients are found for the lowest measurement height at OWEZ and at Lichteiland Goeree.

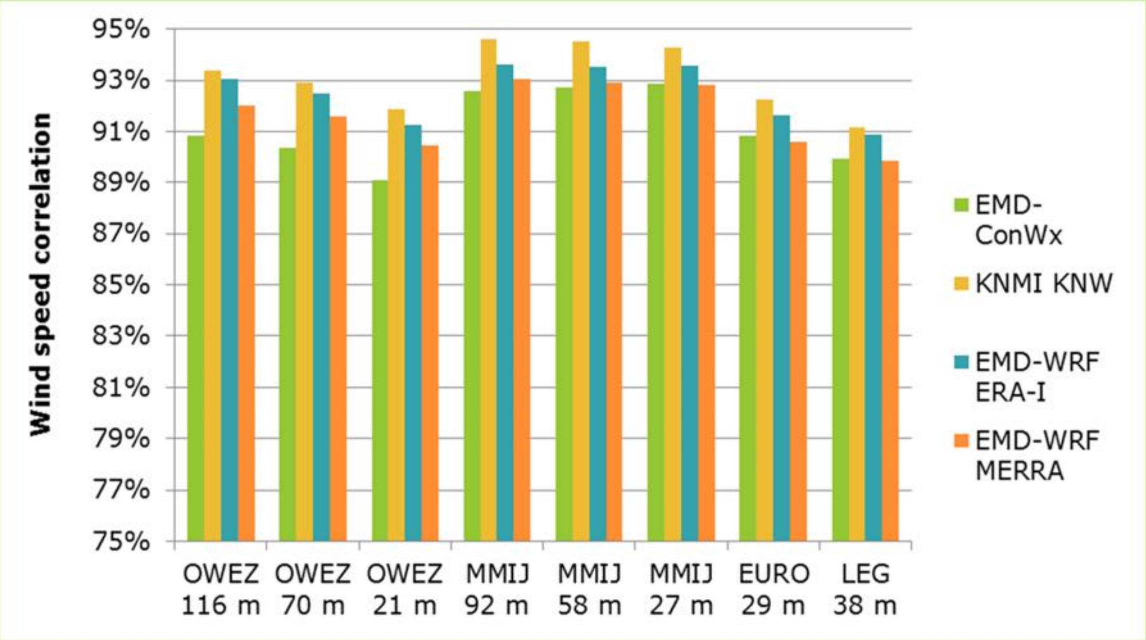

Figure 36 – Wind speed correlation coefficients, between mesoscale and measured datasets

Table 33 – Wind speed correlation coefficients
(best highlighted in green)

	EMD-ConWx	KNMI KNW	EMD-WRF ERA-I	EMD-WRF MERRA
OWEZ 116 m	91%	93%	93%	92%
OWEZ 70 m	90%	93%	92%	92%
OWEZ 21 m	89%	92%	91%	90%
MMIJ 92 m	93%	95%	94%	93%
MMIJ 58 m	93%	95%	94%	93%
MMIJ 27 m	93%	94%	94%	93%
EURO 29 m	91%	92%	92%	91%
LEG 38 m	90%	91%	91%	90%

Similarly, the wind direction correlation coefficients are high, exceeding 85% in all cases. The differences between datasets are minimal, although KNMI KNW results are always highest.

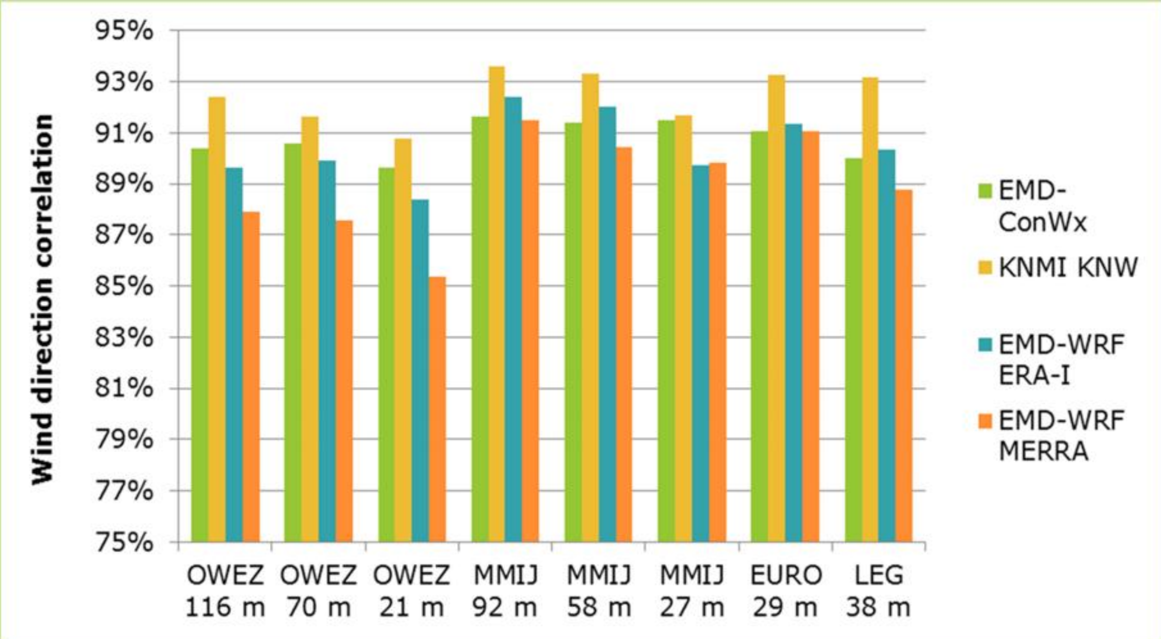

Figure 37 – Wind direction correlation coefficients (circular), between mesoscale and measured datasets

Table 34 – Wind direction correlation coefficients (best highlighted in green)

	EMD-ConWx	KNMI KNW	EMD-WRF ERA-I	EMD-WRF MERRA
OWEZ 116 m	90%	92%	90%	88%
OWEZ 70 m	91%	92%	90%	88%
OWEZ 21 m	90%	91%	88%	85%
MMIJ 92 m	92%	94%	92%	92%
MMIJ 58 m	91%	93%	92%	90%
MMIJ 27 m	91%	92%	90%	90%
EURO 29 m	91%	93%	91%	91%
LEG 38 m	90%	93%	90%	89%

Mean difference in wind speed (bias)

The bias is negative in all cases, and smallest for the EMD-ConWx and KNMI KNW data meaning that all mesoscale datasets underestimate the measured wind speed. The EMD-ConWx biases are lowest at OWEZ and Europlatform, while KNMI KNW is lowest at Meteomast IJmuiden and Lichteiland Goeree.

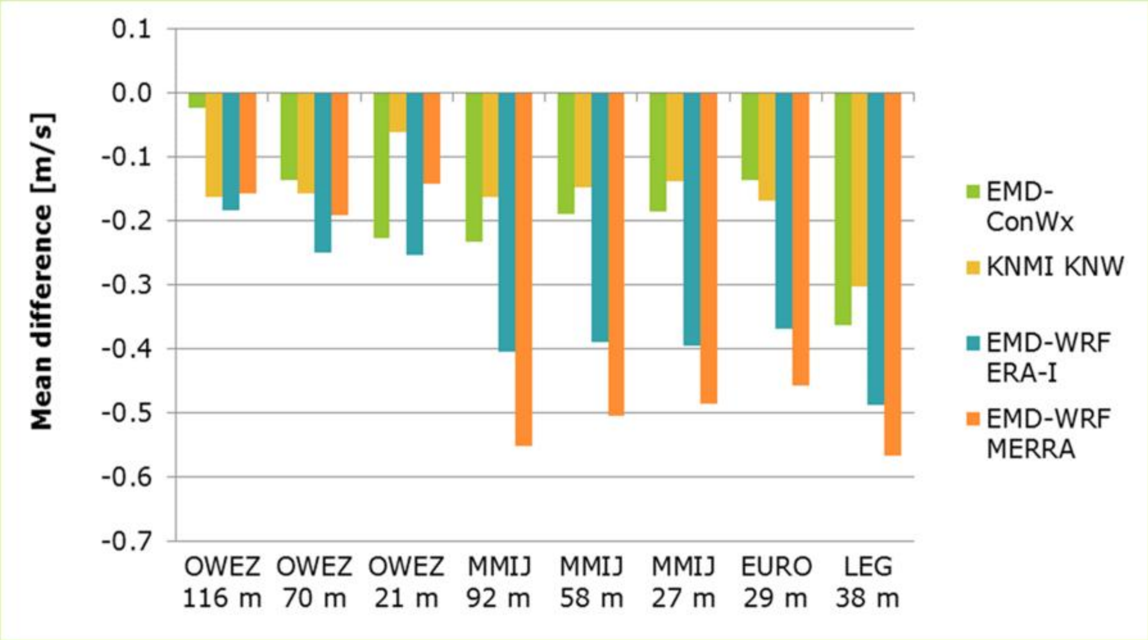

Figure 38 – Mean difference in wind speed (bias) between mesoscale and measured datasets

Table 35 – Mean difference in wind speed (bias) [m/s]
(best highlighted in green)

	EMD-ConWx	KNMI KNW	EMD-WRF ERA-I	EMD-WRF MERRA
OWEZ 116 m	0.0	-0.2	-0.2	-0.2
OWEZ 70 m	-0.1	-0.2	-0.2	-0.2
OWEZ 21 m	-0.2	-0.1	-0.3	-0.1
MMIJ 92 m	-0.2	-0.2	-0.4	-0.6
MMIJ 58 m	-0.2	-0.1	-0.4	-0.5
MMIJ 27 m	-0.2	-0.1	-0.4	-0.5
EURO 29 m	-0.1	-0.2	-0.4	-0.5
LEG 38 m	-0.4	-0.3	-0.5	-0.6

There is little to distinguish the model performance in terms of mean absolute difference in wind speed. The models all achieve similar levels of mean absolute difference, in the range of about 1.1-1.3 m/s (up to 1.4 m/s for Lichteiland Goeree). The KNMI KNW mesoscale model consistently has the lowest mean absolute difference.

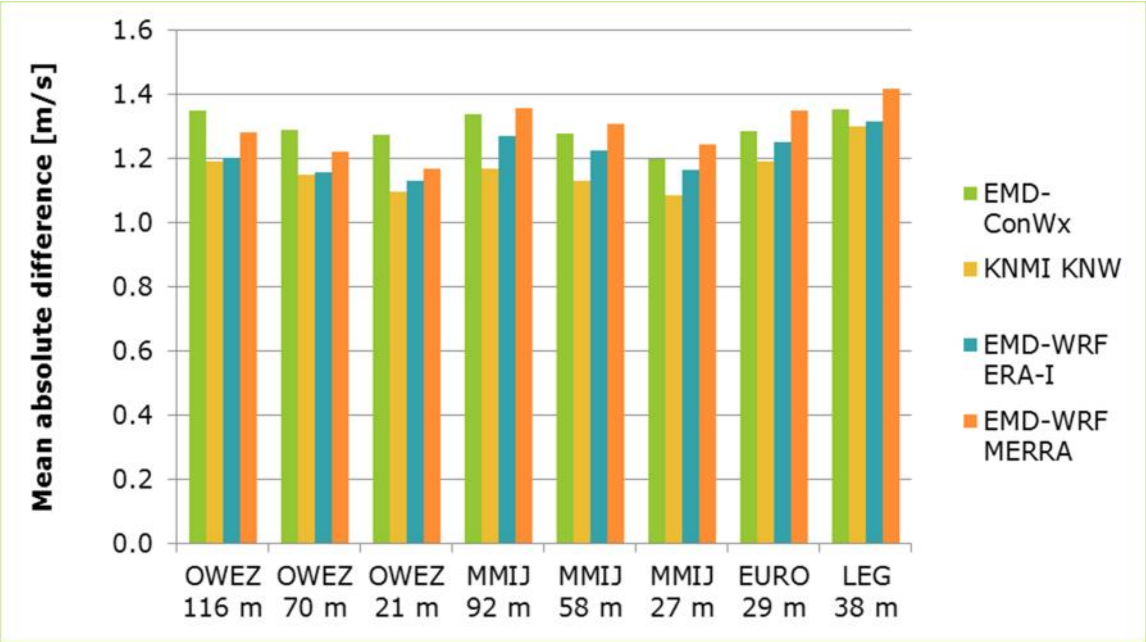

Figure 39 – Mean absolute difference in wind speed between mesoscale and measured datasets

Table 36 – Mean absolute difference in wind speed [m/s]
(best highlighted in green)

	EMD-ConWx	KNMI KNW	EMD-WRF ERA-I	EMD-WRF MERRA
OWEZ 116 m	1.4	1.2	1.2	1.3
OWEZ 70 m	1.3	1.2	1.2	1.2
OWEZ 21 m	1.3	1.1	1.1	1.2
MMIJ 92 m	1.3	1.2	1.3	1.4
MMIJ 58 m	1.3	1.1	1.2	1.3
MMIJ 27 m	1.2	1.1	1.2	1.2
EURO 29 m	1.3	1.2	1.3	1.3
LEG 38 m	1.4	1.3	1.3	1.4

Tests of wind speed distribution

The results of the Kolmogorov-Smirnov tests show that the EMD-ConWx model has the best fit at OWEZ, Lichteiland Goeree and Europlatform, while KNMI KNW has the best fit at Meteomast IJmuiden. The test statistics for those two models are generally low, between 2-4% for all comparisons. The EMD-WRF datasets show a relatively poor fit, with test statistics of 4-7%.

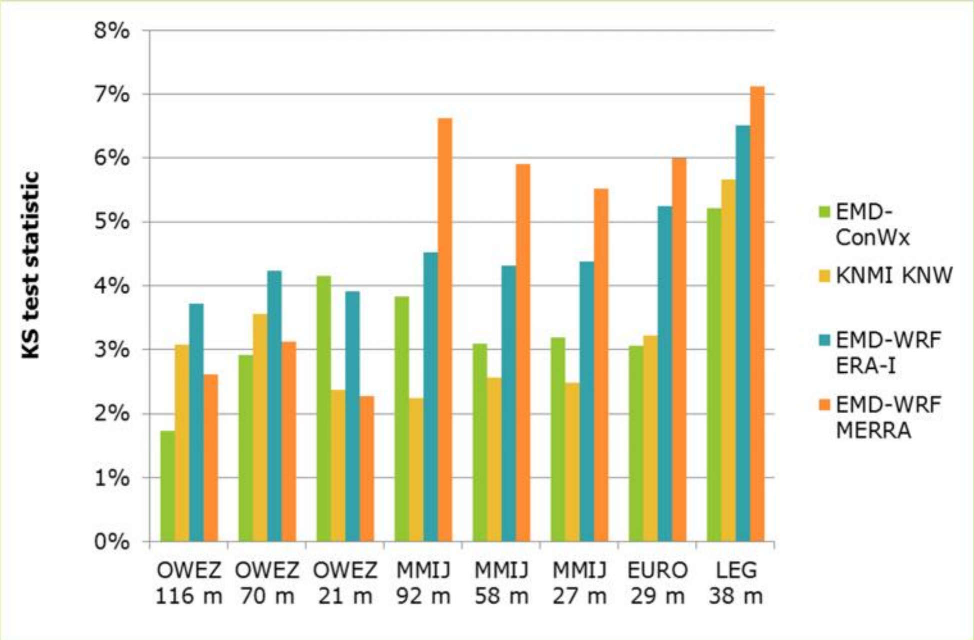

Figure 40 – Two-sample Kolmogorov–Smirnov test statistic for wind speed distributions between mesoscale and measured datasets

Table 37 – Two-sample Kolmogorov–Smirnov test statistic for wind speed distributions (best highlighted in green)

	EMD-ConWx	KNMI KNW	EMD-WRF ERA-I	EMD-WRF MERRA
OWEZ 116 m	2%	3%	4%	3%
OWEZ 70 m	3%	4%	4%	3%
OWEZ 21 m	4%	2%	4%	2%
MMIJ 92 m	4%	2%	5%	7%
MMIJ 58 m	3%	3%	4%	6%
MMIJ 27 m	3%	2%	4%	6%
EURO 29 m	3%	3%	5%	6%
LEG 38 m	5%	6%	7%	7%

The EMD-ConWx data consistently performs best in the test of difference in energy yield. As seen in the graph below, the difference is ±2% in most comparisons and less than 6% in all cases. The KNMI KNW model shows similar difference levels, between 2-4% in most comparisons.

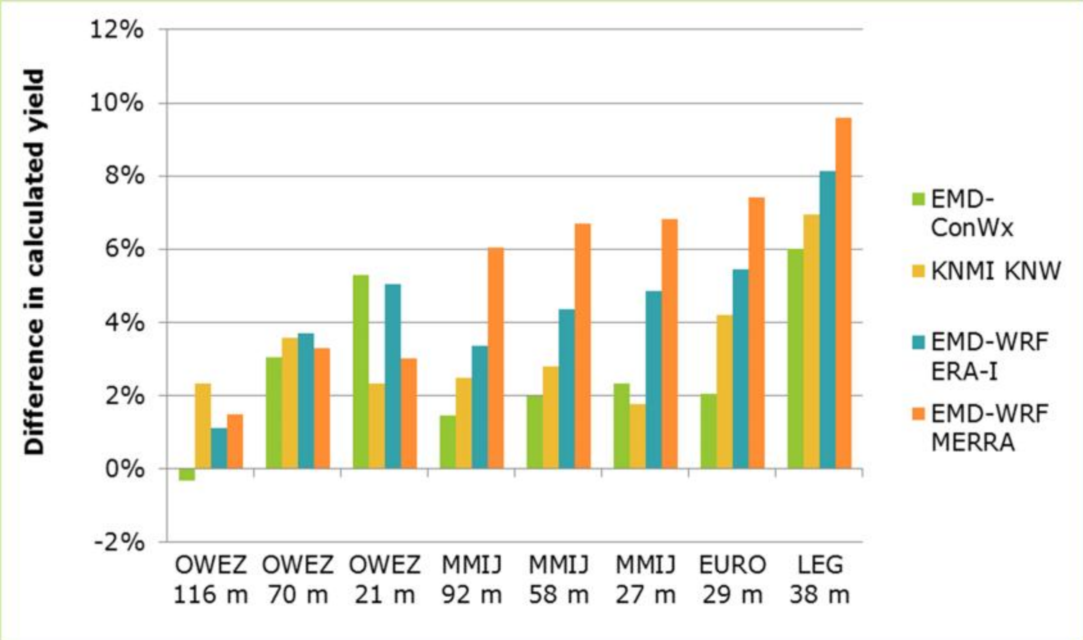

Figure 41 – Difference in calculated energy yield between mesoscale and measured datasets

Table 38 – Difference in calculated energy yield (best highlighted in green)

	EMD-ConWx	KNMI KNW	EMD-WRF ERA-I	EMD-WRF MERRA
OWEZ 116 m	0%	2%	1%	1%
OWEZ 70 m	3%	4%	4%	3%
OWEZ 21 m	5%	2%	5%	3%
MMIJ 92 m	1%	2%	3%	6%
MMIJ 58 m	2%	3%	4%	7%
MMIJ 27 m	2%	2%	5%	7%
EURO 29 m	2%	4%	5%	7%
LEG 38 m	6%	7%	8%	10%

Conclusions

This validation analysis has shown that the EMD-ConWx and KNMI KNW mesoscale model datasets represent reasonably well the wind speeds at the four measurement locations. The KNMI KNW model performs slightly better in terms of correlation, bias and mean absolute error. The EMD-ConWx datasets have slightly more accurate distributions, as demonstrated with low Kolmogorov-Smirnov test statistics and difference in energy yield tests. The results of the comparisons show that either model could be suitable for use in horizontal extrapolation to the Borssele wind farm zone.

Based on this evaluation, and relatively better shear modelling at the measurement locations, it was decided to use the KNMI KNW datasets (based on ERA-Interim input data) as the mesoscale model for this wind resource assessment for the Borssele offshore wind farm zone.

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Appendix E Cross-prediction using KNW mesoscale model

The four offshore measurement datasets, described in Chapter 2, are used to test the accuracy of the horizontal extrapolation using the KNW mesoscale model. First, the four datasets are extrapolated to a hub-height, long-term wind climate estimate at each location, using the same method as in Chapter 3. The results of each calculation are shown below for the four datasets. Finally, a cross-prediction exercise is performed to assess the accuracy of horizontal extrapolation from each measurement location to the other three sites.

The calculated mean wind speed at 100 m height, and the associated uncertainty in vertical extrapolation is shown in Table 39 for all measurement datasets.

Table 39 – Extrapolation of wind speed measurements to height of 100 m

	Europlatform	Lichteiland Goeree	OWEZ	Meteomast IJmuiden
Selected measurement period	01/01/2004 – 31/12/2013	01/01/2004 – 31/12/2013	01/07/2005 – 30/06/2006	01/01/2012 – 31/12/2014
Measurement height	29.1 m	38.3 m	70 m	92 m
Data availability [%]	98.2%	98.7%	95.7%	98.8%
Measured mean wind speed at measurement height [m/s]	8.69	8.75	8.65	9.88
Resulting mean wind speed at 100 m [m/s]	9.72	9.57	8.96	9.96
Estimated uncertainty in vertical extrapolation [%]	3.9%	3.1%	0.3%	0.3%

The KNMI datasets are based on a 10-year period, so no correction is required for the long-term. The other datasets are extended to cover the same 10-year period, by means of an MCP procedure with the KNW mesoscale data from the co-located grid point.

The datasets were first compared within Windographer. A number of different statistical algorithms were tested, by using one half of the measured data to predict the data for the remaining half, then comparing the errors in the prediction. The lowest error was found following the 'Orthogonal Least Squares' method with 12 sectors. This a method of correlating target and reference speed data that minimizes the orthogonal distance to the line of best fit in order to generate the predicted wind speed data [12].

As a result of the long-term correction, the OWEZ mean wind speeds increase by about 4.5%, while leading to a minor decrease for the Meteomast IJmuiden dataset. As explained in Section 3.2, it was therefore decided to use the 3-year dataset from Meteomast IJmuiden, rather than introduce a long-term correction.

The uncertainty in the MCP procedure can be estimated based on the distribution error in the mesoscale model (see Appendix D, estimated to be 2.2%) together with the jack-knife estimate of variance, which considers the variability of results when subsequent subsets of the data are removed from the analysis. The calculated jack-knife uncertainty in the MCP procedure is found to be 0.7% for the OWEZ dataset.

The calculated long-term mean wind speed at 100 m height, and the associated uncertainty in long-term correction is shown in Table 40 for all measurement datasets.

Table 40 – Long-term extrapolation of wind speed measurements

	Europlatform	Lichteiland Goeree	OWEZ	Meteomast IJmuiden
Selected measurement period (short-term)	01/01/2004 – 31/12/2013	01/01/2004 – 31/12/2013	01/07/2005 – 30/06/2006	01/01/2012 – 31/12/2014
Mean wind speed at 100 m (short-term) [m/s]	9.72	9.57	8.96	9.96
Long-term corrected mean wind speed (2004-2013) [m/s]	9.7	9.6	9.4	10.0
Estimated uncertainty in long-term correction [%]	0%	0%	2.2%	0%
Estimated uncertainty in long term representation [%]	1.9%	1.9%	1.9%	3.5%

A correction factor is then calculated based on the relative difference in mean wind speeds between the KNW mesoscale mode grid points nearest to each measurement point. This allows for the extrapolation of wind speeds at each location to the other three measurement sites. The calculated value is then compared to the wind speeds in Table 40, and the relative error is shown in Table 41.

Table 41 – Cross-prediction error in horizontal extrapolation of wind speed measurements

Reference dataset	Extrapolation to Europlatform	Extrapolation to Lichteiland Goeree	Extrapolation to OWEZ	Extrapolation to Meteomast IJmuiden
Europlatform	x	-1.8%	1.3%	0.8%
Lichteiland Goeree	1.8%	x	3.2%	2.6%
OWEZ	-1.3%	-3.1%	x	-0.6%
Meteomast IJmuiden	-0.8%	-2.6%	0.6%	x

The uncertainty in horizontal extrapolation using the KNW mesoscale model is then estimated based on a combination of the largest absolute deviation in Table 41 and an estimated factor relating to the uncertainty of this exercise. The uncertainty in horizontal extrapolation, based on this cross-prediction, is found to be 3.1% - 4.1%, as seen in Table 42.

This detailed assessment of the four datasets also allows for a comparison of the predicted wind speeds at the Borssele zone centre. As described in Chapter 3, the wind speeds at each measurement location are extrapolated to the Borssele zone, with the results shown in Table 42.

Table 42 – Horizontal extrapolation of wind speed measurements

	Europlatform	Lichteiland Goeree	OWEZ	Meteomast IJmuiden
Estimated uncertainty in horizontal extrapolation [%]	3.1%	4.1%	4.0%	3.6%
Long-term mean wind speed at measurement location [m/s]	9.7	9.6	9.4	10.0
Ratio of mean wind speeds in mesoscale model, between Borssele zone centre and measurement location	-0.8%	2.5%	4.4%	-3.8%
Calculated long-term hub-height mean wind speed at Borssele zone centre [m/s]	9.6	9.8	9.5	9.6
Estimated uncertainty in horizontal extrapolation [%]	3.1%	4.1%	4.0%	3.6%

The calculated wind speed at the Borssele zone is shown in Table 43 for the four possible data sources, along with the associated uncertainty. It is worthwhile noting that these four estimates are in close agreement, within ±2.5% of the Meteomast IJmuiden result. This uncertainty analysis shows that the best primary data source for this wind resource assessment is the Meteomast IJmuiden mast, which allows for an uncertainty of approximately 5%.

Table 43 – Calculated mean wind speed at Borssele wind farm zone and the associated uncertainty

	Europlatform	Lichteiland Goeree	OWEZ	Meteomast IJmuiden
Calculated mean wind speed at Borssele wind farm zone and the associated uncertainty [m/s]	9.6 ± 0.9	9.8 ± 0.9	9.5 ± 0.6	9.6 ± 0.5

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Appendix F Uncertainties

Uncertainties – Wind speed

Wind statistics

Measurement errors can be affected by the quality of the instruments, the calibration process, the meteorological mast design, data coverage and data processing.

Traceability of the wind data is an important factor in assessing the quality of the wind statistics. Highly traceable data allows for a precise analysis of uncertainties, while more uncertainty must be attributed to poorly traceable data.

Long term representation

The annual variability of wind speed leads to an uncertainty in the long-term representation of short-term measurements. The standard error for a single year of measurements has been statistically determined to be 5.5% (based on a large number of Dutch meteorological stations) and 6% (based on stations throughout Europe). Therefore, the standard error in measurements with a longer duration can be approximated as: $\sigma = 6\%/\sqrt{y}$.

If MCP methods were used to extend a short-term time series, an additional uncertainty should be added to account for errors in this process.

Horizontal extrapolation

The accuracy in the horizontal extrapolation of wind speeds depends primarily on the complexity of the terrain and the distance between the measurement site and the wind turbines.

Vertical extrapolation

In order to minimise errors in vertical extrapolation, the measurement height should be close to the proposed hub height. Using a met mast with multiple instrument heights, it is possible to verify the vertical profile and estimate the uncertainties.

Larger uncertainties are inherent using measurements at the WMO standard height of 10 m (for instance, masts at airports or meteorological stations). The vertical profile is highly dependent on the surface roughness description, as well as the accuracy of the measurement height.

Other

This uncertainty can cover any additional errors related to wind speed.

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