Europlatform, 2016 – 2023

Offshore wind resources at the North Sea

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Energy & Materials
Transition
www.tno.nl
+31 88 866 50 65
info@tno.nl

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Author(s)	D. A. J. Wouters C. B. H. Eeckels E. T. G. Bot J. P. Verhoef G. Bergman P. A. Van der Werff
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- Power performance measurements conform to IEC 61400-12-1, MEASNET Power Performance measurement procedure, FGW TR2, FGW TR5
- NTF/NPC measurements conform to IEC 61400-12-2
- Mechanical loads measurements conform to IEC 61400-13
- Meteorological measurements (wind speed, wind direction, temperature, air pressure and relative humidity) conform to IEC 61400-50-1
- Verification of ground-based or nacelle-mounted Remote Sensing Devices conform to IEC 61400-50-2
- Verification of Floating Lidar Systems conform to IEC 61400-50-2 and IEA Recommended Practices 18

Summary

The Netherlands has set clear ambitions to accelerate the energy transition. By 2050 all energy used in the country shall come from sustainable sources and offshore wind energy plays a vital role in the transition to a carbon-free energy supply. The government has defined a roadmap for the Dutch offshore wind portfolio aiming to add 4.5 GW by 2023 as a first phase, to further expand to 21 GW by 2030. The Netherlands is moving ahead with almost yearly tendering rounds for upcoming development areas. New developments have been started for the search areas *Ten noorden van de Waddeneilanden* Wind Farm Zone.

TNO has been performing offshore wind measurement campaigns at strategic locations in the North Sea since 2011 with the installation and data management of both a 100-meter meteorological mast and a co-located lidar situated 75 km west of IJmuiden. From 2014 onwards, TNO has further organized wind measurement campaigns with lidars on offshore platforms for the Dutch Ministry of Economic Affairs and Climate Policy. These campaigns are part of the *Wind op Zee* project to support the Dutch wind offshore roadmap. They consist of three long-standing locations: Lichteiland Goeree (LEG), Europlatform (EPL) and Wintershall platform K13-A. Since 15 March 2023 a lidar has been deployed for wind measurements at a fourth platform, L2-FA-1, located north of the Wadden Islands. TNO is accredited for performing these measurements in accordance with IEC 61400-50-2.

This report refers to the measurement campaign at the EPL platform where a ZX300 has been deployed, providing high quality data since 2016. The data are publicly available to be used for further purposes (offshorewind-measurements.tno.nl).

At the EPL platform, the wind analysis for the 2016 - 2023 period shows that the wind profiles are dominated by the regional climate, mainly by the positive phase effect of the North Atlantic Oscillation. The prevailing wind direction is from the southwest. The average wind speed ranges from 9.06 m/s at the lowest measurement height of 63 m up to 10.29 m/s at 291 m.

The Weibull distribution, which describes the probability distribution of the measured wind speeds, shows shape and scale parameters that are typical for the North Sea (k = 2.081 and c = 11.01 m/s at 141 m height).

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Abbreviations

EPL	Europlatform
GWO	Global Wind Organisation
HUET	helicopter underwater escape training
kde	kernel density estimate
KNMI	Koninklijk Nederlands Meteorologisch Instituut (Royal Netherlands Meteorological Institute)
LEG	Lichteiland Goeree
MMIJ	meteorological mast IJmuiden
MoMM	mean of monthly means
OWEZ	Offshore Windpark Egmond aan Zee (Offshore wind farm Egmond aan Zee)
pdf	probability density function
RI&E	risico-inventarisatie en evaluatie (risk-assessment and evaluation)
UTC	coordinated universal time
WRA	wind resource assessment

1 Introduction

The Netherlands has set clear ambitions to accelerate the energy transition. By 2050 all energy used in the country shall come from sustainable sources and offshore wind energy plays a vital role in the transition to a carbon-free energy supply [1]. The government has defined a roadmap for the Dutch offshore wind portfolio to reach 21 GW by 2030 [2][1]. The intermediate milestone of reaching 4.5 GW by 2023 has been reached with an installed capacity of 4.7 GW in the Dutch part of the North Sea. The Netherlands is moving ahead with almost yearly tendering rounds for upcoming development areas such as Hollandse Kust West and *Ten noorden van de Waddeneilanden* Wind Farm Zone.

To reach such ambitious realization of operational offshore wind farms in the Dutch part of the North Sea, importance must be given to both spatial planning, and characterization of this precious, valuable and variable resource in order to ensure profitability and an overall sound business case.

One crucial requirement to evaluate the financing of an offshore wind farm is the wind resource assessment (WRA) of a given site. Accurate long-term offshore wind measurements allow for improved WRAs which reduce uncertainties and increase the financial success of these projects. This increases the trust between interested stakeholders including developers, consultants, the financial community, the government and policymakers. At the same time it allows the selection and identification of strategic locations.

TNO has been performing offshore wind measurement campaigns at strategic locations in the North Sea since 2011 with the installation and data management of both a 100-meter meteorological mast and a co-located lidar situated 75 km west of IJmuiden. From 2014 onwards, TNO has further organized wind measurement campaigns with lidars on offshore platforms for the Dutch Ministry of Economic Affairs and Climate Policy. These campaigns are part of the *Wind op Zee* project to support the Dutch wind offshore roadmap. They consist of three longstanding locations: Lichteiland Goeree (LEG), Europlatform (EPL) and Wintershall platform K13-A. Since March 2023 a lidar has been deployed for wind measurements at a fourth platform, L2-FA-1, located north of the Frisian Islands (figure 1.1). TNO is accredited for performing these measurements in accordance with IEC 61400-50-2 [3].

This report will focus on the wind conditions characterization of the EPL platform, located about 60 km west from the coast of Hoek van Holland.

[1] On 14 May 2024, an updated planning was published indicating a new end date to 2032.

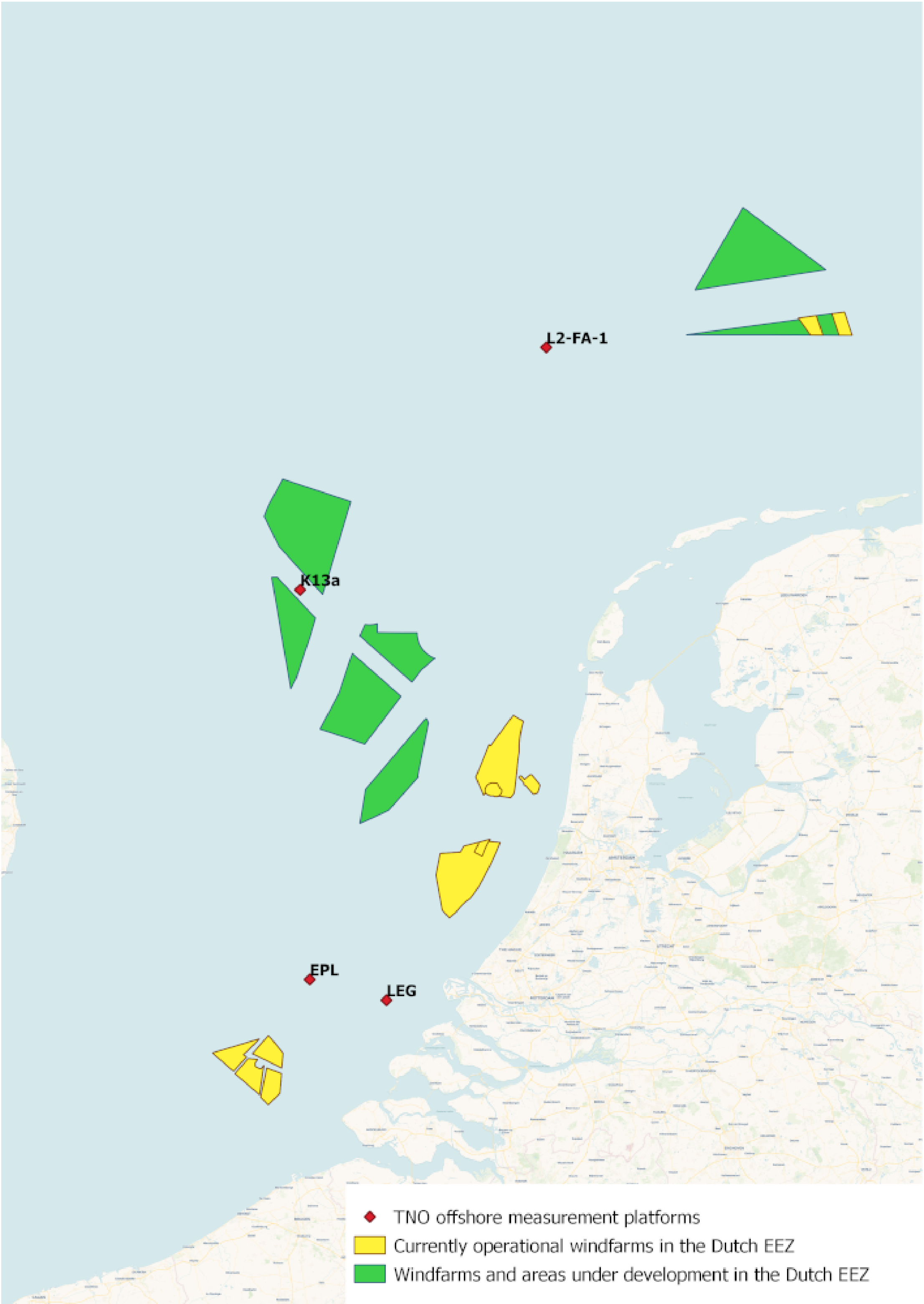

Figure 1.1: TNO long-term offshore wind measurement campaign locations at Lichteiland Goeree (LEG), Europlatform (EPL), Wintershall platform K13-A (K13a) and L2-FA-1, along with wind farm development zones in the Dutch North Sea.

2 Wind measurement campaigns at the North Sea

2.1 TNO's leading role in wind conditions measuring campaigns

Before the introduction of lidars in offshore wind resource assessments, meteorological masts have been widely used at TNO with examples such as the meteorological mast at IJmuiden (MMIJ), and the meteorological mast at the Offshore wind farm Egmond aan Zee (OWEZ).

Onshore measurement campaigns are also part of the activities of TNO for more than 20 years, including independent ISO 17025 and IECRE based measurements (power performance, mechanical loads, meteorological measurements, remote sensing device verification and floating lidar verification) to support wind turbine prototype certification from small (330 kW) to larger turbines (>10 MW). During the measurement campaign, TNO is responsible for the entire life cycle: from selection of the instrumentation and planning the installation, to the purchase, validation, installation, and maintenance of the lidar, as also analyzing, reporting and dissemination of the data.

2.2 Open-access and public datasets

Since 2020 TNO has published annual reports on the wind conditions for the EPL location, see table 2.1. These reports are available at offshorewind-measurements.tno.nl. This report includes the specific wind conditions for the period 2016 - 2023 at the EPL platform. This report has been updated with improved practices for deducing the wind direction, wind veer and wind shear.

Table 2.1: Publication history of wind conditions at EPL

Period	Report
2016 – 2019	TNO 2020 R10551 [4]
2016 – 2020	TNO 2021 R10919 [5]
2016 – 2021	TNO 2022 R10909 [6]
2016 – 2022	TNO 2023 R10578 [7]

The data measured in the *Wind op Zee* project are retrieved and post-processed before making the information publicly accessible through the web-service nimbus.windopzee.net. Post-processed data are reported each month for verification purposes. Users can download the data after free registration.

To use *Wind op Zee* measured data in publications, further research or commercial purposes, users must acknowledge the use of the data as:

1. citation to the instrumentation report *with the type of data used, location and date*:

```
author      = {Bergman, G. and Verhoef, J. P. and van der Werff, P. A.},
```

```
institution = {TNO},
title       = {Europlatform LiDAR measurement campaign},
subtitle    = {Instrumentation Report 2022},
number      = {TNO 2022 R10766},
date        = {2022-07-28},
url         = {https://publications.tno.nl/publication/34642708/dWsxDcst/TNO-2024-R10960.pdf},
```

2. citation to this report:

```
author      = {Wouters, D. A. J. and Eeckels, C. B. H. and Bot, E. T. G. and Verhoef, J. P.
               and Bergman, G. and van der Werff, P. A.},
institution = {TNO},
title       = {Offshore wind resources at the North Sea},
subtitle    = {Europlatform, 2016 - 2023},
number      = {TNO 2024 R11675},
```

The publication date at which the data have last been accessed must be indicated along the citations, e.g. “Last accessed November 2024”.

The data is shared in .csv format. In the case of the EPL measurement campaign please adhere to the following information:

- offshorewind-measurements.tno.nl/en/measurement-locations/europlatform-epl/
- For monthly files use: `EPL-yyyy-mm.csv`.
- After a quarter of a year is completed the monthly files will be replaced by `EPL-yyyy-Qx.csv`.
- After a year is completed the quarterly files will be replaced by a yearly file `EPL-yyyy.csv`.

3 Measurement campaign at EPL

3.1 Location, lidar installation and operation

The Europlatform (EPL) is located about 60 km from the coast of Hoek van Holland, see figure 1.1. It includes a helicopter pad and an accommodation deck (see figure 3.2). The platform is part of the North Sea Monitoring Network consisting of several permanent monitoring locations over the North Sea. Since its installation in 2016, TNO has been conducting an ongoing measurement campaign at EPL, and has accumulated meteorological data, knowledge about installation practices, maintenance, replacement, and observations of weather conditions that have occurred at the site. Figure 3.2 shows the lidar at its location on the platform.

On this platform, the Dutch national weather service (KNMI) and Rijkswaterstaat, (both part of the Dutch Ministry of Infrastructure and Water Management) coordinate activities for collection of meteorological information (including the air pressure, wind speed and direction, air temperature, relative humidity and visibility) and oceanographic data (water level, temperature and height) as well.

The lidar at EPL is a ZX300. The instrument measures wind profiles at up to 10 different heights by conically emitting a laser beam into the air, even if an object blocks the laser beam at some positions (see appendix A for additional lidar specifications). Before the lidar was installed at the EPL platform, it was calibrated, see latest calibration report [8].

At EPL, the lidar is installed at the west side of the platform on an extension built between the landing and the deck, see figure 3.2. The lidar provides both wind speed and direction measurements at 10 different heights between 63 m and 291 m above MSL. The data is timestamped at the start of the 10-minute interval. This is the same configuration as for the lidars at other measurement locations like the LEG, K13-A and L2-FA-1 platforms. The manufacturer guarantees data quality up to 300 m.

As defined by TNO's ISO 17025 quality system, the lidar should be serviced after one year of operation and replaced every two years, see table 3.1. All operational aspects with respect to installing and maintaining the lidar are recorded in a logbook of the team responsible for the measurement campaign.

Table 3.1: Replacements of lidars at the EPL platform

Lidar ID	TNO code	Operational period	Reason for replacement
308	94012680	10-05-2016 to 10-08-2018	Periodic replacement
315	94012681	10-08-2018 to 23-10-2019	Power failure
308	94012680	23-10-2019 to 22-03-2022	Periodic replacement
315	94012681	22-03-2022 to present	

During 2023, there were no observed events that would suggest downtime and reduce data availability.

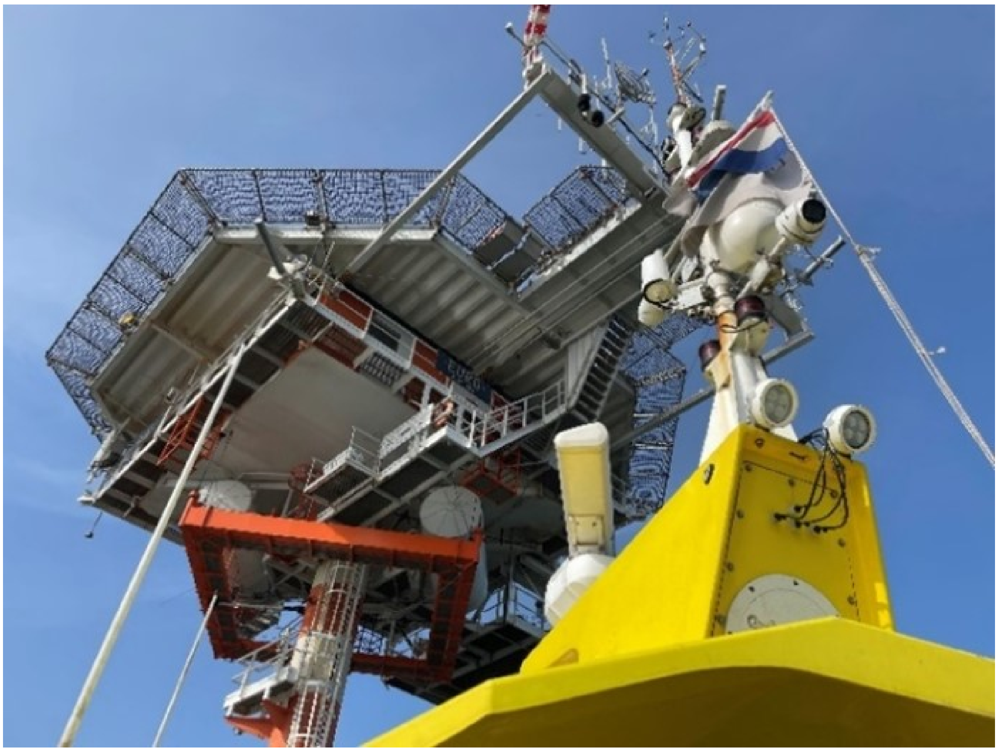

Figure 3.1: Europlatform

Figure 3.2: Lidar unit at EPL

3.2 Health and safety measures

Health, safety and environment are main priorities at TNO. TNO follows a strict program to train the employees for the measurement campaigns. Additional agreed safety measures with Rijkswaterstaat for the safe installation of the frame and the lidar were:

- A job-risk-assessment (AD-130, project RI&E) is made and signed by both parties involved.
- Toolbox meetings among the teams to agree on the alignment of the preparation at the platform.
- TNO employees have valid GWO certificates, proving that they know how to work safely. TNO employees working on the platform will wear fall-arrest systems, helmets and safety shoes.
- TNO employees have valid HUET certificates (only in case of a helicopter visit).

3.3 Lidar performance assessment at EPL

Remote sensing devices bring many advantages such as ease of transportation and measurement capabilities beyond meteorological mast configurations. However, these devices are exposed to harsh environmental conditions offshore and therefore measurements can be impacted. The performance and quality of the data recorded by lidars during a measurement campaign can be impacted by defective or damaged sensors and cables, other system malfunctions, and also by severe meteorological events. All of these events can lower the data availability of the lidar. For this reason, the need for continuous quality assurance and control techniques is paramount during the measurement campaign. The heights considered are 63 m, 91 m, 116 m, 141 m, 166 m, 191 m, 216 m, 241 m, 266 m and 291 m, w.r.t. MSL.

The data is measured on a 10-minute basis. The data collection period started in May 2016. This report considers the measurement period until 31 December 2023 at 23:50 UTC. The campaign is still ongoing, with future yearly assessments envisioned.

Data over the whole period of the measurement campaign has been analysed in previous reports. The data availability depends on the height of the measurements, and manufacturers will typically suggest usage of the lidar up to a certain height. As indicated in table 3.3 and figure 3.3, the data available for heights up to 200 m is on average above 75 %, while further up to 241 m the availability decreases to 71 %, and to 67 % at the 291 m height. The decrease in data availability and coverage with increasing measurement height is mainly due to the lower concentration of aerosols in the air, which implies that there are less moving particles that the device can detect at those heights.

During the measurement campaign, data verification is performed at different levels with quality checks carried out on a daily basis, using daily plots (see example in appendix A). Lead engineers check the signals for deviations or failures to be able to react on a short notice. During these checks, no data filtering is applied on the data availability. As mentioned before, data availability refers to the number of valid data readings within an interval of 10 minutes.

There are complementary reports with data verification comparing with other measurements. In particular, [9] examines the wind speed and direction measurement campaigns at eight offshore measurement locations distributed throughout the North Sea, including the EPL platform. The study focuses on comparing the wind shear and veer from 2012 to the first quarter of 2018 with the aim of better understanding the wind conditions at the North Sea. The analysis is also a part of the data verification.

Table 3.2: List of variables measured by the lidar. HXXX are the different measurement heights w.r.t. MSL: 63 m, 91 m, 116 m, 141 m, 166 m, 191 m, 216 m, 241 m, 266 m and 291 m

Acronym	Signal name	Units
EPL_batvoltage	battery voltage	V
EPL_tempcpu	CPU temperature inside the lidar	°C
EPL_humpod	relative humidity inside the lidar	%
EPL_bearing	lidar bearing	°
EPL_tilt	lidar tilt angle	°
EPL_pair	air pressure at lidar position	hPa
EPL_wsmet	wind speed measured by lidar meteo station	m/s
EPL_wdmet	wind direction measured by lidar meteo station	°
EPL_HXXX_npts	measuring points	-
EPL_HXXX_missed	missed points	-
EPL_HXXX_npackets	packets in fit	-
EPL_HXXX_Wd	wind direction	°
EPL_HXXX_Wshor_avg	horizontal wind speed average	m/s
EPL_HXXX_Wshor_std	horizontal wind speed standard deviation	m/s
EPL_HXXX_Wshor_min	horizontal wind speed minimum	m/s
EPL_HXXX_Wshor_max	horizontal wind speed maximum	m/s
EPL_HXXX_WsVer_avg	vertical wind speed average	m/s
EPL_HXXX_cs	CS	-
EPL_HXXX_BackScatter	back scatter	-

Table 3.3: Annual lidar data availability. Availability > 85 % is highlighted in blue.

	63 m	91 m	116 m	141 m	166 m	191 m	216 m	241 m	266 m	291 m
2016	91.5	92.3	92.1	92.0	91.9	91.6	91.2	90.9	90.6	89.8
2017	48.6	48.7	48.7	48.5	48.4	48.1	47.9	47.7	47.5	47.1
2018	54.1	54.1	53.9	53.8	53.6	53.5	53.4	53.2	53.1	53.0
2019	48.4	48.4	48.4	48.3	48.1	47.7	47.3	46.8	45.9	44.9
2020	89.1	89.3	89.5	88.7	88.2	87.2	86.0	84.2	81.1	77.3
2021	88.4	87.8	87.5	86.4	85.6	84.1	82.5	80.2	75.8	71.5
2022	94.9	94.7	94.8	94.2	94.0	93.4	92.3	90.1	87.8	85.6
2023	94.3	94.9	94.9	93.6	92.6	91.3	90.0	87.2	84.2	80.5
Overall	75.3	75.4	75.4	74.8	74.4	73.7	72.9	71.5	69.7	67.6

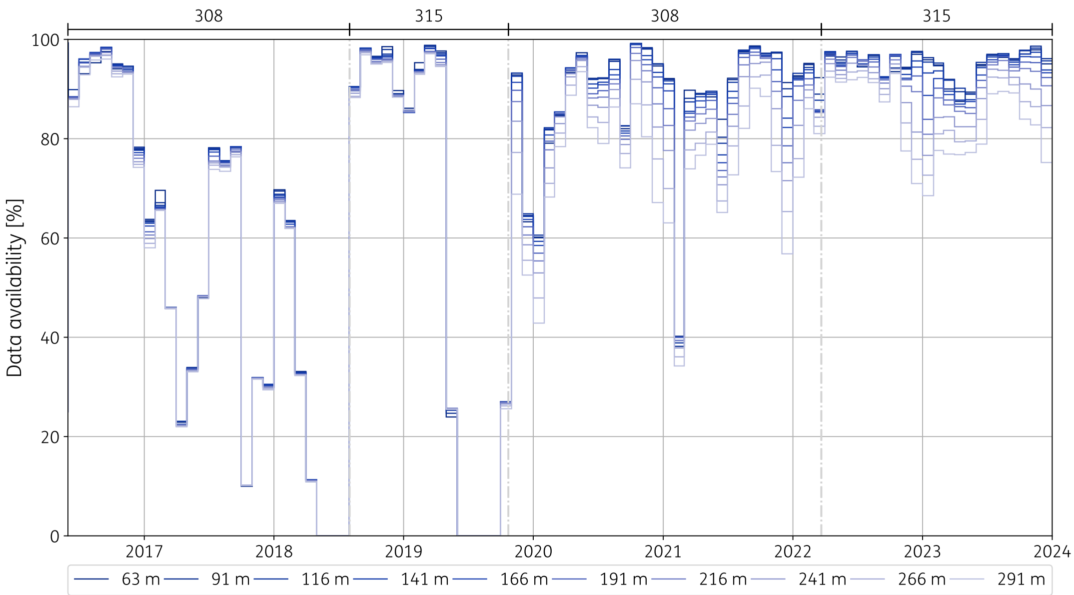

Figure 3.3: Monthly lidar data availability showing the lidar ID's and their operational periods.

4 Wind conditions at EPL

This section presents the results following an assessment of the weather conditions during the entire measurement campaign at EPL. The main meteorological characteristics are presented in the form of wind speed and wind direction distributions at various heights. Shear and veer are also assessed. The annual wind conditions are included in appendix B.

4.1 Distributions

For the presentation of the wind speed and wind direction distributions no filtering is applied besides to the data rejection performed by the lidar itself.

The wind speed distribution is visualised by a kernel density estimate[2] (kde) in figure 4.2 along with its quartiles listed in table 4.1. Annual results are presented in section B.2. In order to mitigate seasonal bias as a result of incomplete years, the mean of monthly means (MoMM) is computed[3]. A Weibull probability density function (pdf) is fitted to the wind speed frequency distribution[4]. The function is given by equation (4.1) and the resulting parameters are listed in table 4.2. Annual results are presented in section B.3. Figure 4.3 shows how well the resulting Weibull pdf matches the actual distribution (kde) for an example height[5].

For the wind direction distribution the MoMM is computed too. The mean direction is computed as the average direction of the wind velocity[6].

The wind speed and wind direction distributions come together in the wind rose, shown in figure 4.1. Annual results are presented in section B.1.

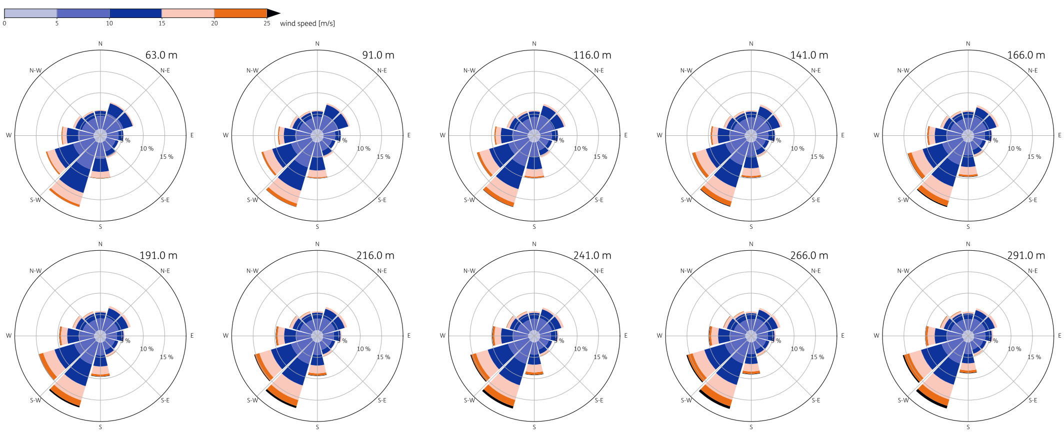

Figure 4.1: Wind roses for the complete measurement campaign

[2]The kde uses a Gaussian kernel with a fixed 0.1 m/s bandwidth.

[3]First the data is categorised according to the 12 months of the year, for each month the mean is computed and finally the mean of the resulting values.

[4]The shape and scale parameters are obtained using maximum likelihood estimation.

[5]The measurement height closest to 141 m is chosen. This height is used as the hub height in section 4.3.

[6]The wind velocities are first averaged per month of the year. Then the 12 resulting vectors are averaged.

Table 4.1: Wind speed and wind direction statistics. The four quartiles of the wind speed distribution are listed, alongside the MoMM wind speed and wind direction. 'N' is the number of valid 10-minute average wind speed samples for each height.

Height	Wind speed						Wind direction
	N	Q_1	median	Q_3	maximum	MoMM	MoMM
m	#	m/s	m/s	m/s	m/s	m/s	°
63	300 577	5.78	8.65	11.93	33.05	9.06	229.7
91	300 941	5.90	8.90	12.39	33.92	9.36	229.2
116	300 740	5.97	9.04	12.66	34.63	9.56	229.3
141	298 567	6.03	9.16	12.88	35.46	9.73	229.6
166	296 826	6.07	9.26	13.06	36.05	9.87	230.1
191	294 133	6.11	9.34	13.22	36.86	9.99	230.5
216	290 789	6.16	9.40	13.36	37.86	10.10	230.9
241	285 430	6.21	9.46	13.47	38.94	10.20	231.5
266	277 974	6.23	9.49	13.57	40.37	10.28	231.8
291	269 663	6.19	9.44	13.56	41.12	10.29	232.6

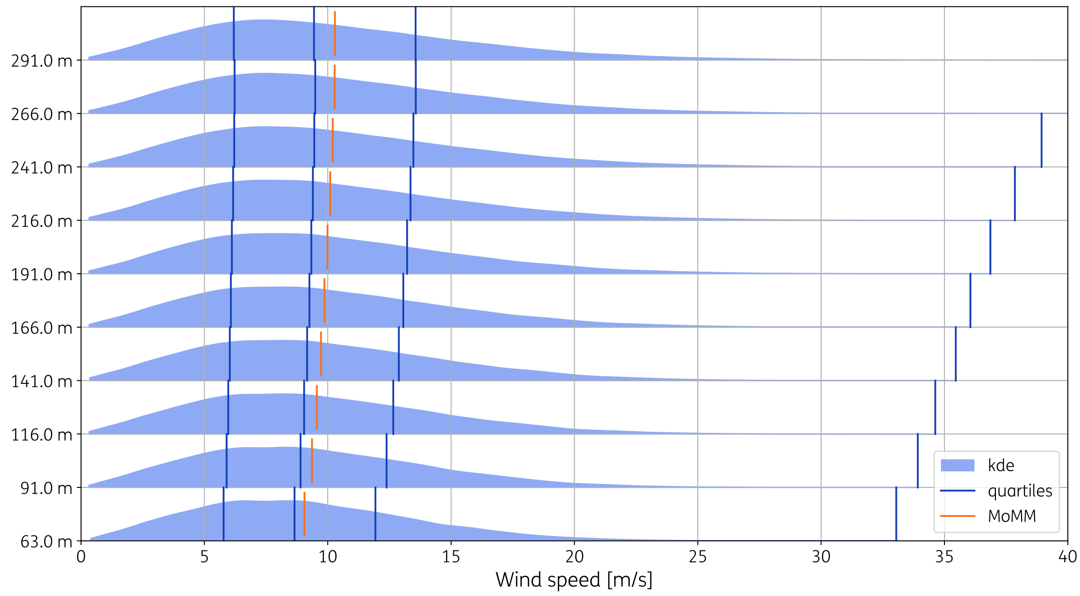

Figure 4.2: Wind speed distributions. The kde is shown with blue markers for the quartiles (Q_1, median, Q_3 and maximum) and an orange marker for the MoMM, as listed in table 4.1.

Table 4.2: Weibull parameters for the wind speed distributions at all heights

Height	Shape (k)	Scale (c)
m	–	m/s
63	2.164	10.28
91	2.133	10.61
116	2.106	10.83
141	2.081	11.01
166	2.057	11.17
191	2.037	11.30
216	2.021	11.42
241	2.008	11.53
266	1.994	11.60
291	1.976	11.60

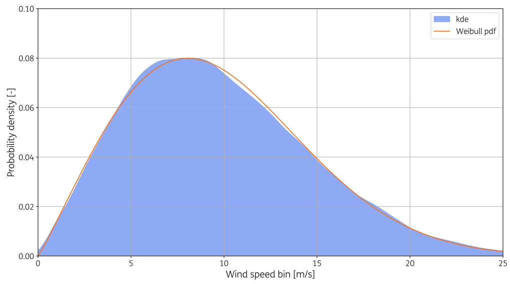

Figure 4.3: Weibull pdf of wind speed distribution at 141 m

$$f(v;k,c) = \frac{k}{c}\left(\frac{v}{c}\right)^{k-1} \exp\left[-\left(\frac{v}{c}\right)^{k}\right] \tag{4.1}$$

where

- v wind speed (m/s), $v > 0$
- k shape parameter (dimensionless), $k > 1$
- c scale parameter (m/s), $c > 0$

4.2 Turbulence intensity

The turbulence intensity is measured by a lidar[7]. The lidar provides an internally computed 10-minute average value for the turbulence intensity.

$$\mathrm{TI} = \frac{v_{\mathrm{std}}}{v_{\mathrm{avg}}} \cdot 100\,\% \tag{4.2}$$

where

- TI turbulence intensity (dimensionless)
- v_{avg} average wind speed (m/s)
- v_{std} standard deviation of the wind speed (m/s)

Figures 4.4 to 4.13 show the bin-wise mean turbulence intensity as a function of the wind speed for every measurement height. The error bars indicate the 95 % confidence interval. For the wind speed 1 m/s wide bins were used, centred on integer multiples of 1 m/s, ranging from 3 m/s to 25 m/s.

[7] The result will be different from the turbulence intensity measured by an anemometer, because a lidar cannot perform a point measurement of the horizontal wind speed.

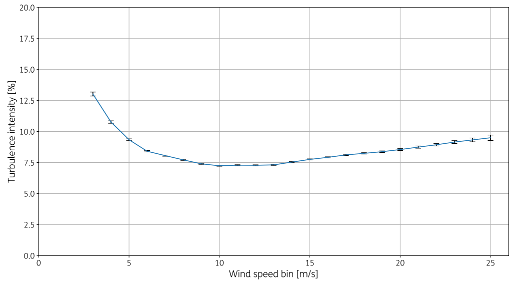

Figure 4.4: Turbulence intensity at 63 m

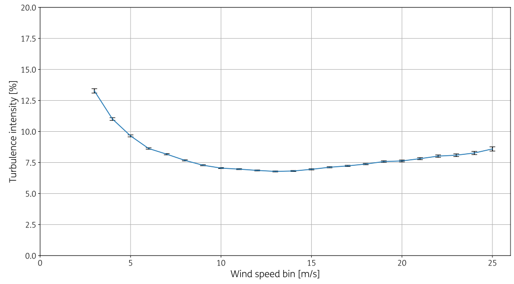

Figure 4.5: Turbulence intensity at 91 m

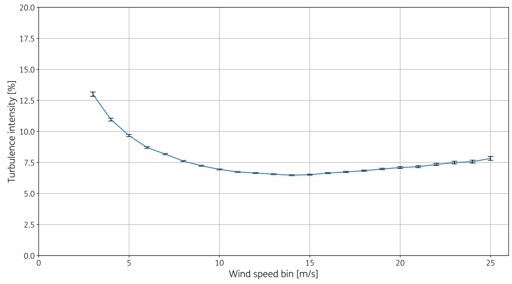

Figure 4.6: Turbulence intensity at 116 m

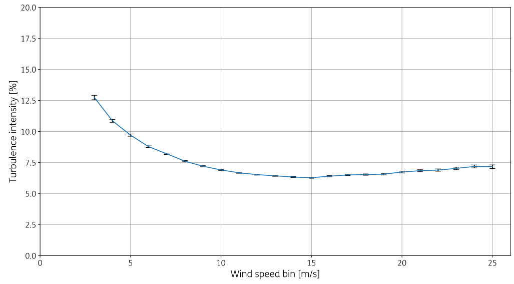

Figure 4.7: Turbulence intensity at 141 m

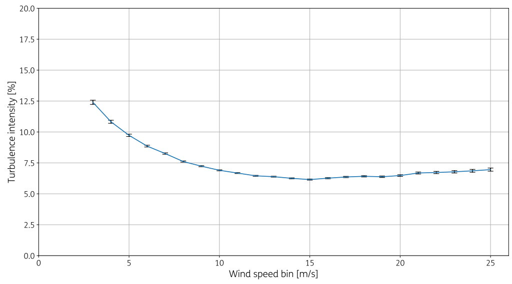

Figure 4.8: Turbulence intensity at 166 m

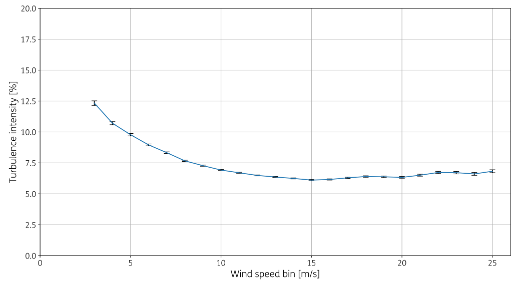

Figure 4.9: Turbulence intensity at 191 m

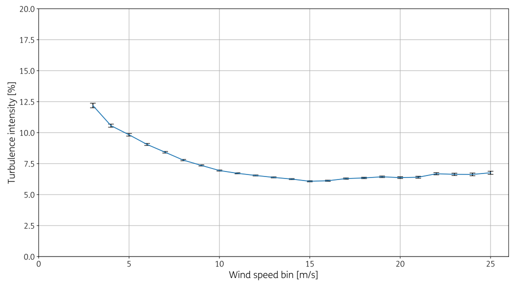

Figure 4.10: Turbulence intensity at 216 m

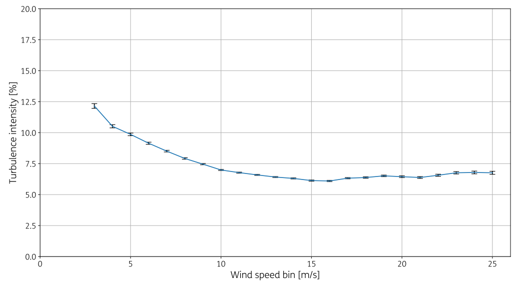

Figure 4.11: Turbulence intensity at 241 m

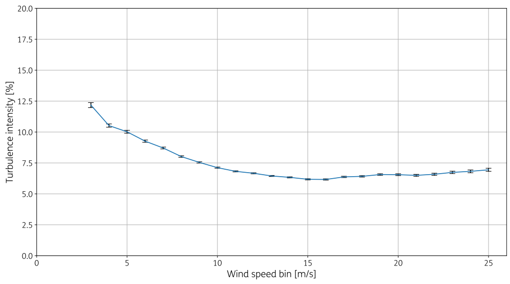

Figure 4.12: Turbulence intensity at 266 m

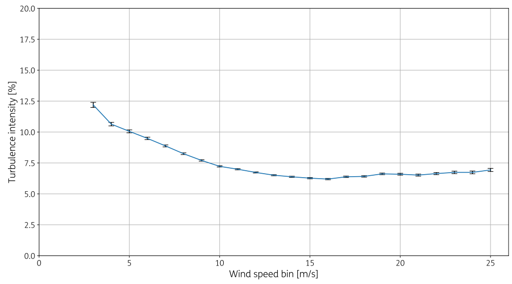

Figure 4.13: Turbulence intensity at 291 m

4.3 Wind shear and veer

When characterizing the shear and veer, only the measurements across the swept area of a large offshore turbine rotor are included. For this (fictive) turbine a hub height of 150 m with a rotor radius of 110 m is assumed.

4.3.1 Data selection

Contrary to the unfiltered dataset used for the distributions in section 4.1, for the shear and veer analysis the following filters are applied in sequence.

1. Only the measurement heights in the range of 40 m to 260 m are considered. This range follows from our rotor choice.
2. Wind speeds below 3 m/s are rejected[8].
3. Incomplete wind speed and wind direction profiles are rejected. I.e., all wind speed and wind direction measurements must be valid across the selected height range.
4. Wind direction profiles with a range in excess of 90° are rejected[9].

Figure 4.14 shows the MoMM values for the wind speed and wind direction for each height after application of these filters.

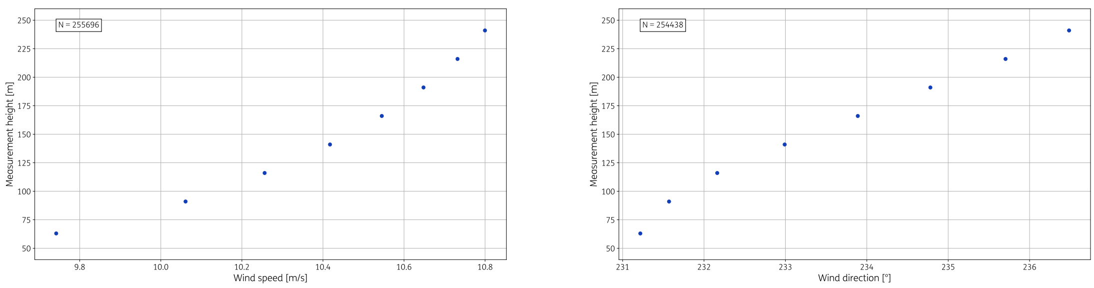

Figure 4.14: Average wind speed and wind direction (MoMM) of the dataset used for shear and veer characterization. 'N' is the number of remaining 10-minute average samples used to compute the MoMM values.

[8] This threshold is based on the MEASNET procedure [10, clause 9.4]

[9] This is most commonly the result of a partially inverted profile due to the homodyne detection ambiguity in continuous wave lidar measurements.

4.3.2 Modelling

The wind shear is modelled by the power law profile in equation (4.3). The wind veer is modelled by a linear profile.

$$v_z = v_H \left(\frac{z}{H}\right)^{\alpha} \tag{4.3}$$

where

- v_z wind speed at height z (m/s)
- v_H wind speed at reference height H (m/s)
- z height (m)
- H reference height, e.g. hub height (m)
- α shear exponent (dimensionless)

The shear and veer are computed for each 10-minute average interval. Then the method of bins is applied to compute the mean values for the shear exponent and the veer rate, as well as the 95 % confidence interval.

Figures 4.16 to 4.19 show the shear and veer as a function of month of the year, hour of day, wind speed and wind direction. For the wind speed 1 m/s wide bins were used, centred on integer multiples of 1 m/s, ranging from 3 m/s to 25 m/s. For the wind direction 15° wide bins were used, centred on integer multiples of 15°. Figure 4.15 shows shear and veer as a function of wind speed and wind direction. For these plots a bin count threshold of six samples (i.e. one hour of data) was used. Annual results are presented in section B.4.

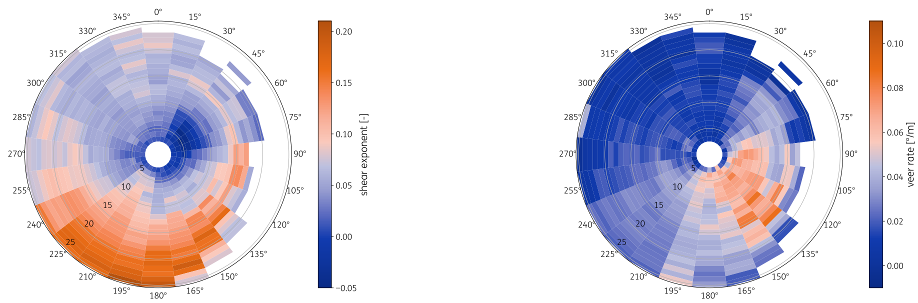

Figure 4.15: Wind shear and veer as function of wind speed and direction. The azimuth indicates the wind direction bin, the radius labels indicate the wind speed bin and the colour represents the mean value for the shear exponent (left) and veer rate (right).

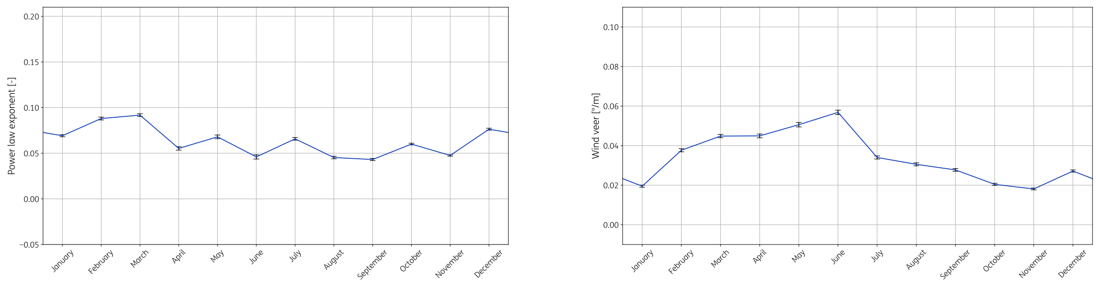

Figure 4.16: Wind shear and veer as function of the month-of-year

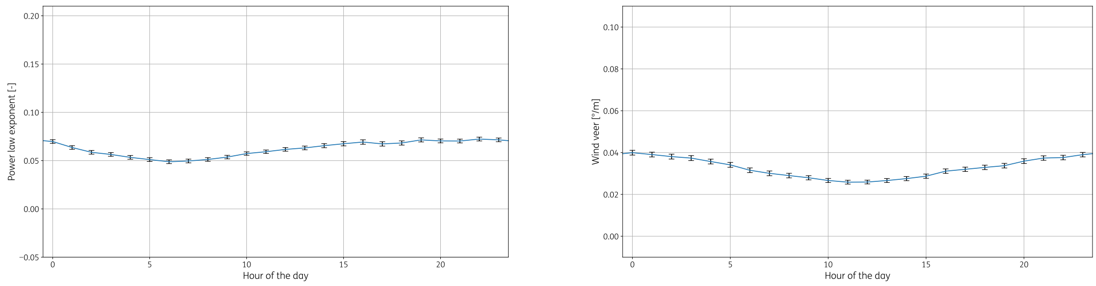

Figure 4.17: Wind shear and veer as function the hour-of-day

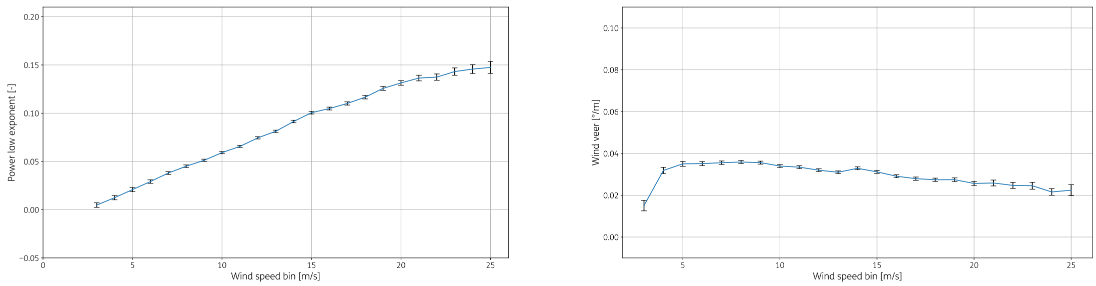

Figure 4.18: Wind shear and veer as function of wind speed

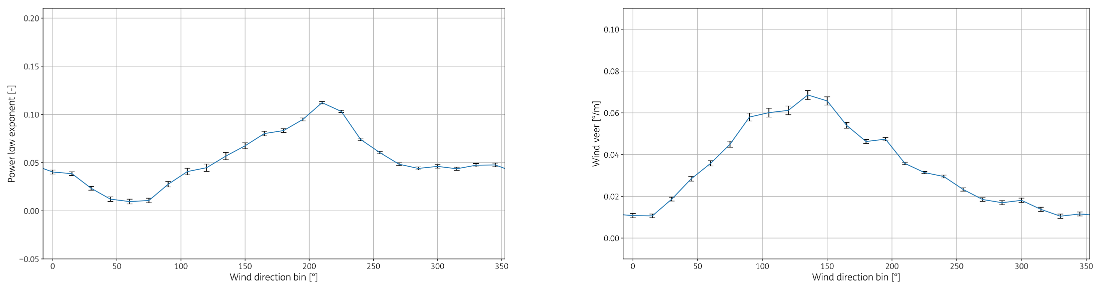

Figure 4.19: Wind shear and veer as function of wind direction

5 Conclusions and recommendations

This report refers to the measurement campaign at the EPL platform where a ZX300 lidar has been deployed since 2016, providing high quality data. The data are publicly available at offshorewind-measurements.tno.nl.

At the EPL platform, the wind analysis for the 2016 – 2023 period shows that the wind profiles are dominated by the regional climate, mainly caused by the positive phase effect of North Atlantic Oscillation (NAO). The prevailing wind direction is from the south-west with a mean direction ranging from 229° to 233° across the different sensor heights (63 m to 291 m). The average calculated wind speed ranges from 9.06 m/s at the lowest measured height of 63 m up to 10.29 m/s at 291 m.

The Weibull distributions, indicating wind regime and inter-annual variability, show wind speed distributions with typical offshore scale (k), and shape (c) parameters (k = 2.081 and c = 11.01 m/s at 141 m height).

Measurement campaigns play a crucial role for the feasibility studies of offshore wind sites as well as the plant valuation. They are the basis for the financial decision to ensure the profitability. In addition, the measured data can be used for other applications in the energy sector including:

- Long-term and accurate data sets can act as reference points for offshore wind atlases, and models
- Serve as a basis for the development and validation of high fidelity models. It is necessary to improve the accuracy over a wide range of site conditions, with sufficient resolution in both time and space.
- Improving and reducing uncertainties of the variability due to renewable resources and their increase penetration in the power sector. The adequate modelling of high RES-E penetration systems crucially depends on the accurate representation of the spatial and temporal characterization of the weather conditions. Variability and uncertainty of the wind resource is translated into datasets that inherently bear the risk of being imperfect, inappropriate or incomplete. This might lead to errors in power system studies which in turn could result in either overstating or downplaying the possible role of wind energy in the future energy mix.
- Capturing extreme weather events for developers and wind turbine manufactures to help develop, certify and validate new models under site specific conditions.
- Filtering the data can influence the interpretation or period trends, and averaged results.

Acknowledgements

The measurement campaign at the offshore platform EPL is carried out on the authority of the Ministry of Economic Affairs and Climate Policy of The Netherlands.

References

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[10] *Evaluation of site-specific wind conditions*. Version 3. MEASNET, Sept. 2022.

Appendix A
Lidar specifications ZX300

The ZX300 lidar is a vertical wind profiling lidar. This appendix presents an example of the DailyPlots and a screenshot of the Waltz software package.

Furthermore the measurement and product specifications are presented in this Appendix.

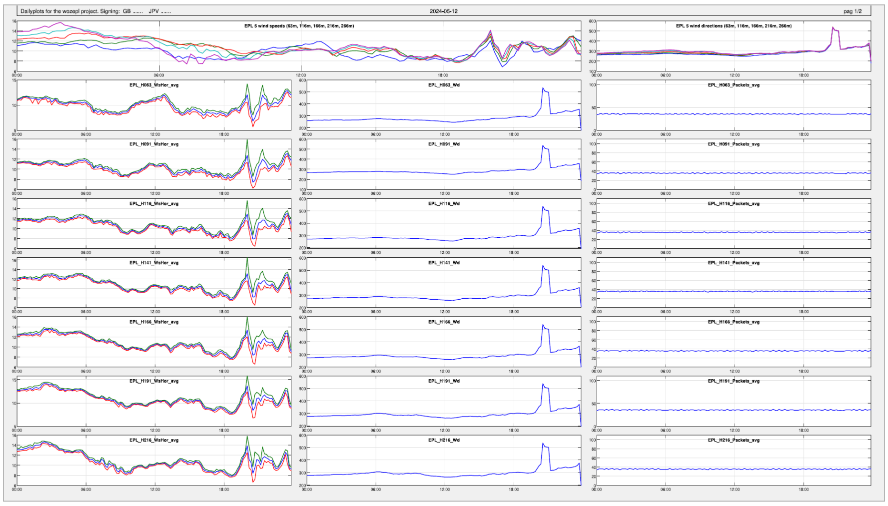

Figure A.1: Daily plots

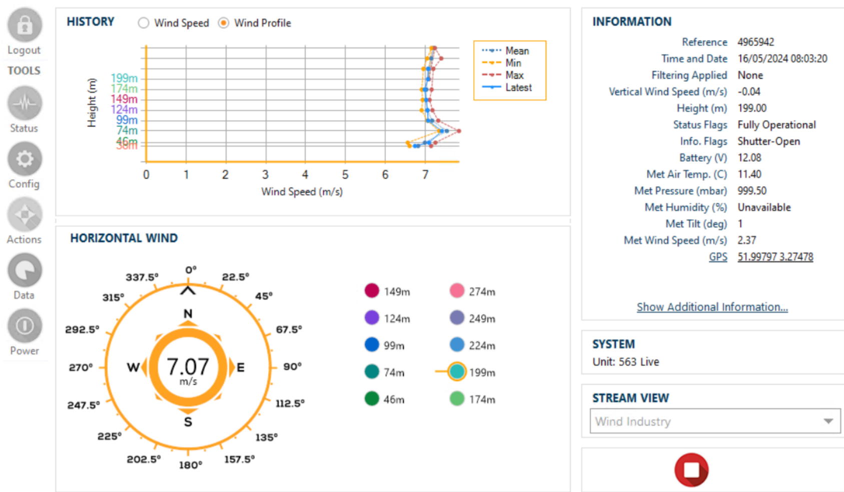

Figure A.2: Waltz output

Range	10 – 300 metres (Lidar measurement) 0 – 10 metres (onboard met weather station)
Probe length	± 0.07 metres @ 10 metres ± 7.70 metres @ 100 metres
Height measured	10 User configurable 1 Additional met weather station measurement
Sampling rate	50Hz (up to 50 measurement points every second)
Averaging rate	True 1-second averaging 10 Minute averaging
Accuracy wind speed	0.1 m/s*
Direction variation	< 0.5°
Service interval	36 months from new
Size	805 x 845 x 966mm
Weight	53.4kg
IP Rating	IP68
Power consumption	55W
Power input	12V
Temperature range	-40 to +50°C
Warranty	3 years
Maintenance	No annual maintenance or calibration in this period

Figure A.3: ZX300 product specifications

Appendix B
Annual wind conditions during the campaign at EPL

B.1 Wind rose

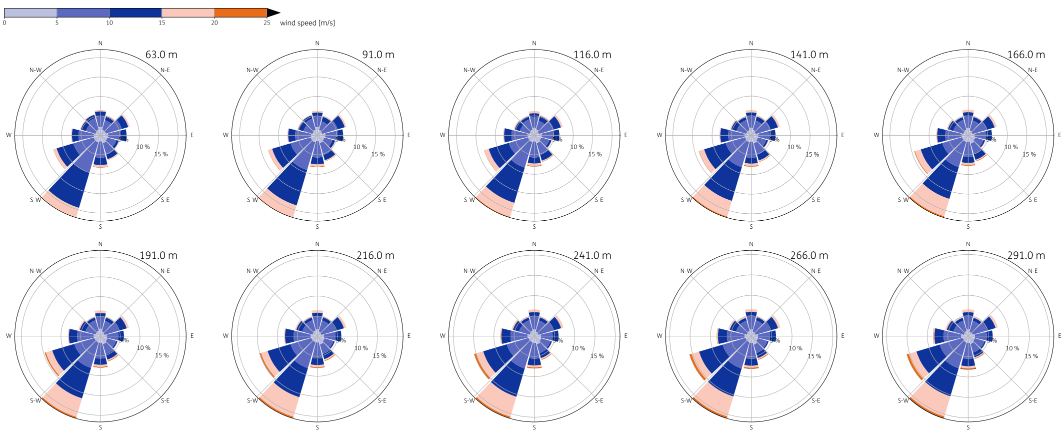

Figure B.1: Wind roses for 2016

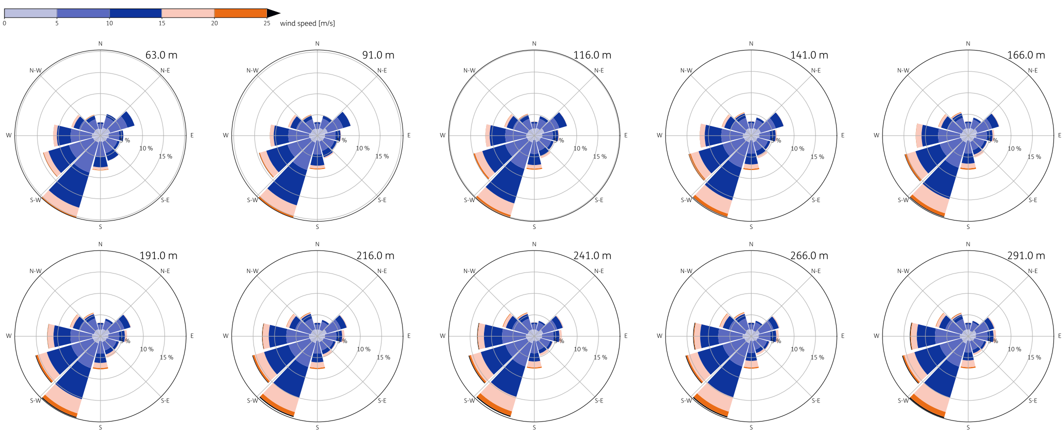

Figure B.2: Wind roses for 2017

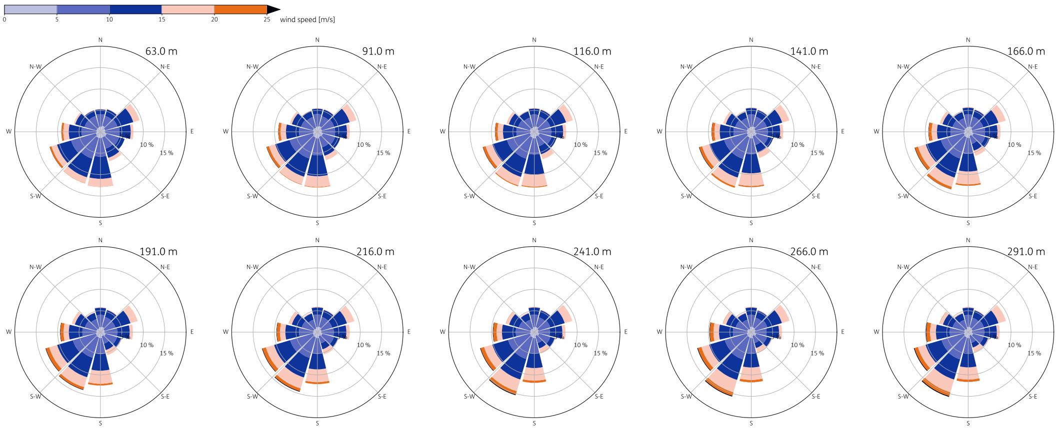

Figure B.3: Wind roses for 2018

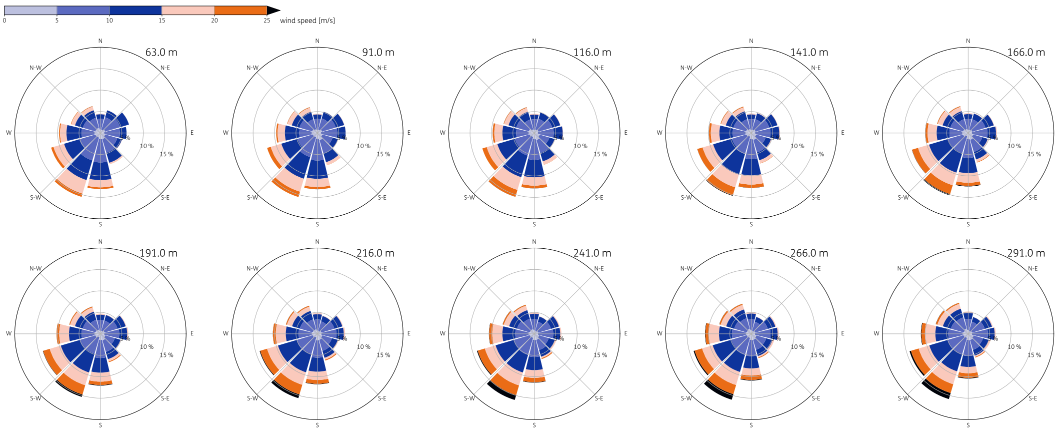

Figure B.4: Wind roses for 2019

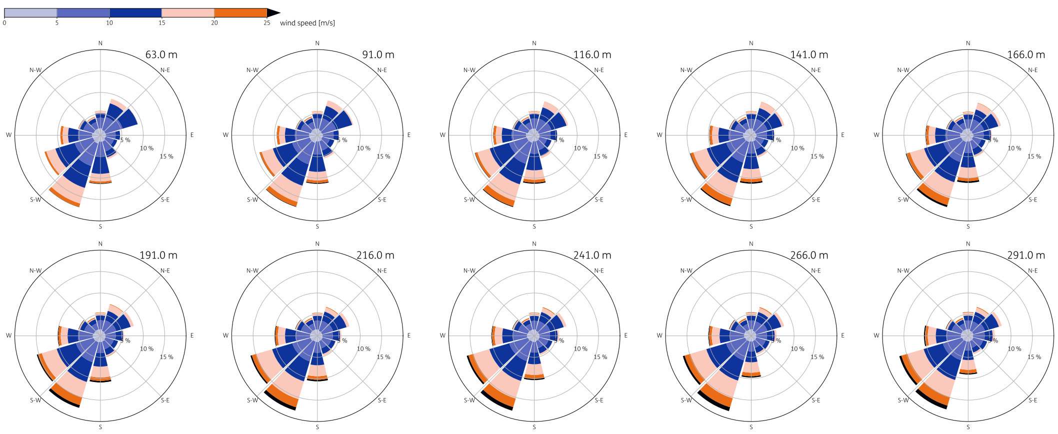

Figure B.5: Wind roses for 2020

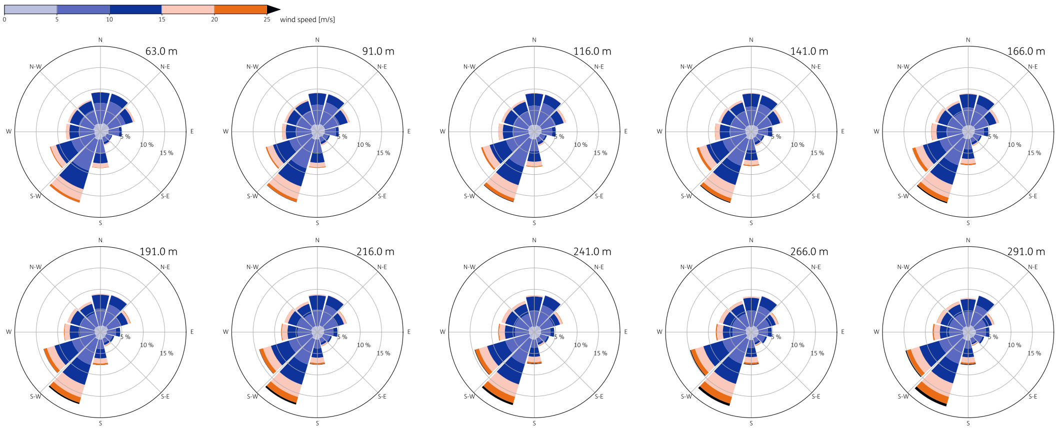

Figure B.6: Wind roses for 2021

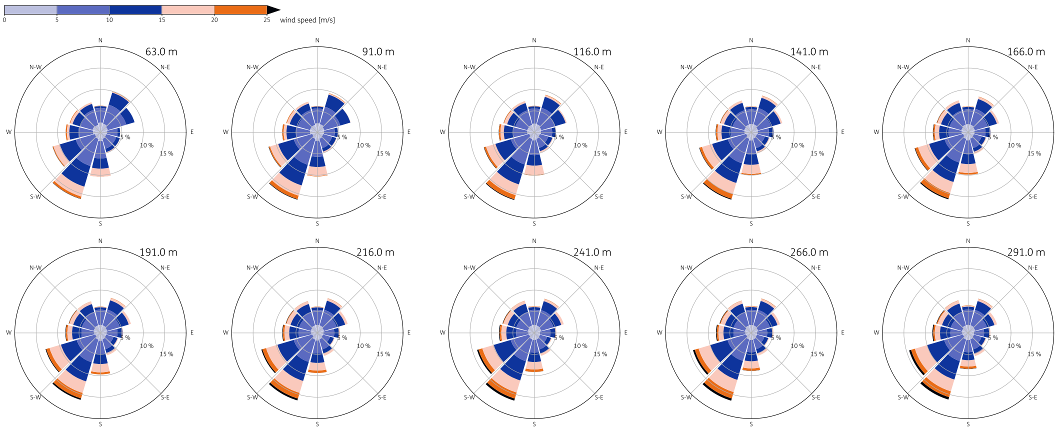

Figure B.7: Wind roses for 2022

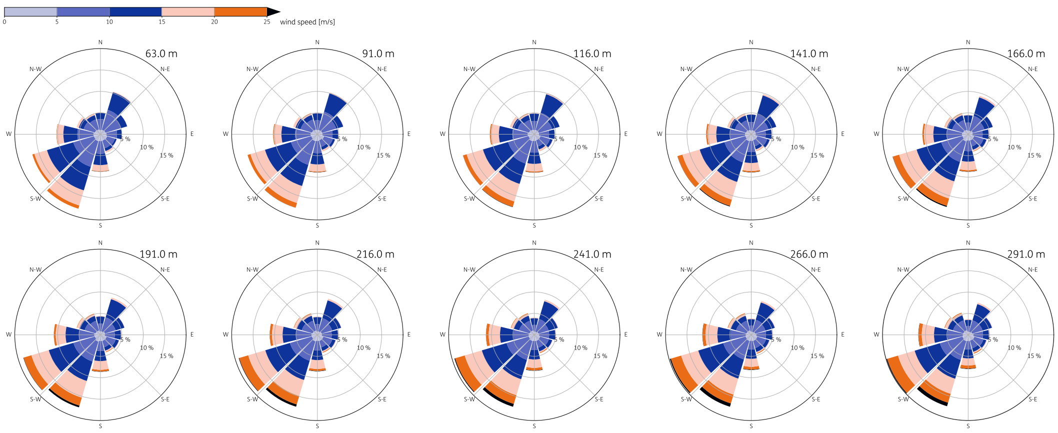

Figure B.8: Wind roses for 2023

B.2 Wind speed and direction statistics

Table B.1: Wind speed and wind direction statistics for 2016

Height	Wind speed						Wind direction
	N	Q_1	median	Q_3	maximum	MoMM	MoMM
m	#	m/s	m/s	m/s	m/s	m/s	°
63	28 315	5.47	8.23	11.05	30.48	8.68	247.9
91	28 591	5.52	8.35	11.40	31.23	9.12	248.0
116	28 504	5.58	8.43	11.60	32.34	9.43	248.5
141	28 485	5.63	8.49	11.73	31.85	9.61	249.5
166	28 449	5.69	8.52	11.85	31.81	9.72	250.4
191	28 355	5.72	8.56	11.93	31.90	9.79	251.0
216	28 237	5.75	8.59	11.97	32.48	9.83	252.1
241	28 134	5.80	8.61	12.00	32.03	9.90	252.9
266	28 057	5.83	8.62	12.03	32.64	9.94	253.1
291	27 802	5.89	8.64	12.08	33.03	9.97	252.8

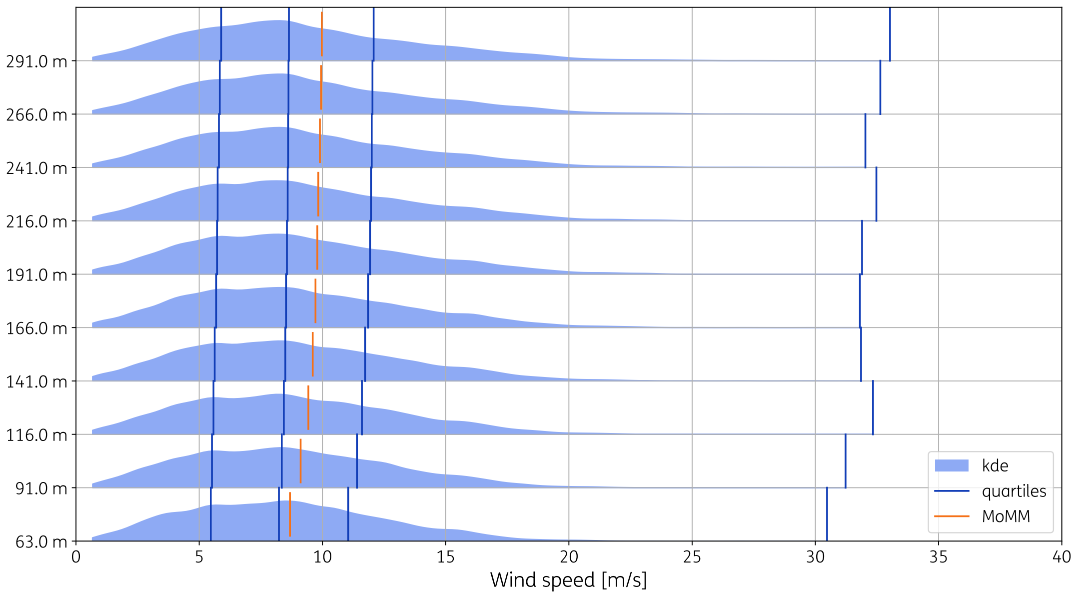

Figure B.9: Wind speed distributions for 2016

Table B.2: Wind speed and wind direction statistics for 2017

Height	Wind speed						Wind direction
	N	Q_1	median	Q_3	maximum	MoMM	MoMM
m	#	m/s	m/s	m/s	m/s	m/s	°
63	25 560	5.45	8.22	11.37	27.03	8.94	236.6
91	25 619	5.52	8.45	11.92	27.63	9.24	237.3
116	25 581	5.56	8.57	12.24	29.24	9.43	238.2
141	25 506	5.58	8.66	12.45	29.52	9.57	239.1
166	25 437	5.60	8.70	12.60	29.70	9.68	240.2
191	25 294	5.64	8.74	12.69	31.37	9.77	240.8
216	25 156	5.70	8.78	12.78	32.01	9.84	241.6
241	25 063	5.75	8.79	12.82	32.13	9.89	242.7
266	24 946	5.80	8.82	12.86	32.08	9.94	243.5
291	24 766	5.87	8.85	12.88	32.28	9.98	244.1

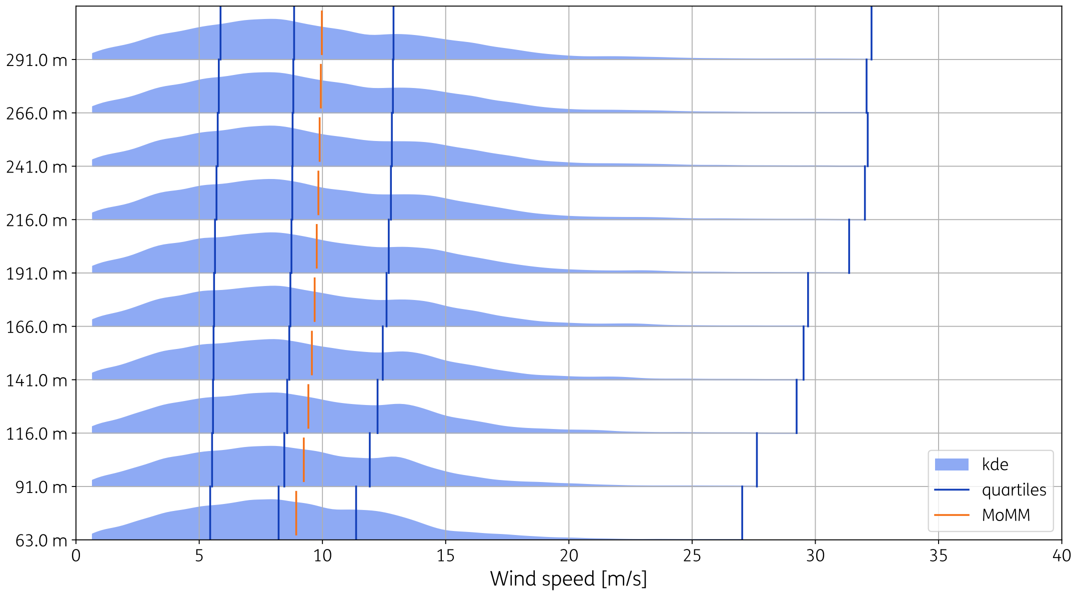

Figure B.10: Wind speed distributions for 2017

Table B.3: Wind speed and wind direction statistics for 2018

Height	Wind speed						Wind direction
	N	Q_1	median	Q_3	maximum	MoMM	MoMM
m	#	m/s	m/s	m/s	m/s	m/s	°
63	28 411	6.51	9.26	12.41	31.99	9.67	193.8
91	28 422	6.64	9.46	12.76	32.76	9.97	197.0
116	28 333	6.73	9.60	12.95	33.20	10.15	199.5
141	28 283	6.79	9.69	13.09	33.37	10.28	201.5
166	28 190	6.84	9.77	13.22	33.73	10.40	203.8
191	28 127	6.87	9.84	13.33	34.29	10.51	205.7
216	28 044	6.93	9.90	13.43	34.79	10.60	207.5
241	27 973	6.95	9.93	13.52	35.27	10.66	209.2
266	27 897	6.98	9.94	13.58	35.50	10.70	210.6
291	27 831	6.99	9.94	13.62	35.99	10.73	211.8

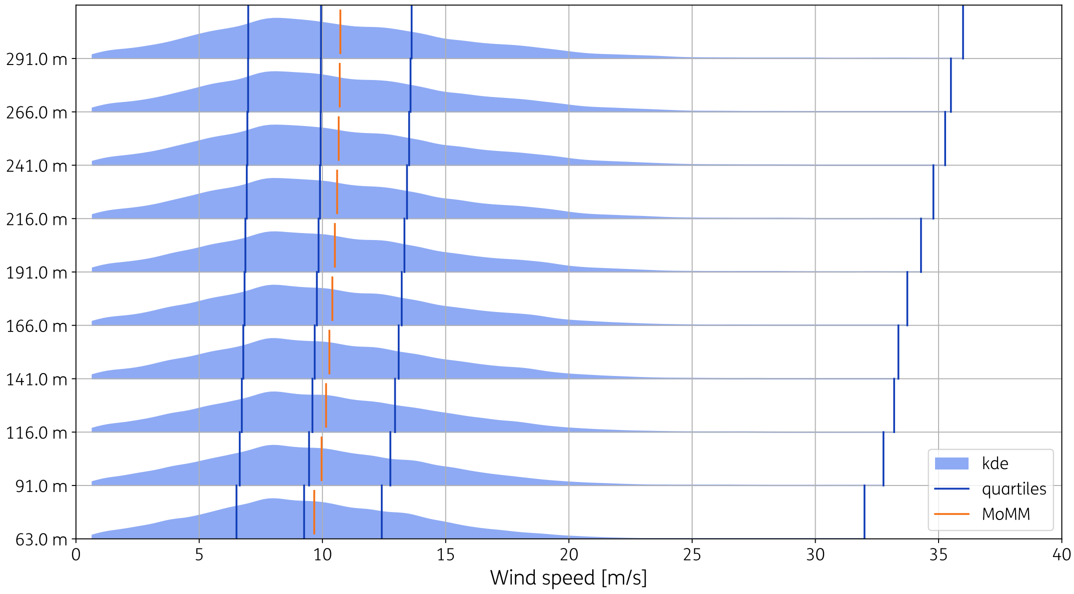

Figure B.11: Wind speed distributions for 2018

Table B.4: Wind speed and wind direction statistics for 2019

Height	Wind speed						Wind direction
	N	Q_1	median	Q_3	maximum	MoMM	MoMM
m	#	m/s	m/s	m/s	m/s	m/s	°
63	25 422	6.62	9.30	12.55	26.89	9.69	222.6
91	25 439	6.73	9.55	13.04	27.67	9.97	221.7
116	25 457	6.77	9.68	13.40	28.06	10.15	223.4
141	25 379	6.81	9.78	13.67	28.33	10.30	225.4
166	25 276	6.86	9.87	13.90	28.76	10.45	227.5
191	25 086	6.91	9.94	14.07	31.59	10.58	228.8
216	24 885	6.93	9.96	14.26	34.07	10.69	230.1
241	24 576	6.95	10.00	14.39	34.62	10.79	231.7
266	24 140	6.93	10.00	14.47	34.94	10.85	232.8
291	23 598	6.87	9.94	14.50	35.00	10.85	234.7

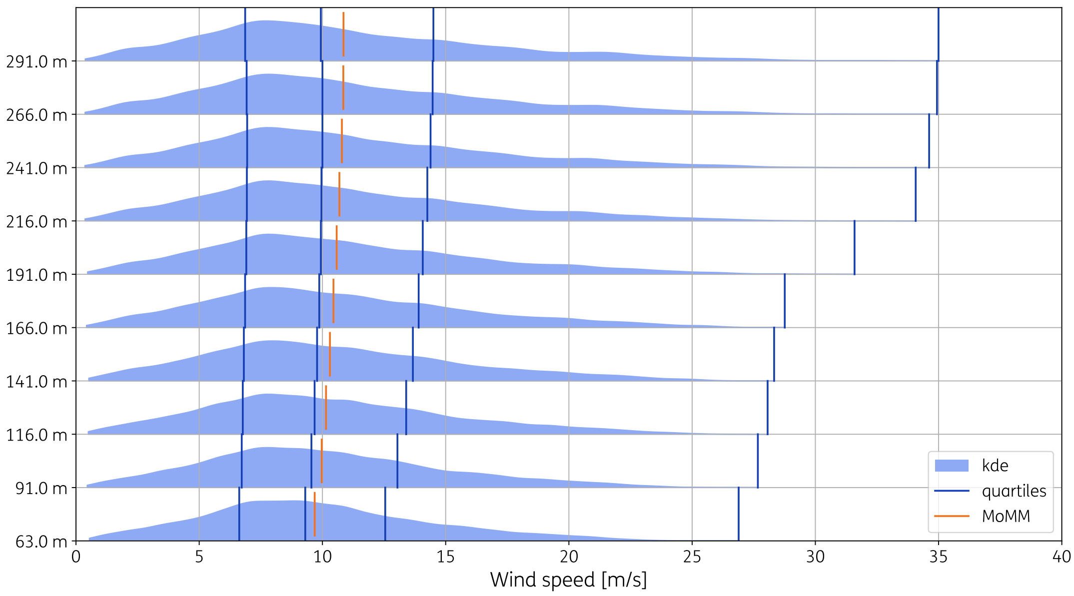

Figure B.12: Wind speed distributions for 2019

Table B.5: Wind speed and wind direction statistics for 2020

Height	Wind speed						Wind direction
	N	Q_1	median	Q_3	maximum	MoMM	MoMM
m	#	m/s	m/s	m/s	m/s	m/s	°
63	46 938	5.91	9.28	12.78	28.99	9.77	223.2
91	47 089	6.05	9.54	13.27	30.89	10.08	223.4
116	47 160	6.13	9.68	13.58	31.85	10.28	223.6
141	46 764	6.19	9.81	13.87	33.23	10.47	224.7
166	46 465	6.21	9.91	14.10	34.13	10.63	225.0
191	45 965	6.24	10.02	14.29	36.28	10.78	225.5
216	45 335	6.28	10.11	14.47	37.66	10.92	225.9
241	44 352	6.31	10.17	14.60	38.94	11.05	226.4
266	42 732	6.31	10.23	14.73	40.37	11.17	227.4
291	40 764	6.25	10.15	14.73	41.12	11.17	229.1

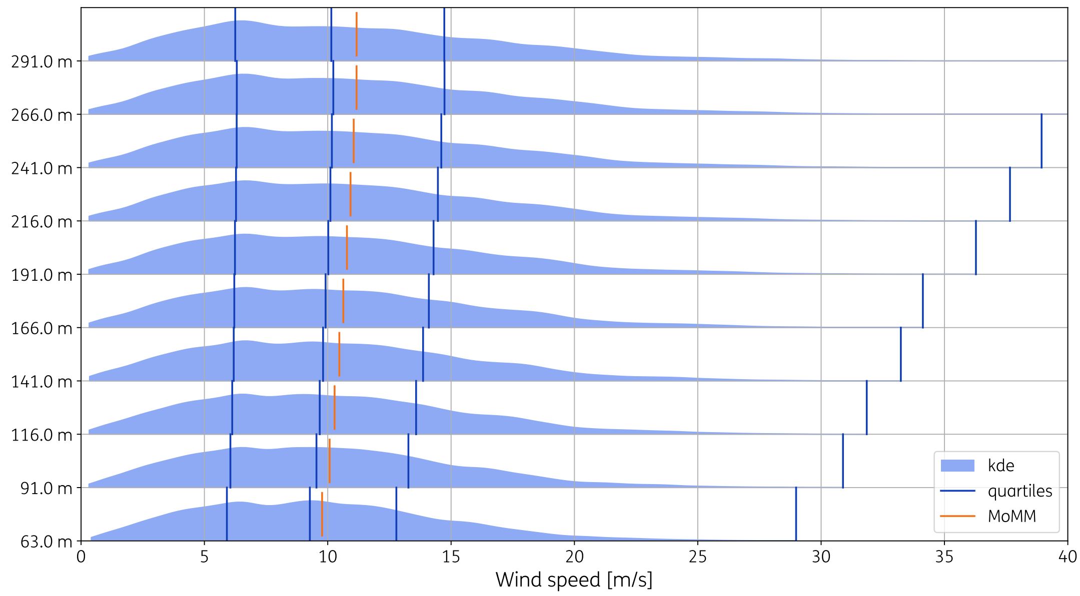

Figure B.13: Wind speed distributions for 2020

Table B.6: Wind speed and wind direction statistics for 2021

Height	Wind speed						Wind direction
	N	Q_1	median	Q_3	maximum	MoMM	MoMM
m	#	m/s	m/s	m/s	m/s	m/s	°
63	46 471	5.47	8.11	11.10	26.98	8.57	265.9
91	46 160	5.61	8.37	11.43	28.06	8.84	264.6
116	46 005	5.70	8.51	11.65	29.03	9.03	262.9
141	45 425	5.77	8.64	11.84	29.75	9.20	261.6
166	44 976	5.81	8.75	12.02	30.60	9.34	260.8
191	44 205	5.82	8.84	12.18	31.48	9.47	260.1
216	43 359	5.86	8.92	12.31	32.13	9.59	258.4
241	42 128	5.90	9.00	12.45	32.81	9.72	257.5
266	39 830	5.89	9.04	12.60	33.28	9.84	255.1
291	37 603	5.80	8.94	12.59	33.57	9.86	253.0

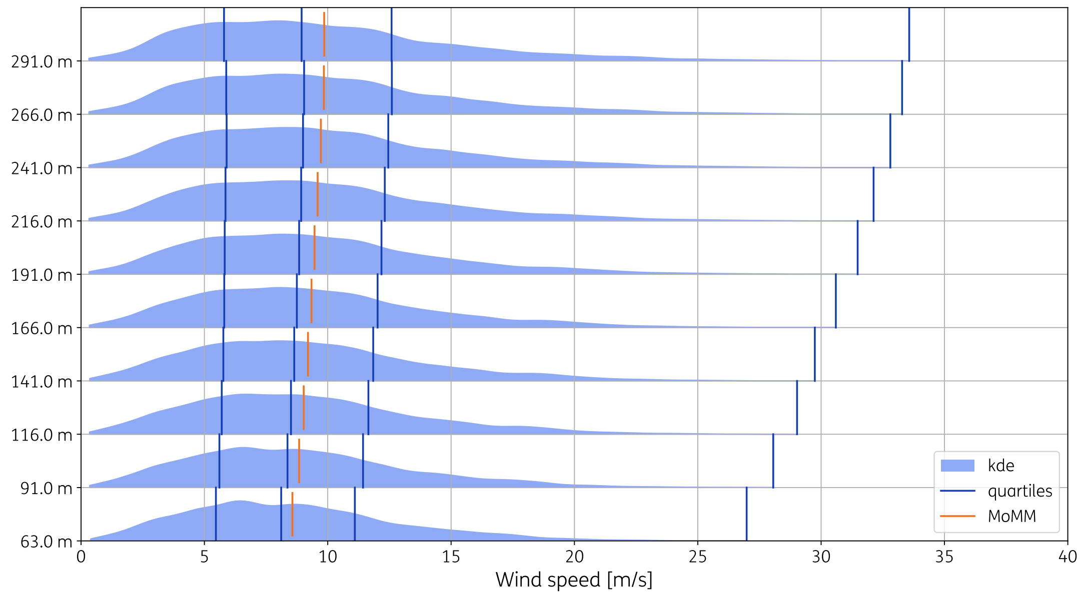

Figure B.14: Wind speed distributions for 2021

Table B.7: Wind speed and wind direction statistics for 2022

Height	Wind speed						Wind direction
	N	Q_1	median	Q_3	maximum	MoMM	MoMM
m	#	m/s	m/s	m/s	m/s	m/s	°
63	49 889	5.42	8.05	11.42	32.52	8.72	239.2
91	49 762	5.53	8.34	11.93	33.92	9.07	238.7
116	49 835	5.59	8.51	12.23	34.63	9.27	238.6
141	49 520	5.63	8.67	12.46	35.46	9.45	238.4
166	49 382	5.66	8.76	12.64	36.05	9.59	238.5
191	49 106	5.70	8.85	12.80	36.86	9.72	238.5
216	48 492	5.74	8.92	12.99	37.86	9.84	239.1
241	47 381	5.79	8.97	13.15	38.32	9.97	240.0
266	46 136	5.80	9.02	13.26	38.75	10.07	240.9
291	44 999	5.78	8.99	13.21	38.99	10.09	242.4

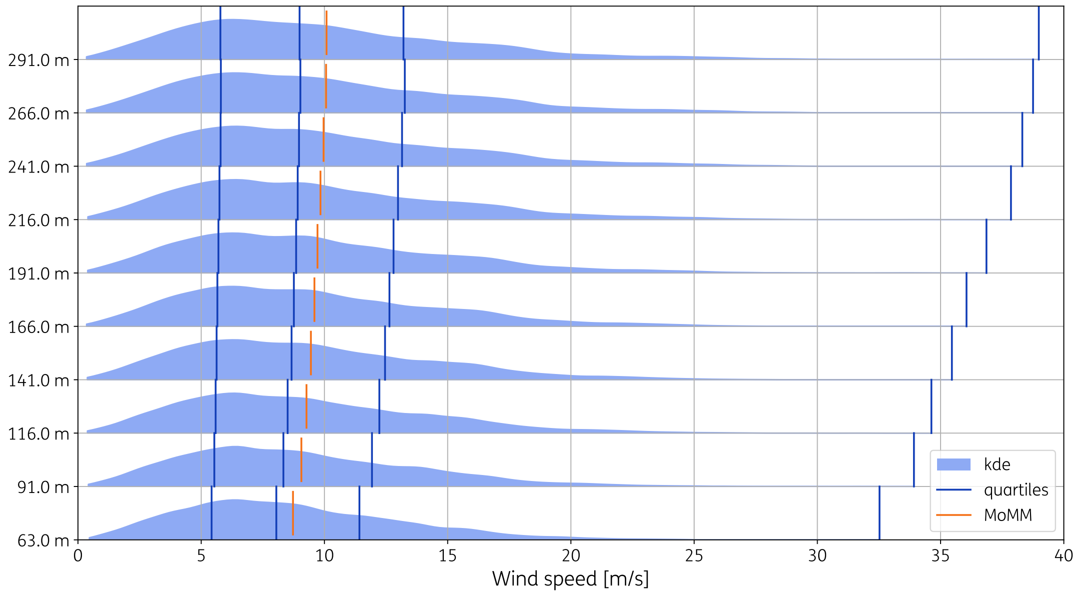

Figure B.15: Wind speed distributions for 2022

Table B.8: Wind speed and wind direction statistics for 2023

Height	Wind speed						Wind direction
	N	Q_1	median	Q_3	maximum	MoMM	MoMM
m	#	m/s	m/s	m/s	m/s	m/s	°
63	49 571	5.96	9.07	12.61	33.05	9.48	235.5
91	49 859	6.13	9.38	13.05	33.91	9.81	235.7
116	49 865	6.24	9.57	13.33	34.17	10.04	235.5
141	49 205	6.33	9.75	13.61	33.78	10.25	235.1
166	48 651	6.41	9.91	13.85	34.05	10.44	234.9
191	47 995	6.49	10.05	14.03	34.48	10.62	235.0
216	47 281	6.57	10.16	14.21	35.12	10.77	235.1
241	45 823	6.63	10.29	14.39	35.41	10.93	234.7
266	44 236	6.62	10.36	14.50	35.47	11.04	234.5
291	42 300	6.57	10.28	14.50	35.81	11.07	235.1

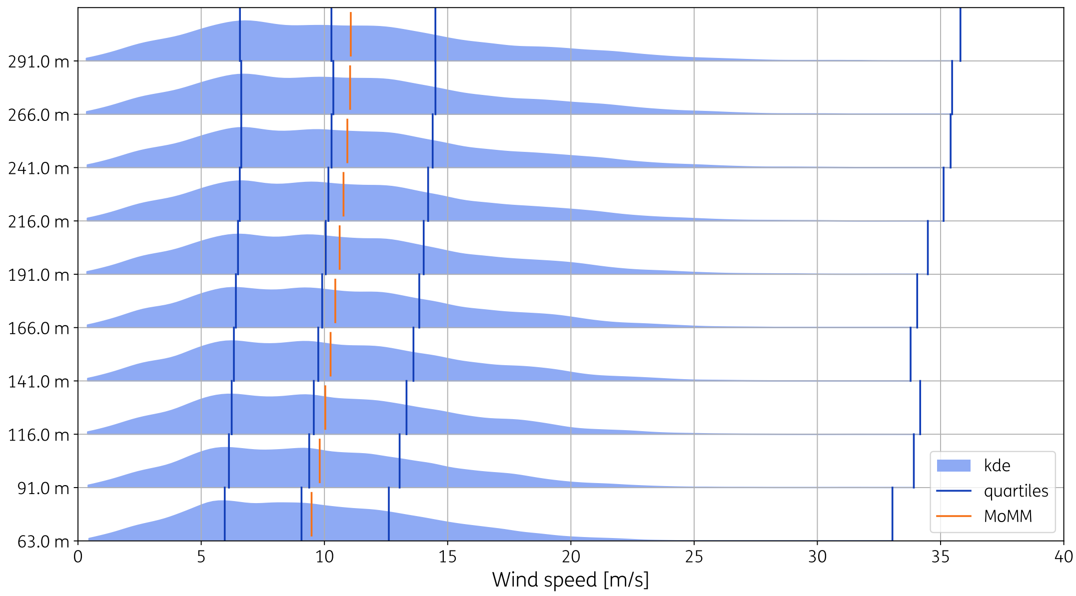

Figure B.16: Wind speed distributions for 2023

B.3 Wind speed distribution

Table B.9: Weibull parameters for 2016

Height	Shape (k)	Scale (c)
m	–	m/s
63	2.289	9.56
91	2.251	9.77
116	2.224	9.94
141	2.201	10.06
166	2.179	10.16
191	2.164	10.26
216	2.152	10.32
241	2.148	10.38
266	2.145	10.43
291	2.143	10.47

Table B.10: Weibull parameters for 2017

Height	Shape (k)	Scale (c)
m	–	m/s
63	2.177	9.65
91	2.134	9.99
116	2.096	10.19
141	2.066	10.34
166	2.038	10.46
191	2.016	10.55
216	2.008	10.63
241	2.004	10.69
266	2.006	10.74
291	2.010	10.79

Table B.11: Weibull parameters for 2018

Height	Shape (k)	Scale (c)
m	–	m/s
63	2.377	10.76
91	2.350	11.04
116	2.331	11.23
141	2.307	11.37
166	2.288	11.50
191	2.271	11.61
216	2.256	11.70
241	2.244	11.78
266	2.235	11.83
291	2.227	11.86

Table B.12: Weibull parameters for 2019

Height	Shape (k)	Scale (c)
m	–	m/s
63	2.304	11.05
91	2.266	11.41
116	2.221	11.63
141	2.184	11.82
166	2.152	11.99
191	2.121	12.14
216	2.088	12.27
241	2.058	12.38
266	2.029	12.44
291	1.998	12.46

Table B.13: Weibull parameters for 2020

Height	Shape (k)	Scale (c)
m	–	m/s
63	2.087	10.89
91	2.051	11.24
116	2.018	11.46
141	1.991	11.68
166	1.967	11.84
191	1.949	11.99
216	1.936	12.14
241	1.927	12.24
266	1.918	12.33
291	1.897	12.28

Table B.14: Weibull parameters for 2021

Height	Shape (k)	Scale (c)
m	–	m/s
63	2.152	9.70
91	2.128	10.00
116	2.113	10.20
141	2.095	10.39
166	2.078	10.54
191	2.058	10.67
216	2.043	10.80
241	2.029	10.94
266	2.000	11.04
291	1.962	11.02

Table B.15: Weibull parameters for 2022

Height	Shape (k)	Scale (c)
m	–	m/s
63	2.078	9.82
91	2.046	10.20
116	2.018	10.43
141	1.994	10.62
166	1.972	10.77
191	1.950	10.90
216	1.934	11.02
241	1.919	11.14
266	1.905	11.22
291	1.889	11.21

Table B.16: Weibull parameters for 2023

Height	Shape (k)	Scale (c)
m	–	m/s
63	2.209	10.75
91	2.187	11.12
116	2.165	11.37
141	2.141	11.61
166	2.118	11.81
191	2.099	11.99
216	2.083	12.16
241	2.069	12.31
266	2.049	12.41
291	2.017	12.40

B.4 Wind shear and veer

B.4.1 Wind shear and veer as function of the month

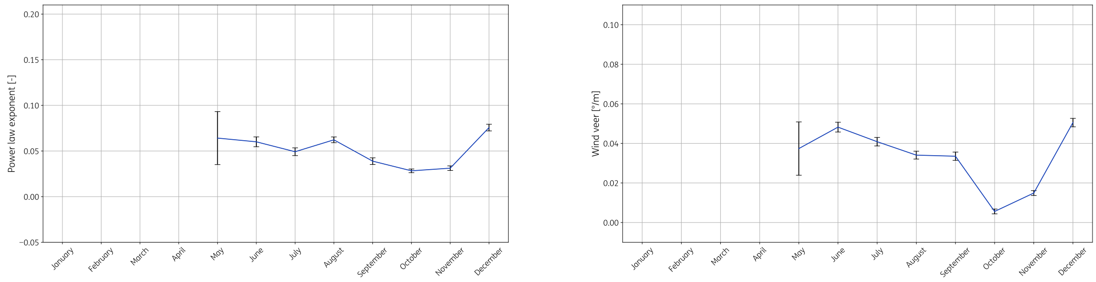

Figure B.17: Wind shear and veer as function of the month-of-year for 2016

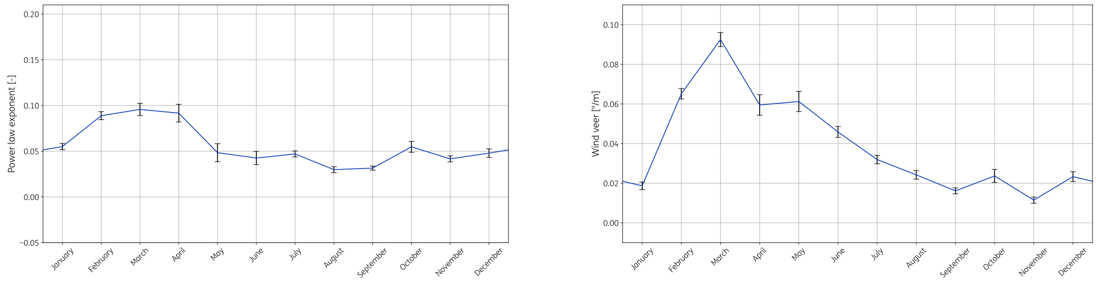

Figure B.18: Wind shear and veer as function of the month-of-year for 2017

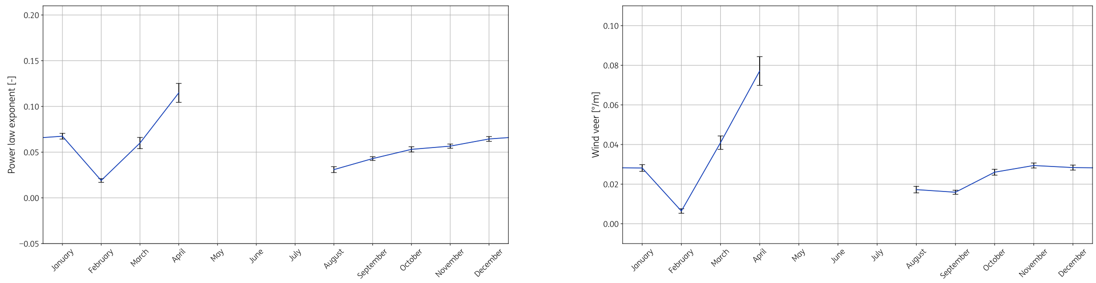

Figure B.19: Wind shear and veer as function of the month-of-year for 2018

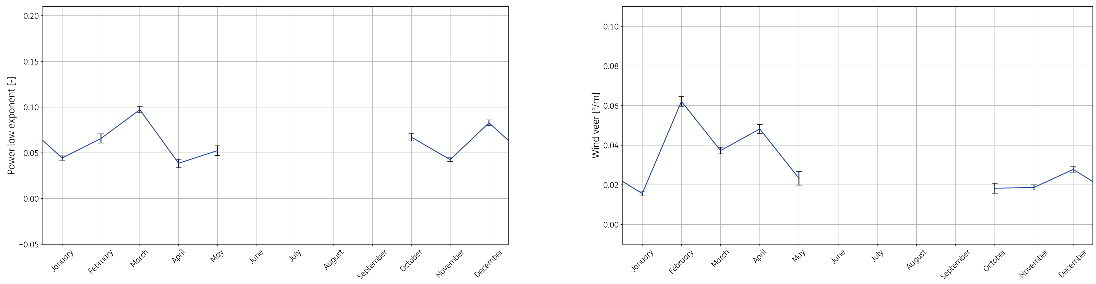

Figure B.20: Wind shear and veer as function of the month-of-year for 2019

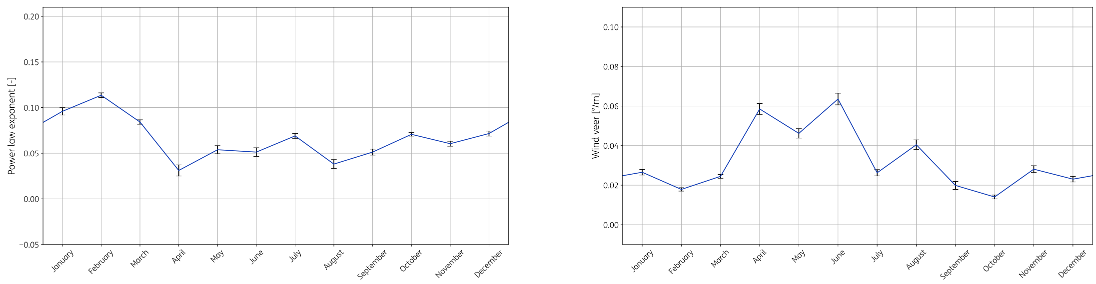

Figure B.21: Wind shear and veer as function of the month-of-year for 2020

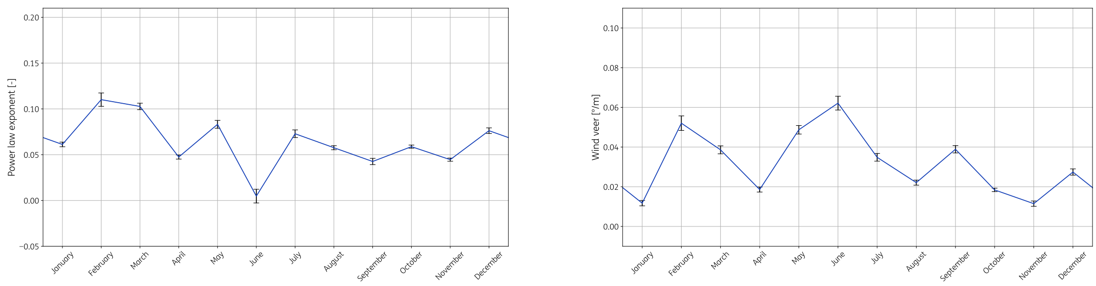

Figure B.22: Wind shear and veer as function of the month-of-year for 2021

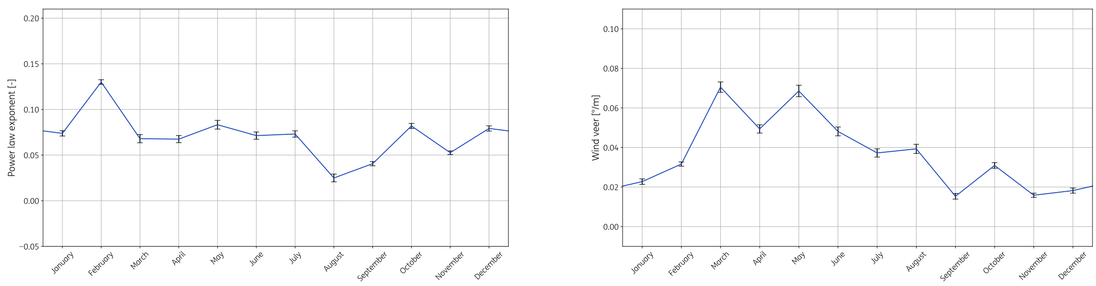

Figure B.23: Wind shear and veer as function of the month-of-year for 2022

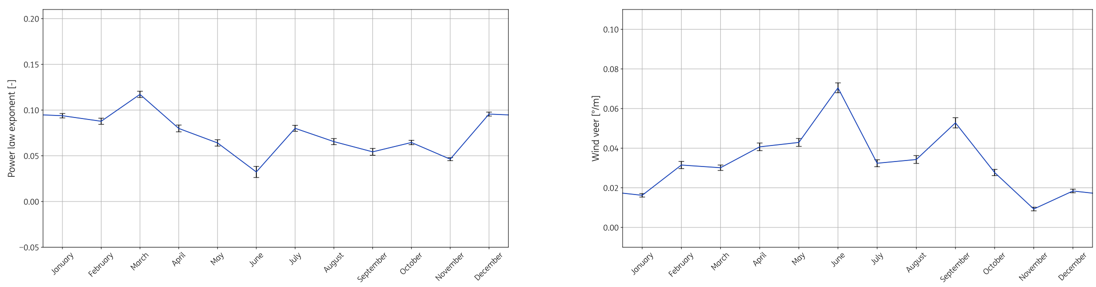

Figure B.24: Wind shear and veer as function of the month-of-year for 2023

B.4.2 Wind shear and veer as function of hour

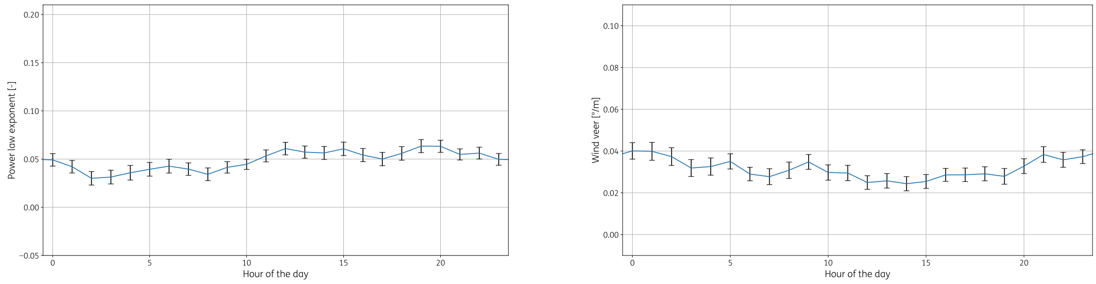

Figure B.25: Wind shear and veer as function the hour-of-day for 2016

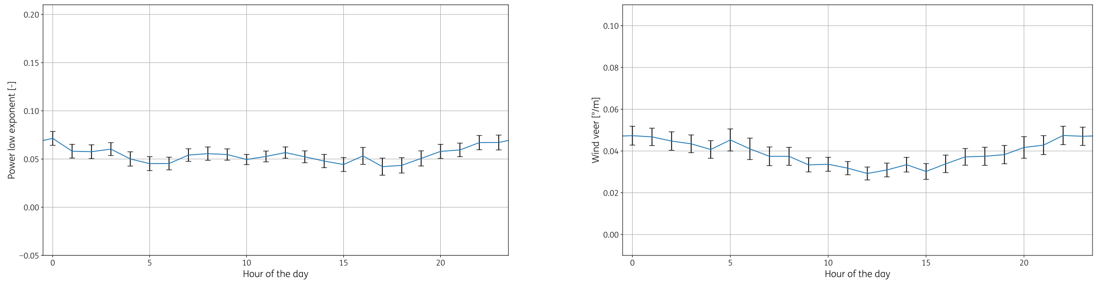

Figure B.26: Wind shear and veer as function the hour-of-day for 2017

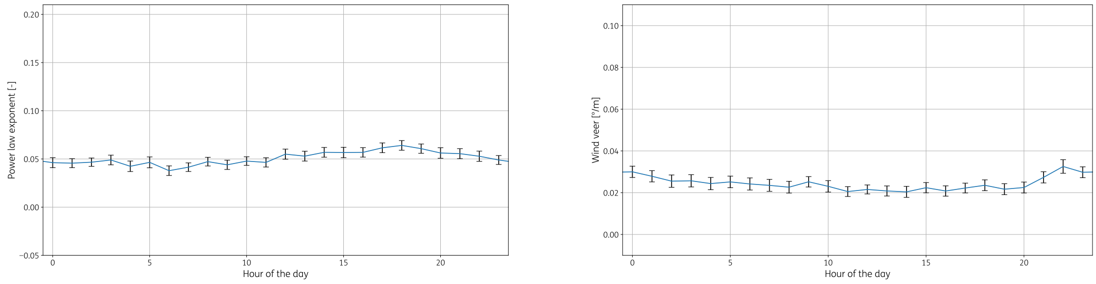

Figure B.27: Wind shear and veer as function the hour-of-day for 2018

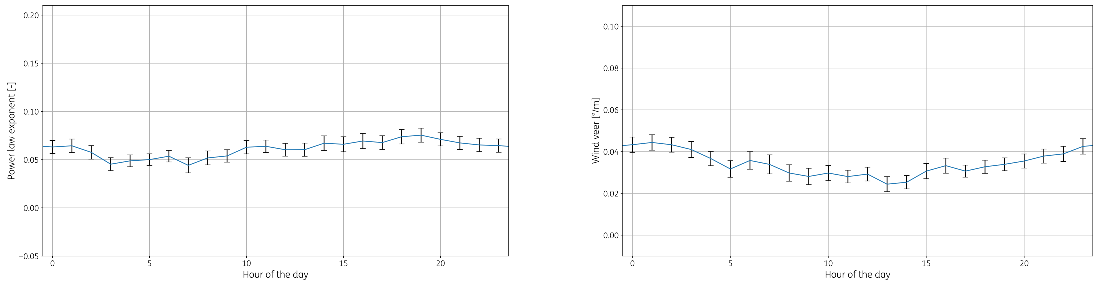

Figure B.28: Wind shear and veer as function the hour-of-day for 2019

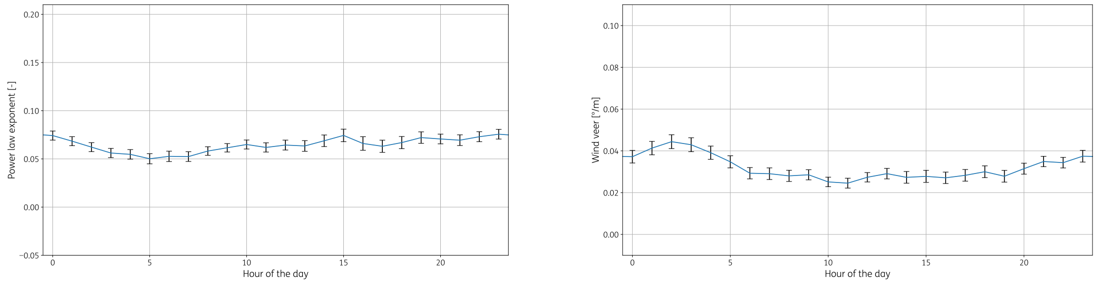

Figure B.29: Wind shear and veer as function the hour-of-day for 2020

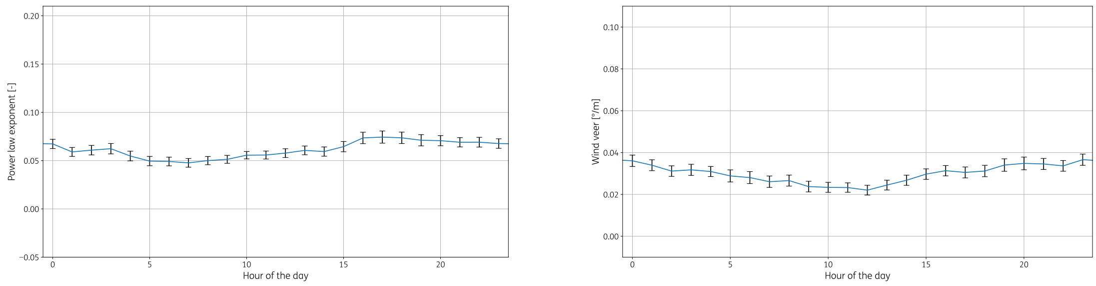

Figure B.30: Wind shear and veer as function the hour-of-day for 2021

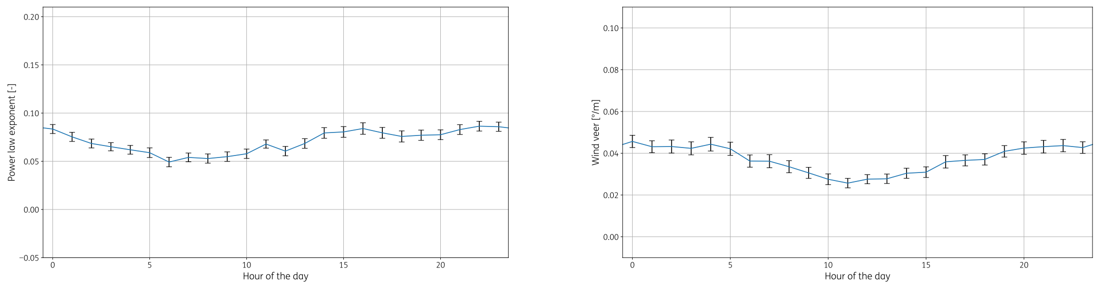

Figure B.31: Wind shear and veer as function the hour-of-day for 2022

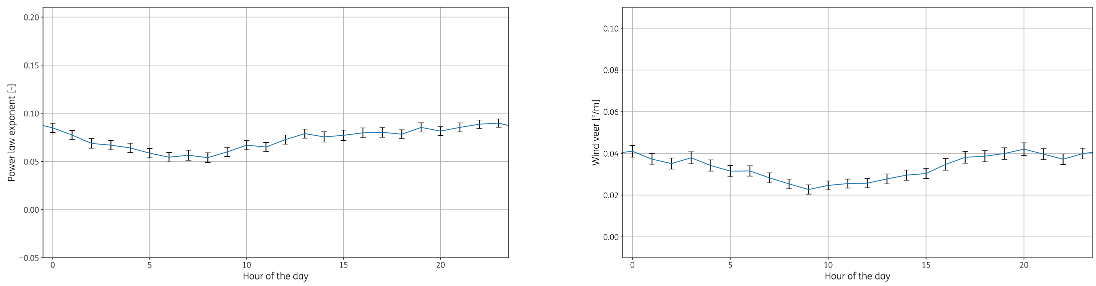

Figure B.32: Wind shear and veer as function the hour-of-day for 2023

B.4.3 Wind shear and veer as function of wind speed

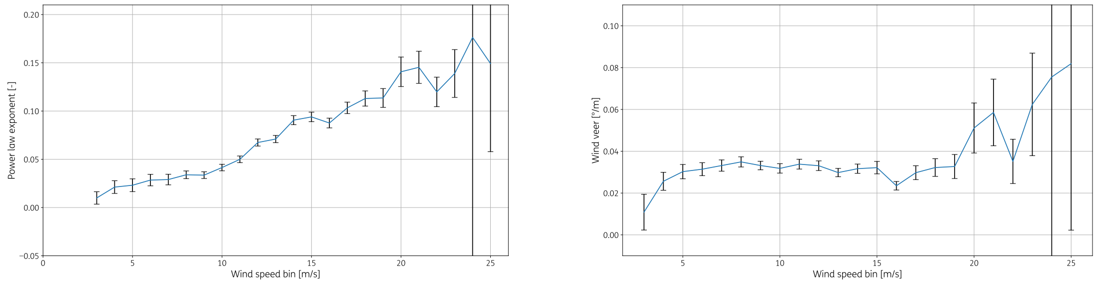

Figure B.33: Wind shear and veer as function of wind speed for 2016

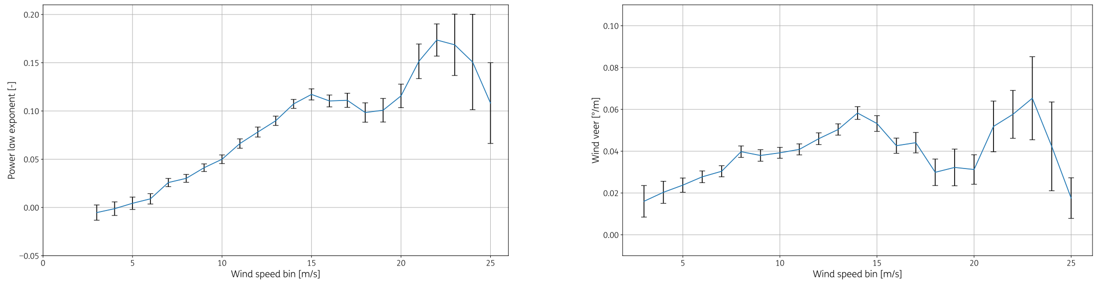

Figure B.34: Wind shear and veer as function of wind speed for 2017

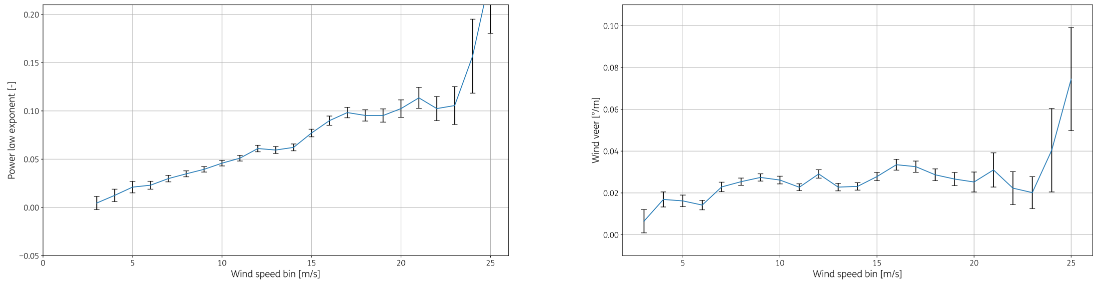

Figure B.35: Wind shear and veer as function of wind speed for 2018

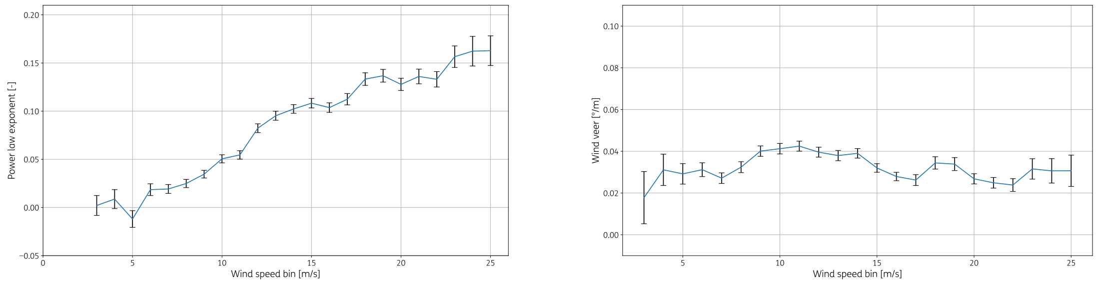

Figure B.36: Wind shear and veer as function of wind speed for 2019

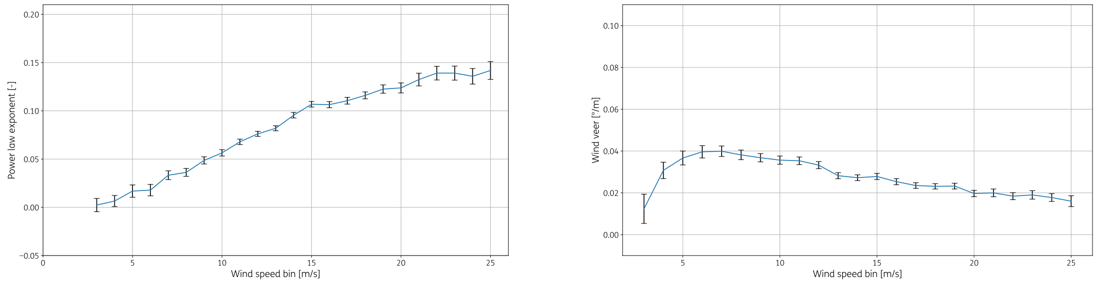

Figure B.37: Wind shear and veer as function of wind speed for 2020

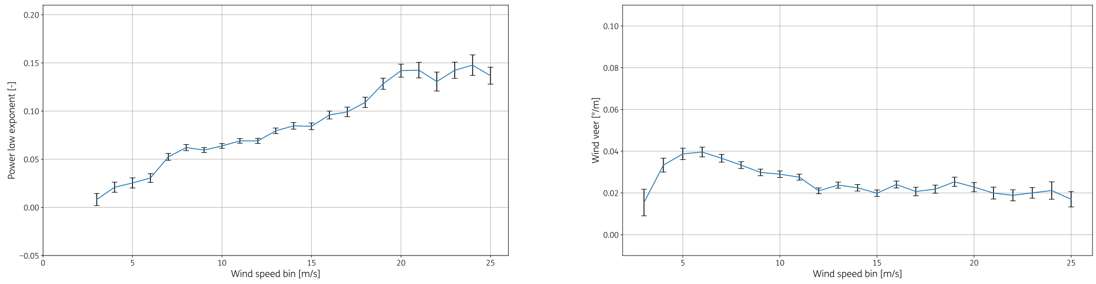

Figure B.38: Wind shear and veer as function of wind speed for 2021

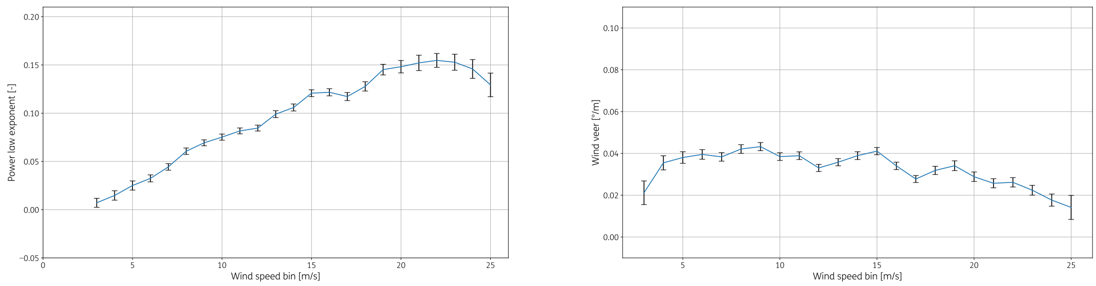

Figure B.39: Wind shear and veer as function of wind speed for 2022

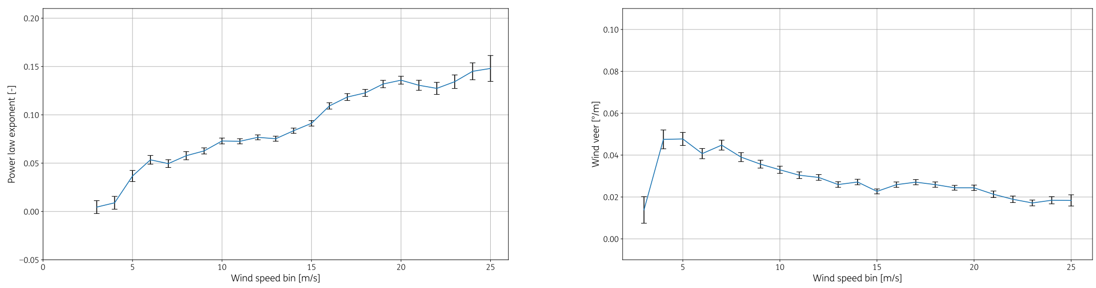

Figure B.40: Wind shear and veer as function of wind speed for 2023

B.4.4 Wind shear and veer as function of wind direction

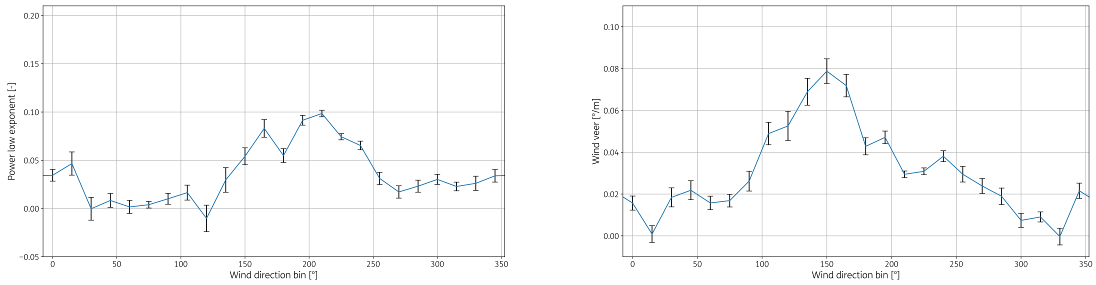

Figure B.41: Wind shear and veer as function of wind direction for 2016

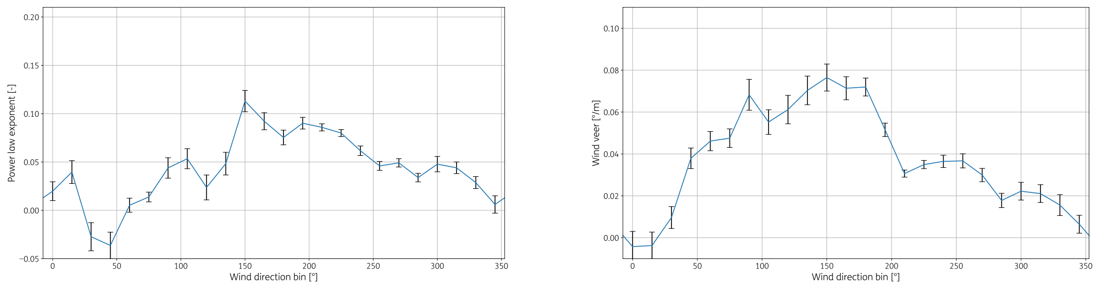

Figure B.42: Wind shear and veer as function of wind direction for 2017

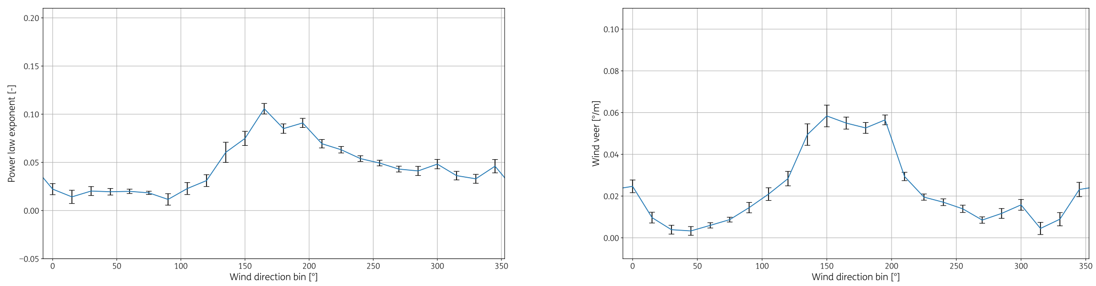

Figure B.43: Wind shear and veer as function of wind direction for 2018

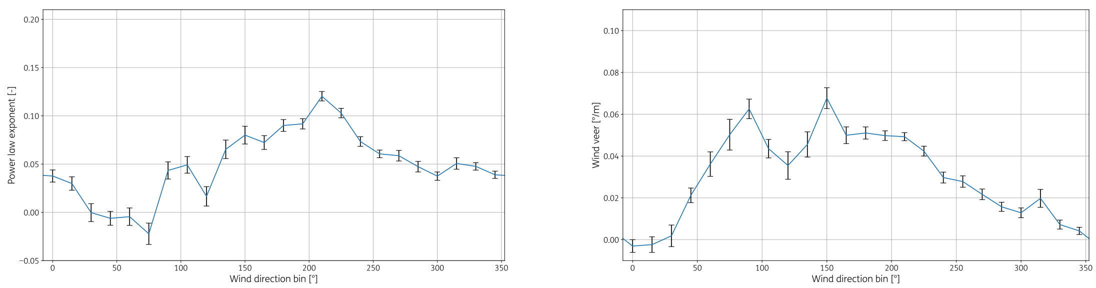

Figure B.44: Wind shear and veer as function of wind direction for 2019

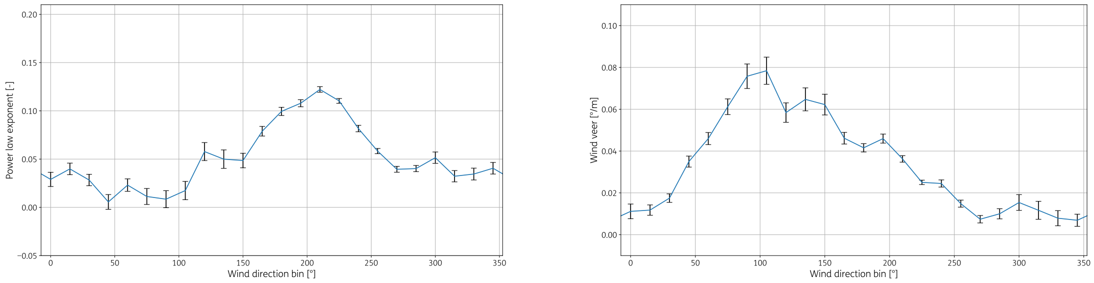

Figure B.45: Wind shear and veer as function of wind direction for 2020

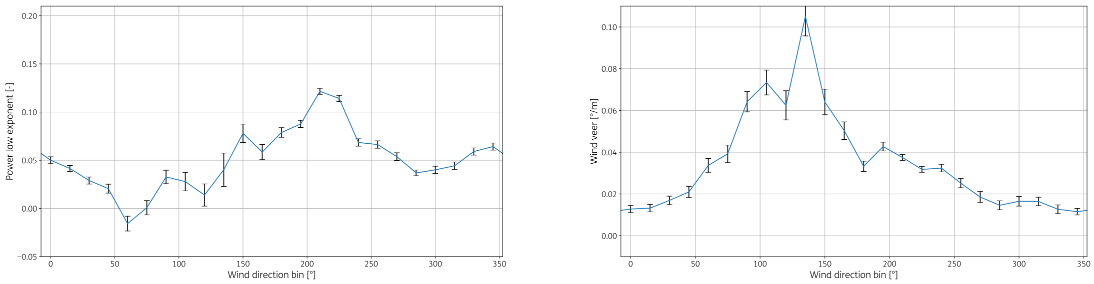

Figure B.46: Wind shear and veer as function of wind direction for 2021

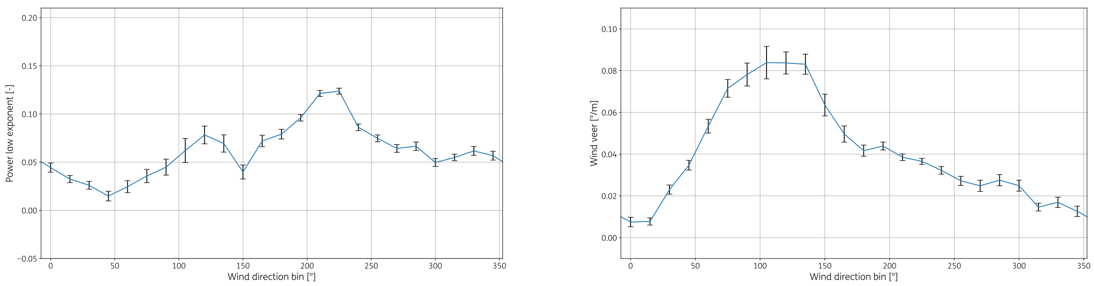

Figure B.47: Wind shear and veer as function of wind direction for 2022

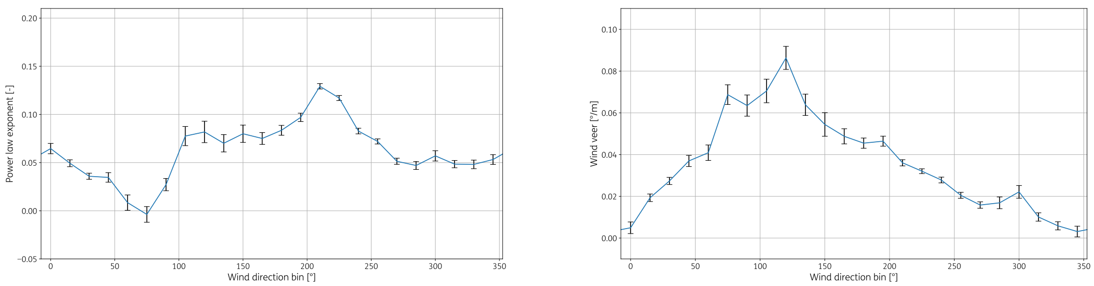

Figure B.48: Wind shear and veer as function of wind direction for 2023

B.4.5 Wind shear and veer as function of wind speed and wind direction

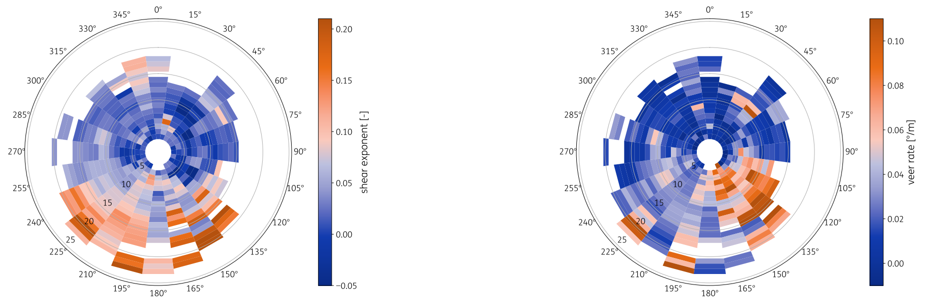

Figure B.49: Wind shear and veer as function of wind speed and direction for 2016

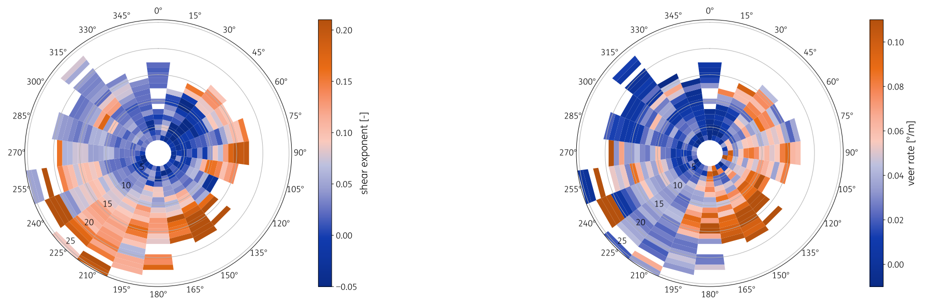

Figure B.50: Wind shear and veer as function of wind speed and direction for 2017

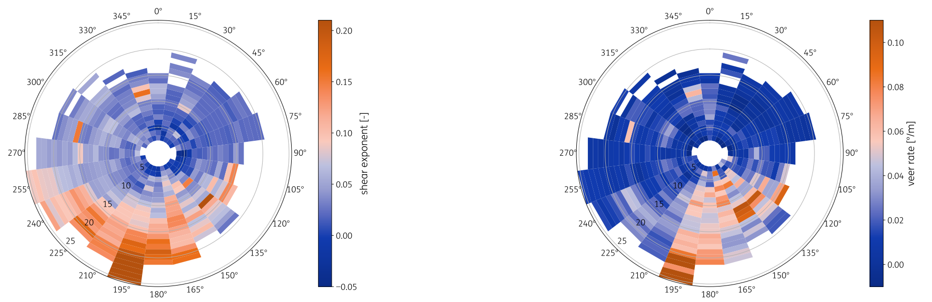

Figure B.51: Wind shear and veer as function of wind speed and direction for 2018

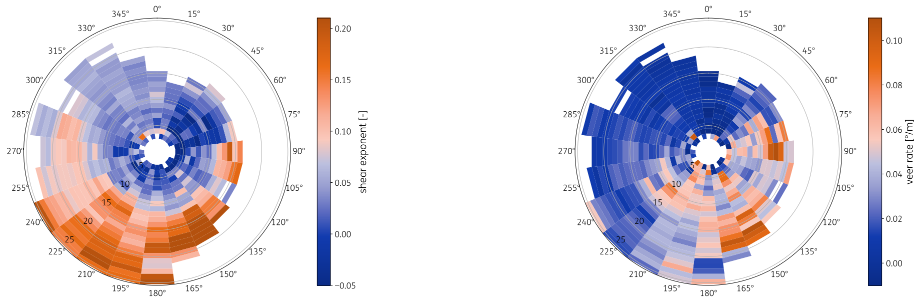

Figure B.52: Wind shear and veer as function of wind speed and direction for 2019

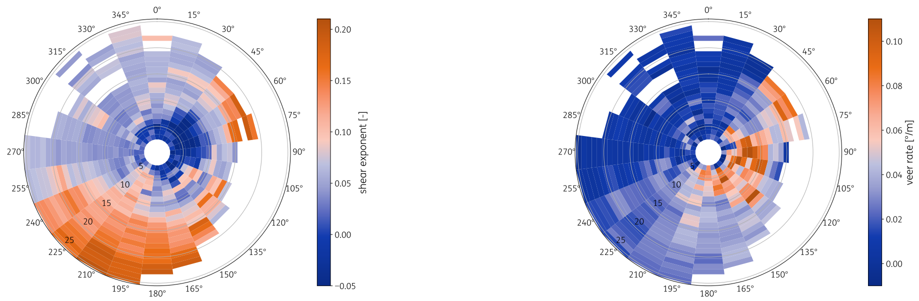

Figure B.53: Wind shear and veer as function of wind speed and direction for 2020

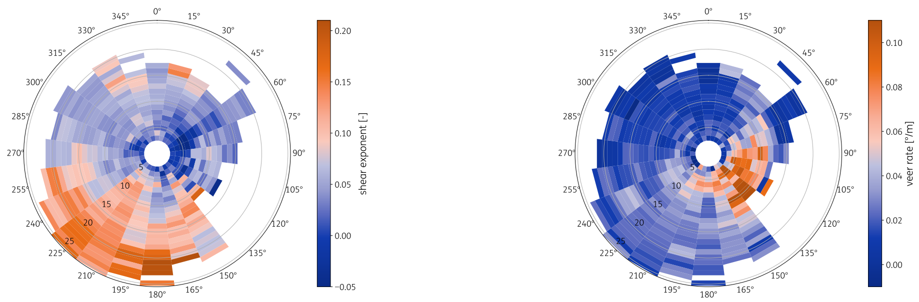

Figure B.54: Wind shear and veer as function of wind speed and direction for 2021

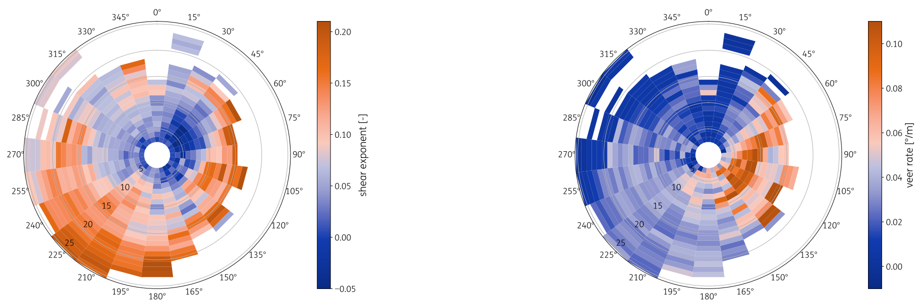

Figure B.55: Wind shear and veer as function of wind speed and direction for 2022

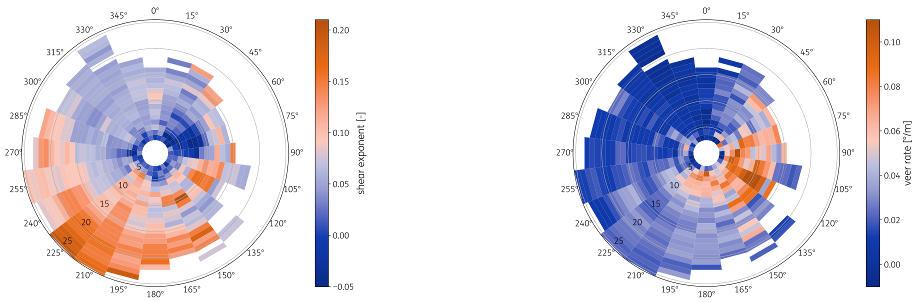

Figure B.56: Wind shear and veer as function of wind speed and direction for 2023

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Westerduinweg 3
1755 LE Petten
www.tno.nl