Lichteiland Goeree, 2014 – 2023

Offshore wind resources at the North Sea

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TNO Wind Energy is accredited conform ISO / IEC 17025 and accepted as RETL under IECRE WE.

- 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 LEG platform where a Vaisala Wind-Cube lidar has been deployed, providing high quality data since 2014. The data are publicly available to be used for further purposes (offshorewind-measurements.tno.nl).

At the LEG platform, the wind analysis for the 2014 - 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 9.05 m/s at the lowest measurement height of 62 m up to 10.56 m/s at 290 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 = 2.125 and c = 11.13 m/s at 140 m height).

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Abbreviations

CNR	carrier-to-noise ratio
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
MSL	mean sea level
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 a project is the wind resource assessment (WRA) of a given site. Therefore, accurate long-term offshore wind measurements allow for improved estimations of WRAs by reducing uncertainties and increasing the financial success of a project. This increases the trust between the 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 LEG platform, located about 30 km south-west from the coast of Hoek van Holland.

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

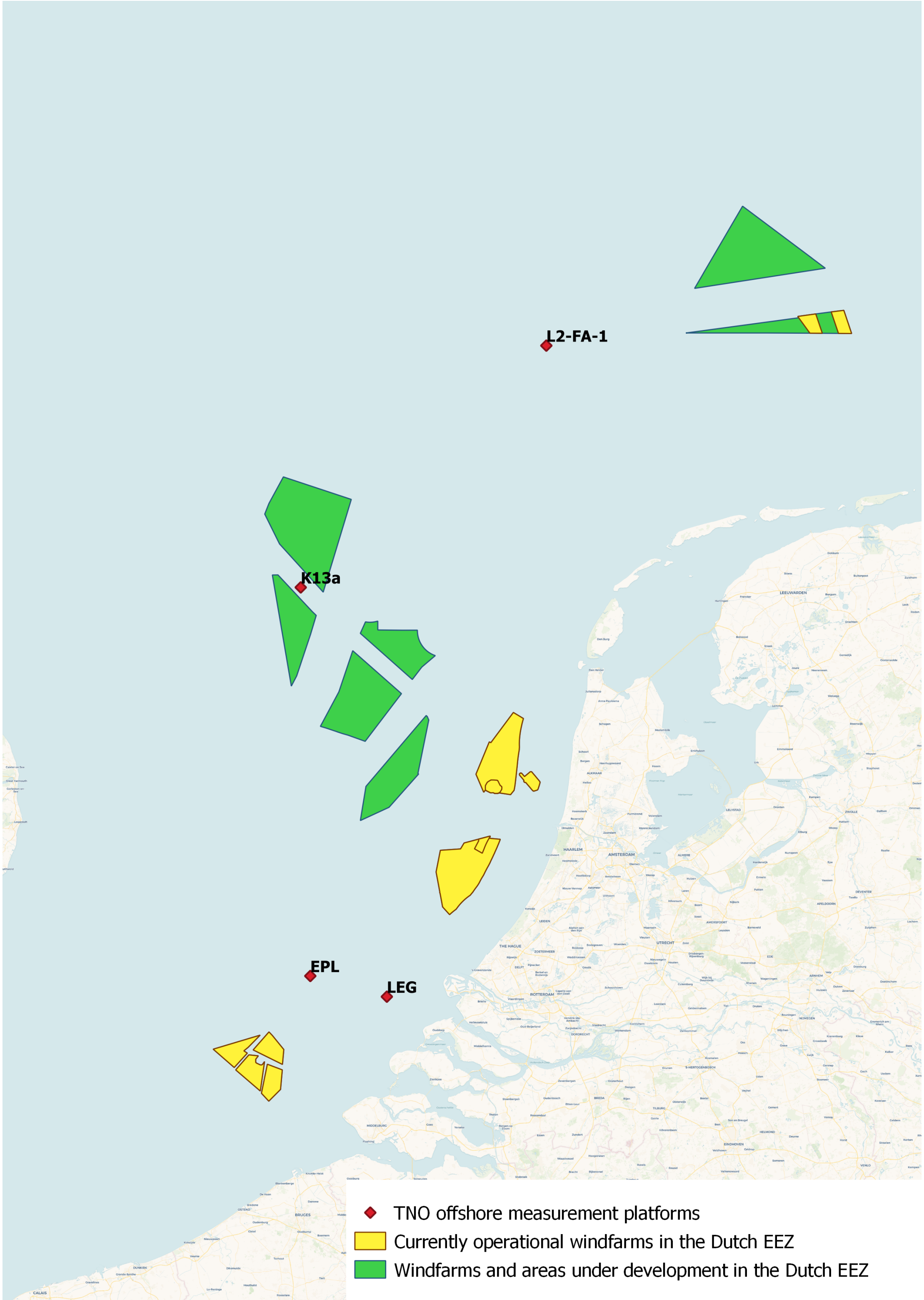


Figure 1.1: TNO long-term offshore wind measurement campaign locations at Lichteiland Goeree (LEG), Europlatform (EPL), Wintershall platform K13-A (K13a) and L2-FA-1, along with wind farm development zones in the Dutch North Sea.

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 LEG location. These reports are available at offshorewind-measurements.tno.nl. This report includes the specific wind conditions for the period 2014-2023 at the LEG platform. This report has been updated with improved practices for deducing the wind direction, wind veer and wind shear [4].

Table 2.1: Publication history of wind conditions at LEG

Period	Report
2014 – 2019	TNO 2020 R10511 [5]
2014 – 2020	TNO 2021 R11202 [6]
2014 – 2021	TNO 2022 R10649 [7]
2014 – 2022	TNO 2023 R10579 [4]

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       = {Lichteiland Goeree LiDAR measurement campaign},
subtitle    = {Instrumentation Report 2022},
number      = {TNO 2022 R10766},
date        = {2022-07-28},
url         = {https://publications.tno.nl/publication/34639948/kSiuMj/TNO-2022-R10766.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 energy deployment in the North Sea by 2030:
                long-term measurement campaign},
subtitle    = {Lichteiland Goeree, 2014 -- 2023},
number      = {TNO 2024 R11674},
date        = {2024-11-14}
```

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 LEG measurement campaign please adhere to the following information:

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

3 Measurement campaign at LEG

3.1 Location, lidar installation and operation

The LEG platform is located about 30 km south-west from the coast of Hoek van Holland, see figure 1.1. Serving as a beacon for ships on the North Sea, it includes a helicopter pad, accommodation deck and a lighthouse, see figure 3.1. The platform is part of the North Sea Monitoring Network consisting of several permanent monitoring locations over the North Sea.

Since its installation in October 2014, TNO has been conducting an ongoing measurement campaign at LEG, and has accumulated meteorological data, knowledge about installation practices, maintenance, replacement, and observations of weather conditions that have occurred at the site. Figure 3.1(c) shows the lidar at its location on the platform.

On this platform, the Royal Netherlands Meteorological Institute (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.

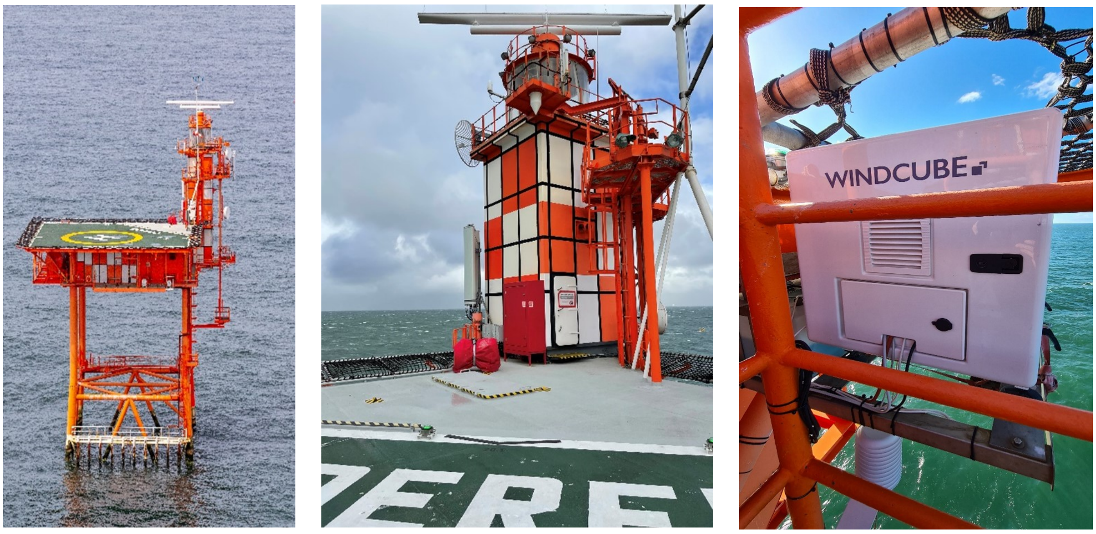
To ensure good quality measurements it is crucial to select the right location for the lidar on the platform. The description and information regarding the installation at the LEG platform is described in the instrumentation report [8].

The lidar at LEG is a Vaisala WindCube. The instrument measures wind profiles up to 10 different heights by sending infrared pulses into the atmosphere (see appendix A for additional lidar specifications). Before the lidar was installed at the LEG platform, it was first calibrated, see latest calibration reports [9, 10]. The lidar was mounted 22 m above mean sea level (MSL) and provides both wind speed and direction measurements at 10 different heights between 62 m and 290 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 EPL, K13a and L2-FA-1 platforms. Manufacturers guarantee data quality up to 200 m although the WindCube can measure up to a height of 300 m. The analysis of the data at the highest measurement levels shows the same quality patterns as at the guaranteed heights .

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.

To ensure that the highest data availability is achieved, especially for the many floating lidar system verification campaigns that take place around the platform, an additional lidar was placed at the end of December 2023.Also this lidar was calibrated before the installation at LEG platform, see latest calibration report [11].



(a) platform (b) lighthouse beacon (c) lidar unit WLS7-127 at LEG

Figure 3.1: Lichteiland Goeree platform

Table 3.1: Replacements of lidar at the LEG platform

Lidar ID	Operational period	Reason for replacement
127	06-10-2014 to 10-04-2015	First installation, 3G communication switch
258	10-04-2015 to 28-09-2015	Switched from satellite to GSM to improve communications
127	28-09-2015 to 05-10-2017	Periodic replacement
577	05-10-2017 to 24-10-2019	Periodic replacement
258	24-10-2019 to 06-09-2021	Periodic replacement
127	06-09-2021 to present	Present lidar onsite
183	18-12-2023 to present	Present lidar onsite

Table 3.2: Down-time periods and actions taken at LEG platform during the year 2023

Date ID	Reason
27-02-2023	Periodic maintenance performed on WLS7-127 and recorded in logbook. Everything is fine.
09-10-2023 to 17-10-2023	Lidar (WLS866-0184) installed at LEG. This lidar serves as a redundant system to ensure the highest data availability.
18-12-2023	Replacement of lidar (WLS866-0184) with lidar (WLS866-0183)

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 LEG

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 measured data is classified into two categories of availability:

System availability not influenced by meteorological events, independent of the measurement height: internal temperature of the lidar, availability and wiper activation count.

Signal availability at different heights; wind speed (horizontal and vertical), wind direction, standard deviation of the horizontal wind speed and CNR. The heights considered are 62 m, 90 m, 115 m, 140 m, 165 m, 190 m, 215 m, 240 m, 265 m and 290 m, w.r.t. MSL.

The data is measured on a 10-minute basis. The data collection period started on 17 November 2014 at 13:00 UTC. 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 3.4 and figure 3.2, the data available for heights up to 215 m is on average above 87 %, while further up to 265 m the availability decreases to 77 %, and to 73 % at the 290 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 years 2017 and 2018, the two highest sensor levels showed invalid data. The analysis of the data availability is based on the available measurements periods. Therefore, the percentage of data availability in table 3.4 are biased by incomplete years along with lidar system replacements or downtime periods. Please note that the measurements started in November 2014, and data was not available from May to August in 2015.

Table 3.3: List of variables measured by the lidar. HXXX are the different measurement heights w.r.t. MSL: 62 m, 90 m, 115 m, 140 m, 165 m, 190 m, 215 m, 240 m, 265 m and 290 m

Acronym	Signal name	Units
LEG_Int_Temp	internal temperature of the WindCube	°C
LEG_Wiper_count	wiper activation count	-
LEG_HXXX_CNR	carrier to noise ratio	dB
LEG_HXXX_CNR_min	minimum carrier to noise ratio	dB
LEG_HXXX_Data_Avail	availability	%
LEG_HXXX_DSB	Doppler spectral broadening	Hz
LEG_HXXX_Wd	average wind direction	°
LEG_HXXX_Ws	average wind speed	m/s
LEG_HXXX_Ws_max	maximum wind speed	m/s
LEG_HXXX_Ws_min	minimum wind speed	m/s
LEG_HXXX_WsDisp	standard deviation of the horizontal wind speed	m/s
LEG_HXXX_Z-Ws	vertical wind speed	m/s

Higher monthly data availability is shown by the system when it has been newly installed, as seen in the periods of October to March 2015, September 2017 and October 2019. Similar behaviour seems to be present over the period of October to December 2021, and following the wiper replacement in September 2022. This leads to a conclusion that the signals suffer degradation over time, providing lower data availability in the end of its operational period. This effect is more prevalent at higher heights. This performance could be improved by a more regular maintenance, cleaning and by regularly replacing the wiper system. This will be further investigated during future maintenance.

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 of 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, [12] examines the wind speed and direction measurement campaigns at eight offshore measurement locations distributed throughout the North Sea, including the LEG 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 3.4: Annual lidar data availability. Availability > 85 % is highlighted in blue.

	62 m	90 m	115 m	140 m	165 m	190 m	215 m	240 m	265 m	290 m
2014	96.8	96.2	96.6	96.7	95.5	93.5	88.2	78.4	65.5	53.0
2015	53.7	53.7	53.0	52.4	51.7	49.9	46.3	40.4	33.5	26.9
2016	93.3	93.8	93.9	92.2	88.9	82.9	74.4	63.6	50.4	37.6
2017	61.3	61.8	61.6	60.3	57.5	52.8	47.4	40.7	12.7	8.9
2018	93.8	92.5	92.1	90.6	86.9	80.8	72.9	63.0	0.0	0.0
2019	80.1	78.7	78.4	77.3	74.5	69.3	59.7	47.3	12.6	10.0
2020	96.3	96.5	95.9	94.9	93.3	88.9	80.9	69.4	55.6	42.4
2021	87.7	87.4	86.8	86.1	84.4	80.9	75.0	66.7	56.3	46.7
2022	96.4	95.8	95.0	94.7	94.2	93.5	91.7	88.3	83.4	78.4
2023	93.9	92.4	90.8	90.4	90.0	89.1	87.0	83.3	77.9	73.7
Overall	84.3	83.8	83.2	82.3	80.3	76.7	70.8	62.7	42.8	36.3

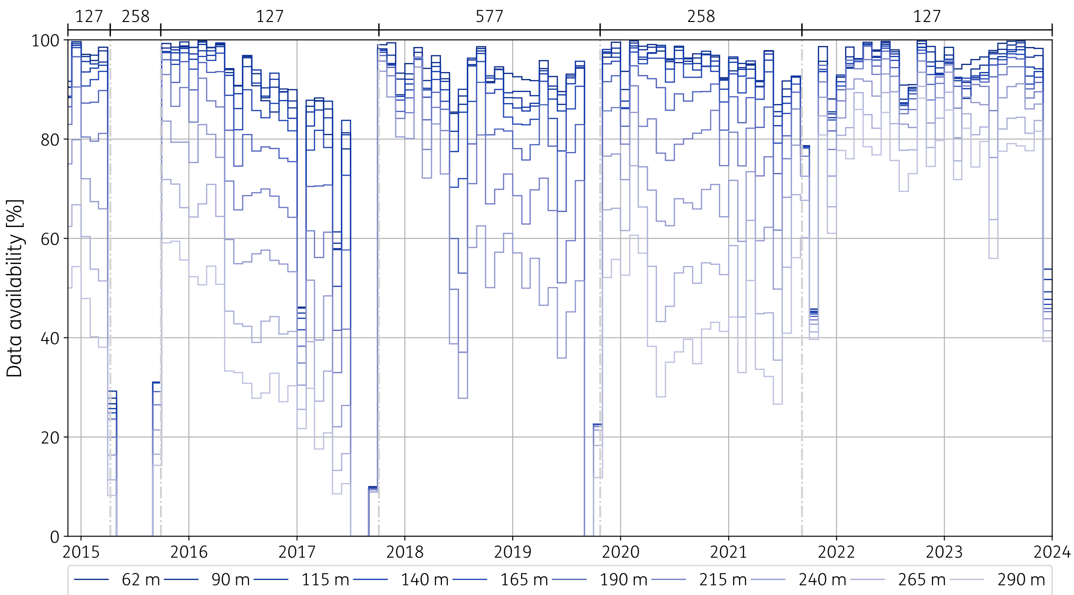


Figure 3.2: Monthly lidar data availability showing the lidar ID's and their operational periods (see table 3.1).

4 Wind conditions at LEG

This section presents the results following an assessment of the weather conditions during the entire measurement campaign at LEG. 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.

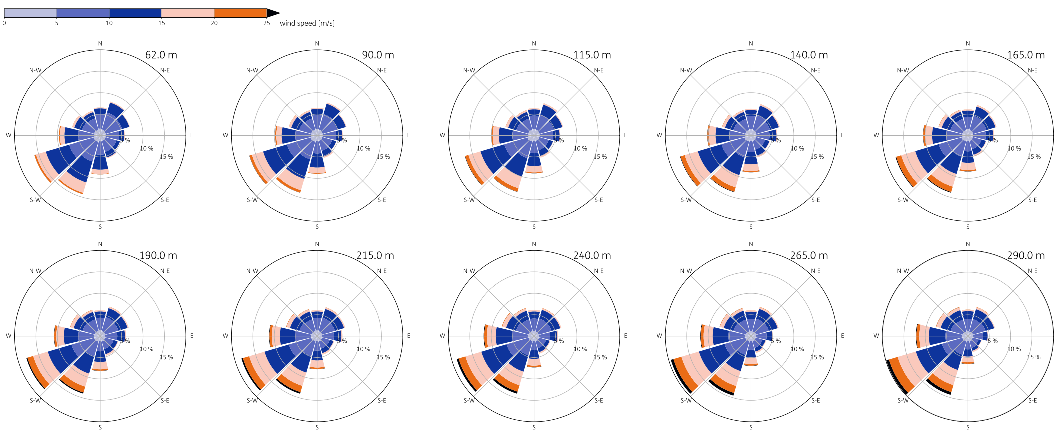


Figure 4.1: Wind roses for the complete measurement campaign

[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 140 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	°
62	404 173	6.00	8.82	11.95	33.02	9.05	235.6
90	401 943	6.09	9.06	12.41	33.46	9.33	235.5
115	399 345	6.13	9.20	12.68	34.21	9.52	235.4
140	394 836	6.21	9.35	12.95	34.99	9.71	235.8
165	385 459	6.30	9.50	13.20	36.97	9.88	236.7
190	367 833	6.39	9.63	13.43	37.50	10.04	238.5
215	339 802	6.49	9.76	13.64	37.91	10.19	241.2
240	300 931	6.61	9.93	13.87	38.27	10.34	244.3
265	205 283	6.62	10.03	14.11	38.30	10.47	245.2
290	174 162	6.62	10.13	14.29	38.62	10.56	248.3

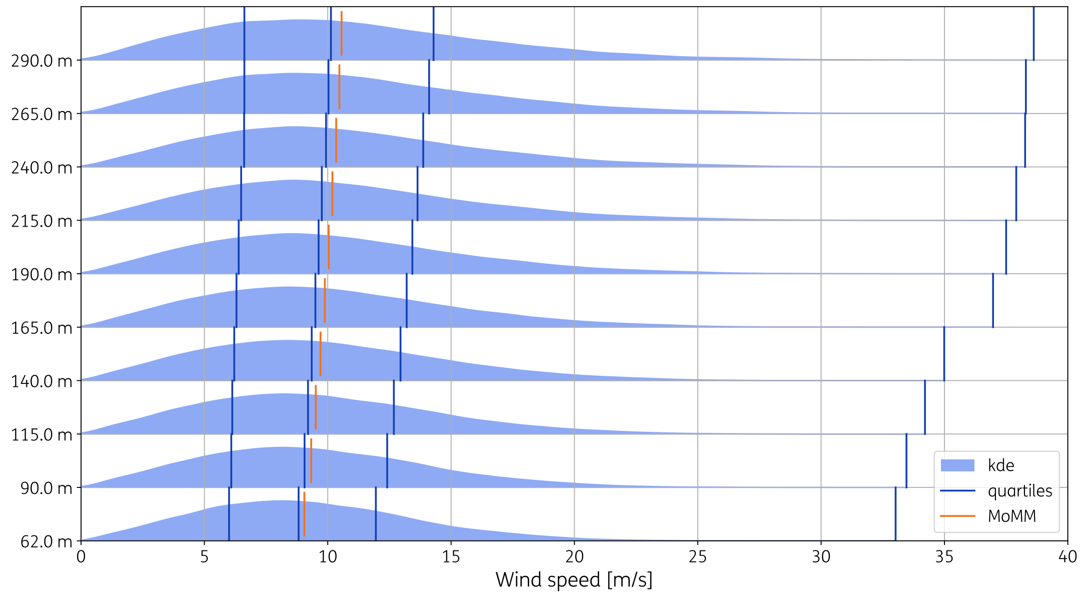


Figure 4.2: Wind speed distributions. The kde is shown with blue markers for the quartiles (Q_1, median, Q_3 and maximum) and an orange marker for the MoMM, as listed in table 4.1.

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

Height	Shape (k)	Scale (c)
m	–	m/s
62	2.253	10.36
90	2.198	10.68
115	2.153	10.89
140	2.125	11.13
165	2.101	11.35
190	2.084	11.55
215	2.075	11.75
240	2.072	11.96
265	2.041	12.13
290	2.027	12.25

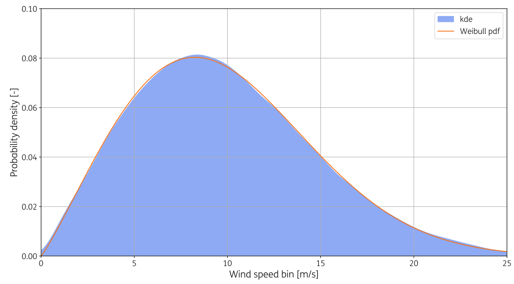


Figure 4.3: Weibull pdf of wind speed distribution at 140 m

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

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 turbulence intensity is computed for every 10-minute interval using equation (4.2). No de-trending is applied.

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

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.

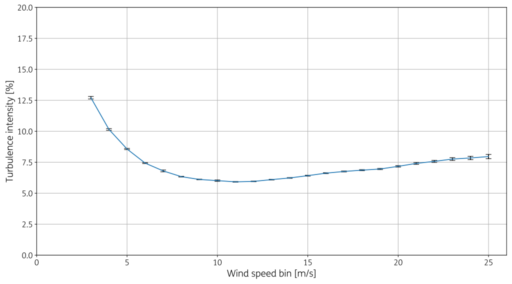


Figure 4.4: Turbulence intensity at 62 m

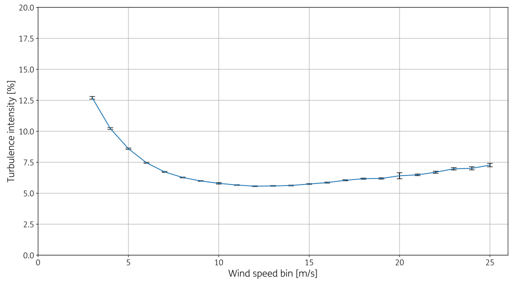


Figure 4.5: Turbulence intensity at 90 m

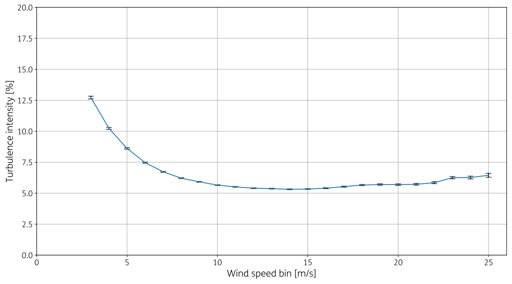


Figure 4.6: Turbulence intensity at 115 m

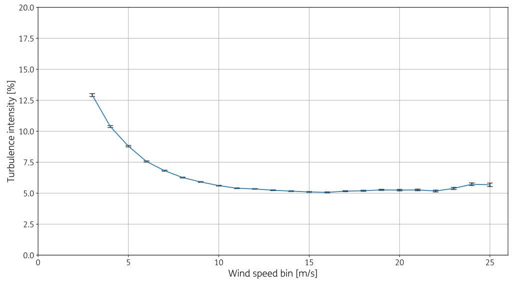


Figure 4.7: Turbulence intensity at 140 m

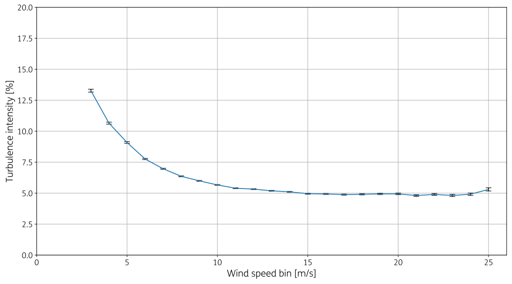


Figure 4.8: Turbulence intensity at 165 m

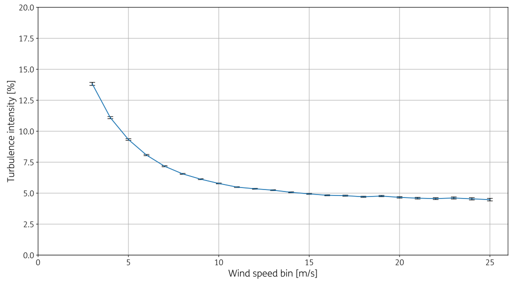


Figure 4.9: Turbulence intensity at 190 m

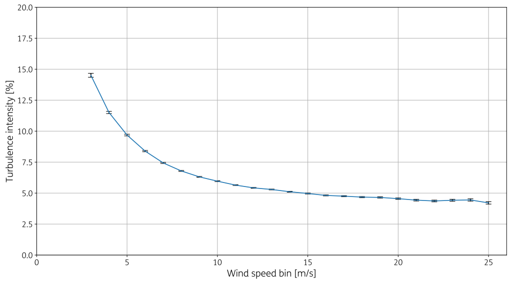


Figure 4.10: Turbulence intensity at 215 m

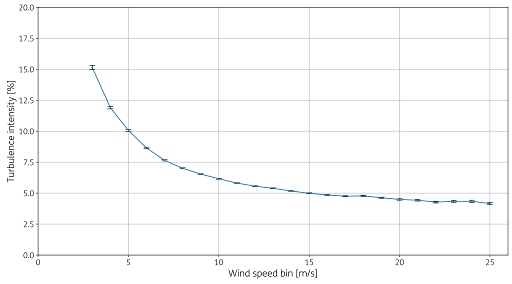


Figure 4.11: Turbulence intensity at 240 m

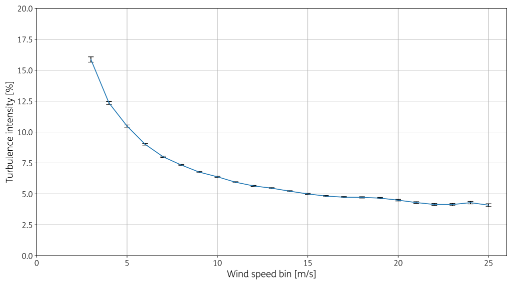


Figure 4.12: Turbulence intensity at 265 m

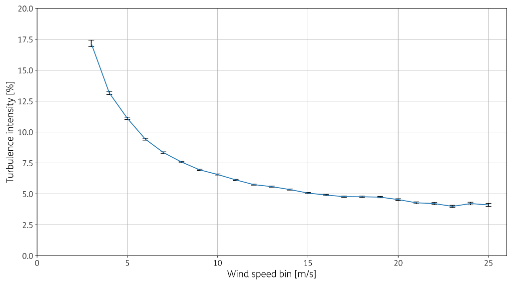


Figure 4.13: Turbulence intensity at 290 m

4.3 Wind shear and veer

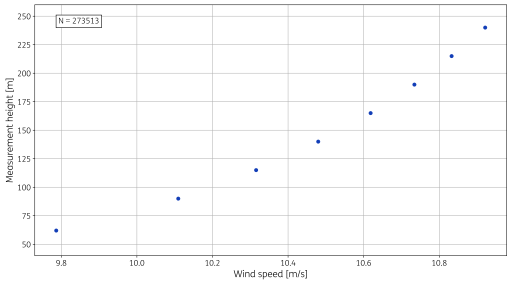
When characterizing the shear and veer, only the measurements across the swept area of a large offshore turbine rotor are included. For this (fictive) turbine a hub height of 150 m with a rotor radius of 110 m is assumed.

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.



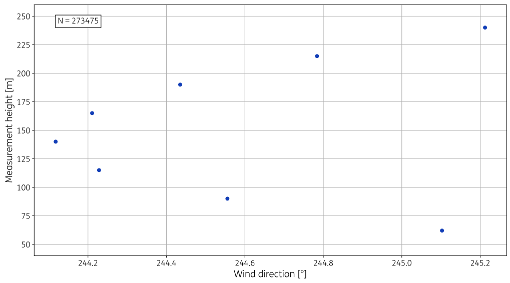


Figure 4.14: Average wind speed and wind direction (MoMM) of the dataset used for shear and veer characterization. 'N' is the number of remaining 10-minute average samples used to compute the MoMM values.

[8]This threshold is based on the MEASNET procedure [13, 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.

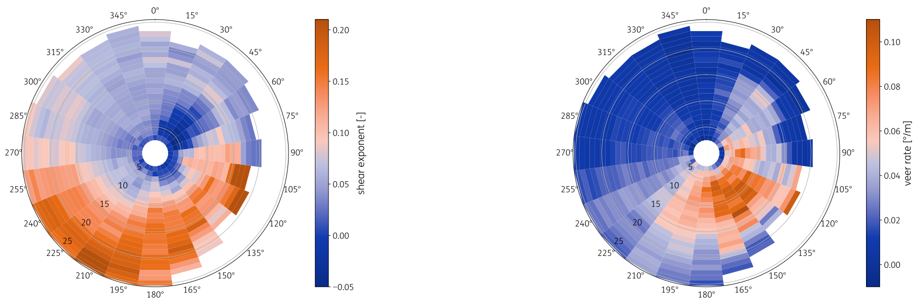


Figure 4.15: Wind shear and veer as function of wind speed and direction. The azimuth indicates the wind direction bin, the radius labels indicate the wind speed bin and the colour represents the mean value for the shear exponent (left) and veer rate (right).

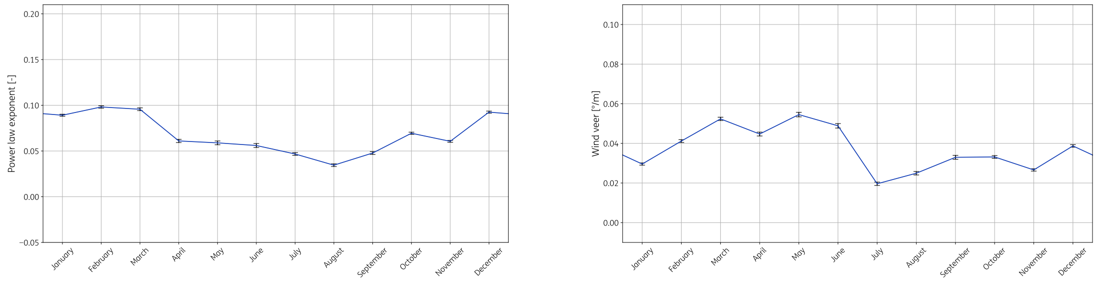


Figure 4.16: Wind shear and veer as function of the month-of-year

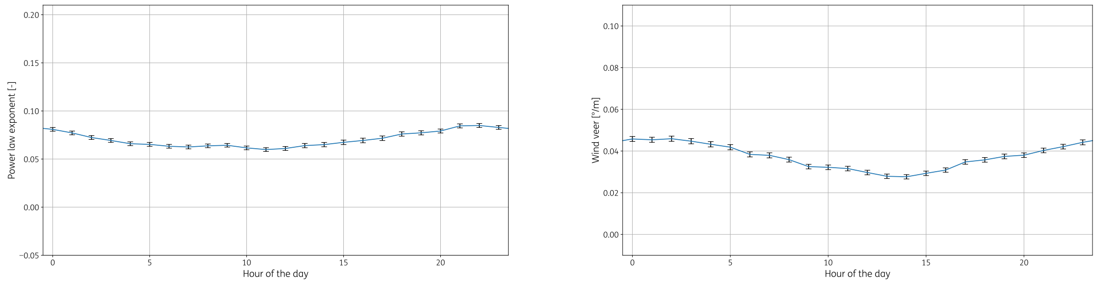


Figure 4.17: Wind shear and veer as function the hour-of-day

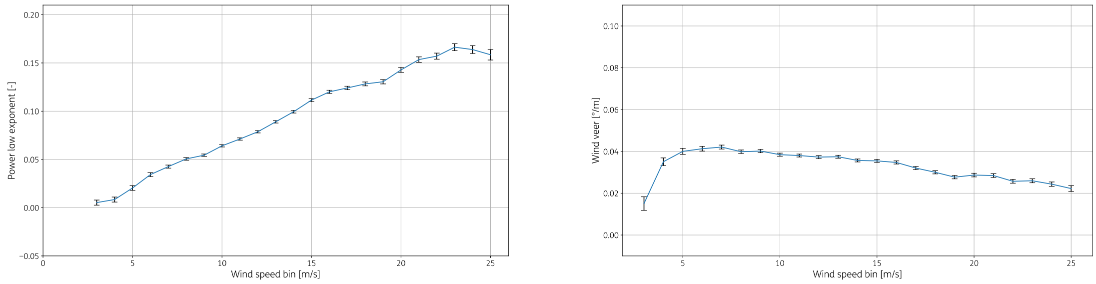


Figure 4.18: Wind shear and veer as function of wind speed

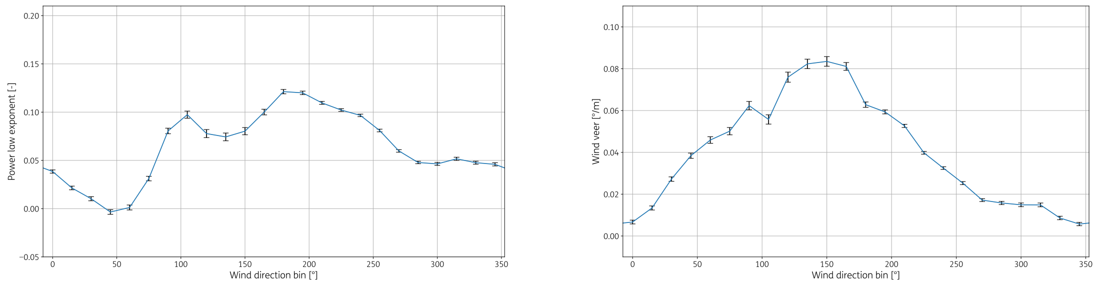


Figure 4.19: Wind shear and veer as function of wind direction

5 Conclusions and recommendations

This report refers to the measurement campaign at the LEG platform where a Vaisala WindCube lidar has been deployed since 2014, providing high quality data. The data are publicly available at offshorewind-measurements.tno.nl.

At the LEG platform, the wind analysis for the 2014 – 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 236° to 248° across the different sensor heights (62 m to 290 m). The average calculated wind speed ranges from 9.05 m/s at the lowest measured height of 62 m up to 10.56 m/s at 290 m, increasing gradually.

The Weibull distribution, indicating wind regimes and inter-annual variability, shows wind speed distributions with typical offshore wind scale (k), and shape (c) parameters (k = 2.125 and c = 11.13 m/s at 140 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 LEG is carried out on the authority of the Ministry of Economic Affairs and Climate Policy of The Netherlands.

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[14] *WindCube v2 Lidar Remote Sensor*. Leosphere, 2010.

Appendix A
Lidar specifications WindCube V2

A.1 Introduction

“The lidar sends infrared laser pulses into the atmosphere. Four beams are sent successively in four cardinal directions along a 28° scanning cone angle. Laser pulses are backscattered by aerosol particles in the air (dust, water droplets, aerosol, etc.), that move at wind speed. The collected backscattered light allows for the calculation of wind speed and direction using Doppler induced laser wavelength shift.” [14, p.10] The lidar takes measurements at 10 different heights.

The safety measures for the specific activities of how to handle the lidar are defined in the specifications and in the Annex. “the WINDCUBEv2 is a class 1M laser product and the system should be handled with caution. It is important not to stare directly into the beam with optical instruments like telescopes or binoculars. The laser beam is eye-safe according IEC EN 60825-1, January 2008” (see Annex A for additional details).

Table A.1: Lidar measurement heights relative to MSL.

Configured height	Measurement height w.r.t. MSL
m	m
40	62
68	90
93	115
118	140
143	165
168	190
193	215
218	240
243	265
268	290

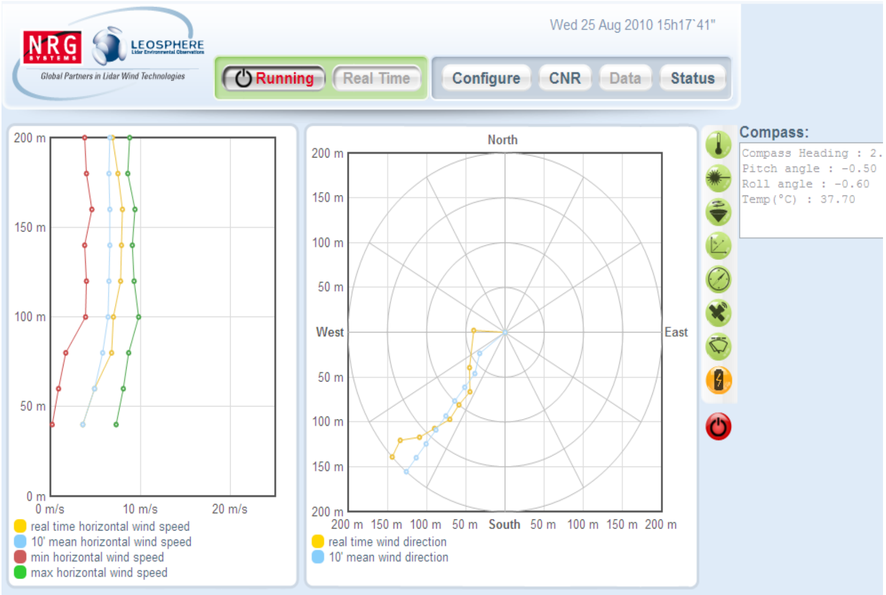

Figure A.1: WindCube V2 graphical user interface [14, p.33]

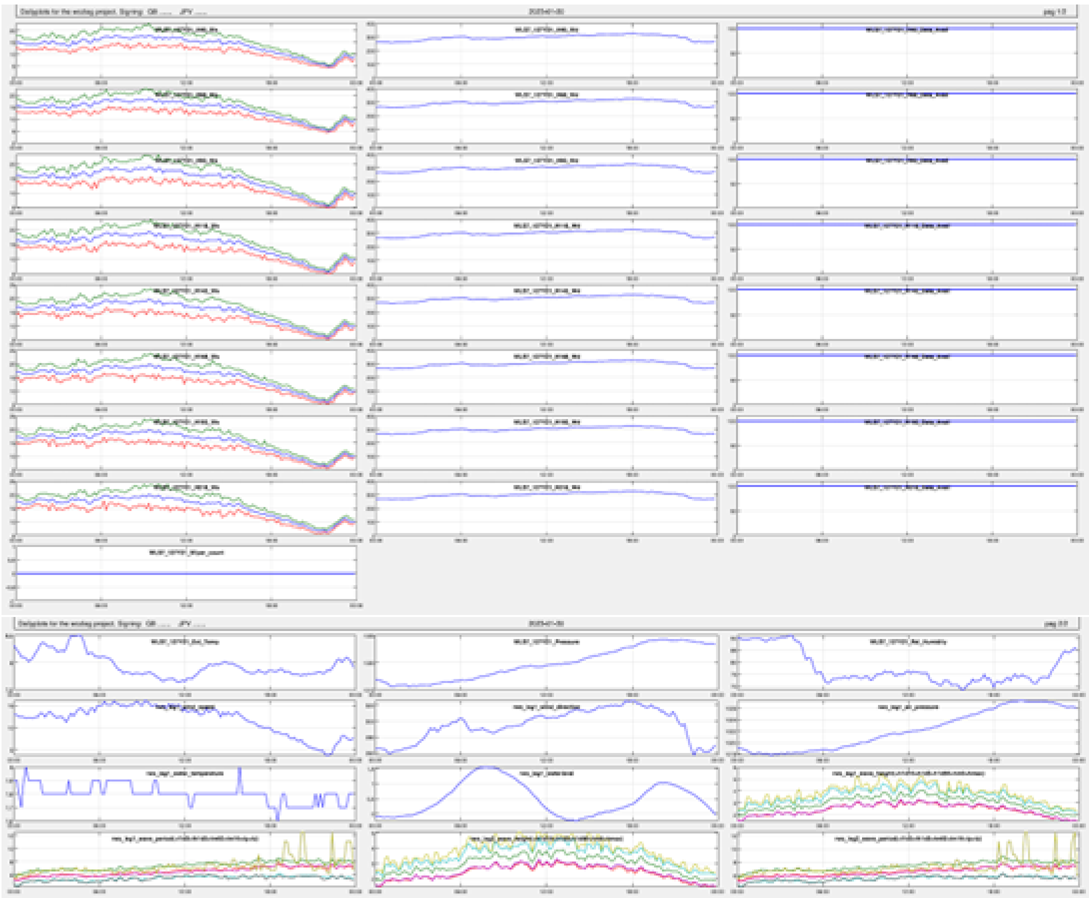

Figure A.2: Example of daily plot

MEASUREMENTS	
Range	40m to 200m
Data sampling rate	1s
Number of measurement heights	10
Speed accuracy min-max bias versus reference	0.1m/s
Speed range	0 to +55m/s
Direction accuracy	1.5°

ELECTRICAL	
Power supply	Input Power Supply (18-32V DC limited to 18-28V DC with Windcube Anywhere 3G option)
Power consumption	45W*
Temperature range	-30°C to +45°C / -22 °F to 113°F
Operating humidity	0 ... 100 %RH (non-condensing)
Rain protection	Wiper
Housing classification	IP67
Shocks & vibration	ISTA/FEDEX 6B
Safety	Class 1M IEC/EN 60825-1
Compliance	CE

* at 20° C.

TRANSPORTATION	
Size	System : 543 x 552 x 540mm Transport case : 685x745x685mm
Weight	System : 45 kg Transport case : 30 kg

SOFTWARE/DATA	
Data format	ASCII
Data storage	SSD and compact flash (backup storage)
Data transfer	LAN
Standard WINDSOFT™ Software	
	Configuration & control
	Real time display
	Diagnostic
Output data	
	1s/10min horizontal, vertical wind speed min & max
	Direction
	Carrier to Noise Ratio (CNR)
	Horizontal & vertical wind speed standard deviation
	Quality factor (data availability)
	GPS coordinates

Figure A.3: Technical specifications of the WindCube V2 [14, p.18-19]

Appendix B
Annual wind conditions during the campaign at LEG

B.1 Wind rose

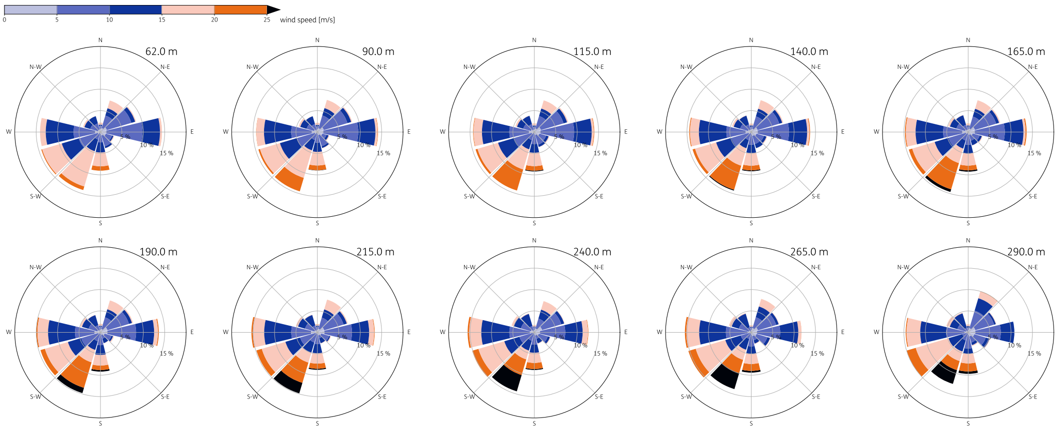

Figure B.1: Wind roses for 2014

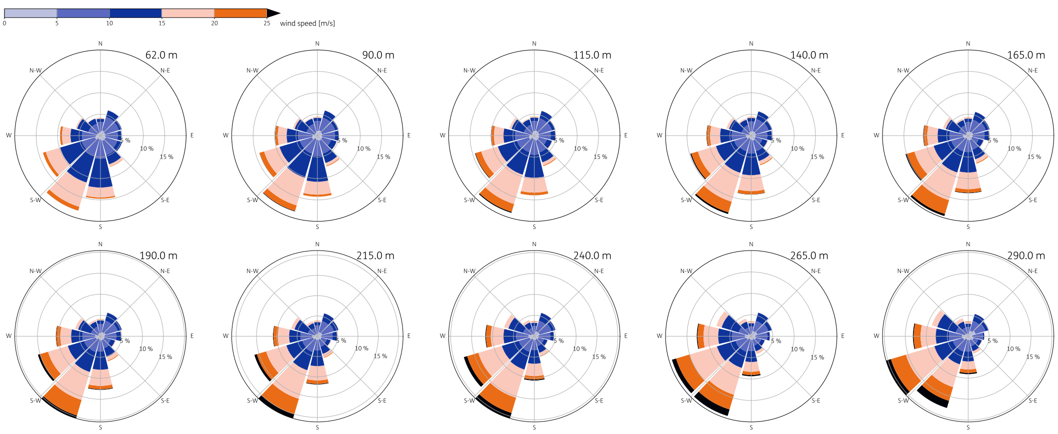

Figure B.2: Wind roses for 2015

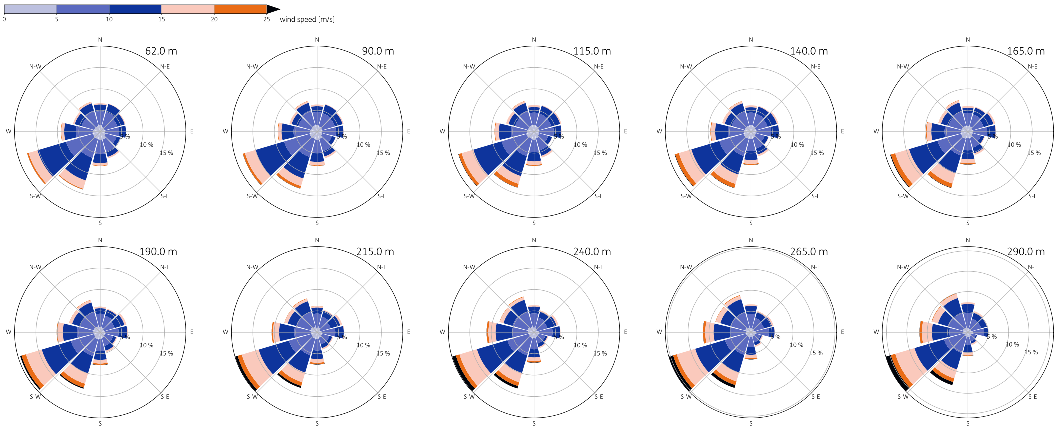

Figure B.3: Wind roses for 2016

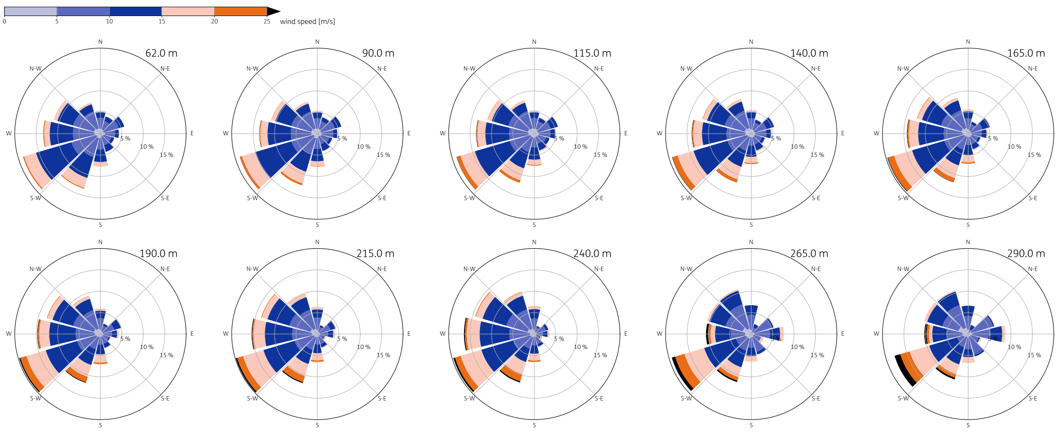

Figure B.4: Wind roses for 2017

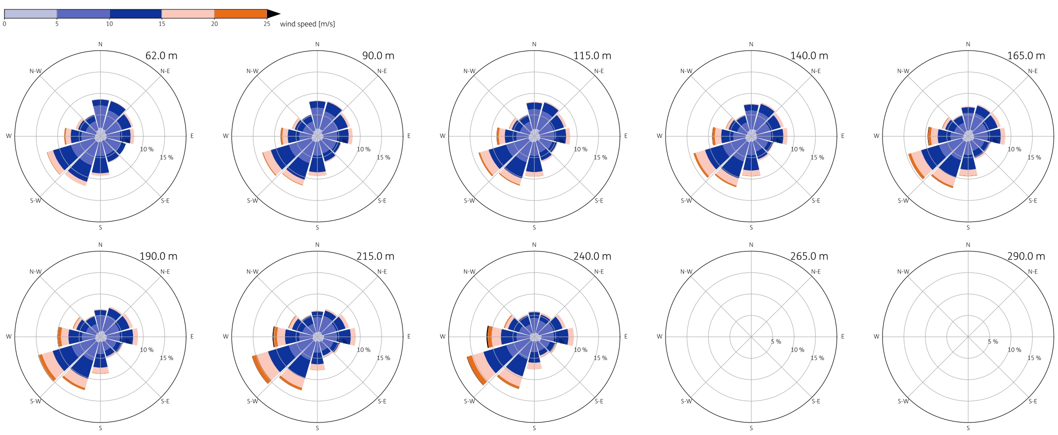

Figure B.5: Wind roses for 2018

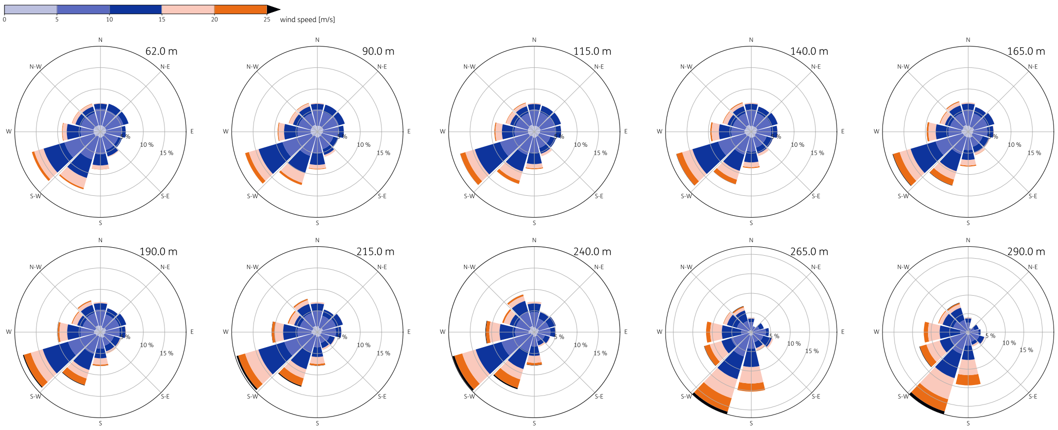

Figure B.6: Wind roses for 2019

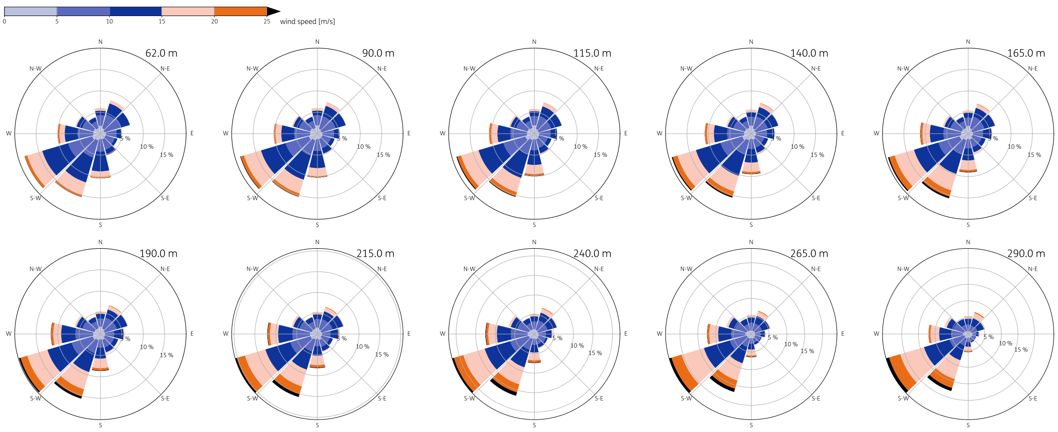

Figure B.7: Wind roses for 2020

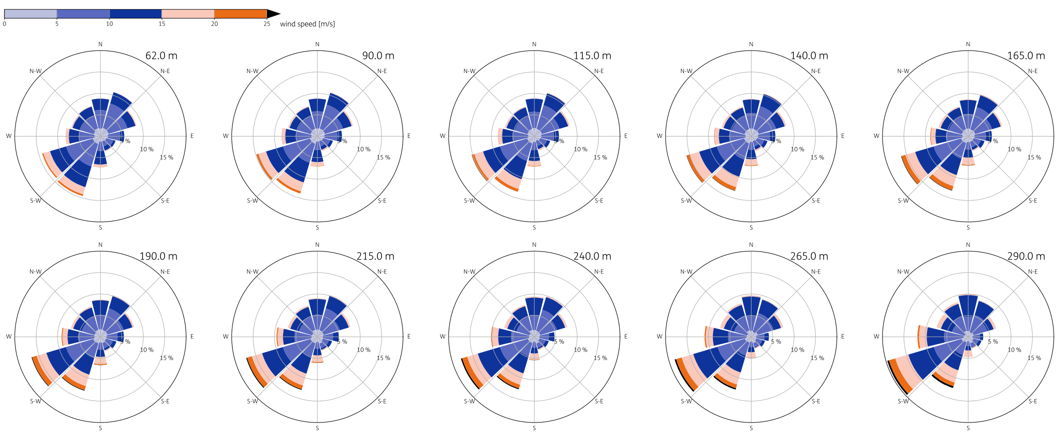

Figure B.8: Wind roses for 2021

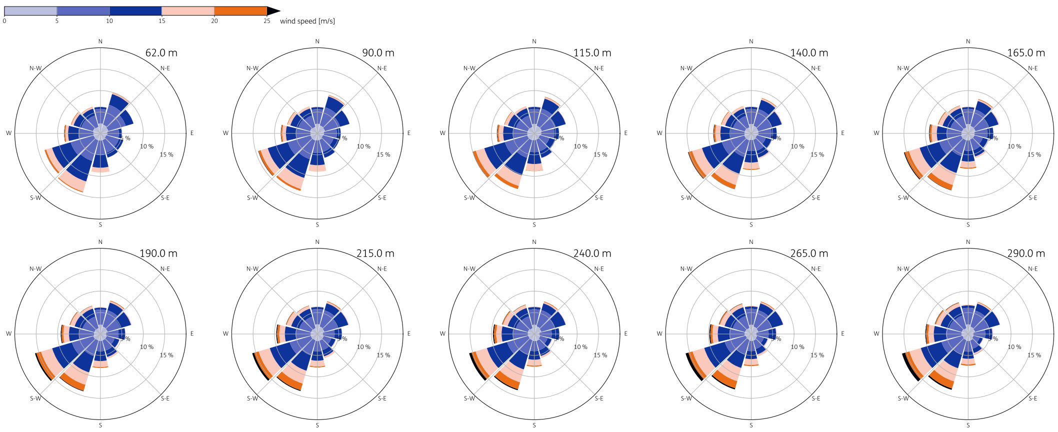

Figure B.9: Wind roses for 2022

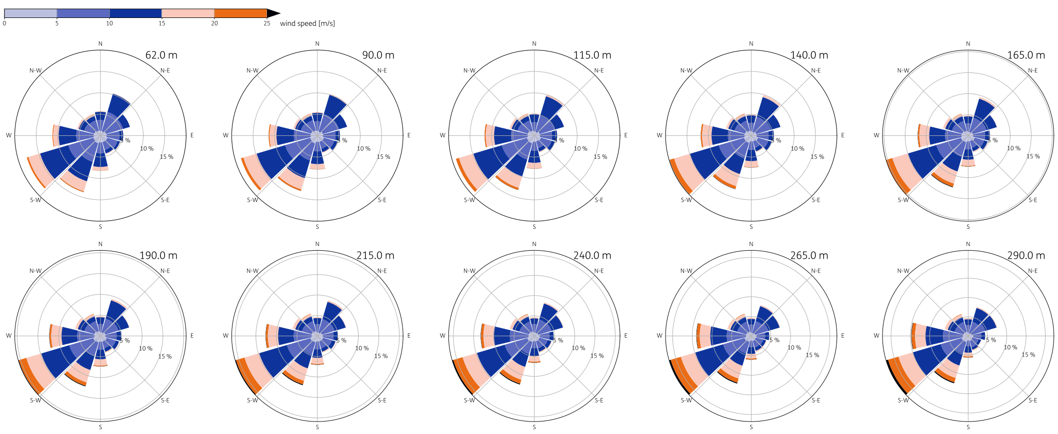

Figure B.10: Wind roses for 2023

B.2 Wind speed and direction statistics

Table B.1: Wind speed and wind direction statistics for 2014

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	°
62	6198	7.19	10.09	14.73	24.72	9.92	170.1
90	6157	7.34	10.31	15.12	25.64	10.18	174.5
115	6181	7.41	10.40	15.28	26.27	10.35	178.8
140	6188	7.42	10.52	15.42	26.85	10.47	183.0
165	6111	7.58	10.74	15.71	27.63	10.68	185.3
190	5988	7.66	10.85	15.81	28.07	10.85	187.2
215	5647	7.80	10.95	15.83	28.70	10.99	192.0
240	5018	7.99	11.16	16.14	29.25	11.19	198.3
265	4190	8.18	11.33	16.28	29.86	11.21	203.8
290	3394	7.77	11.13	16.23	29.55	10.88	208.1

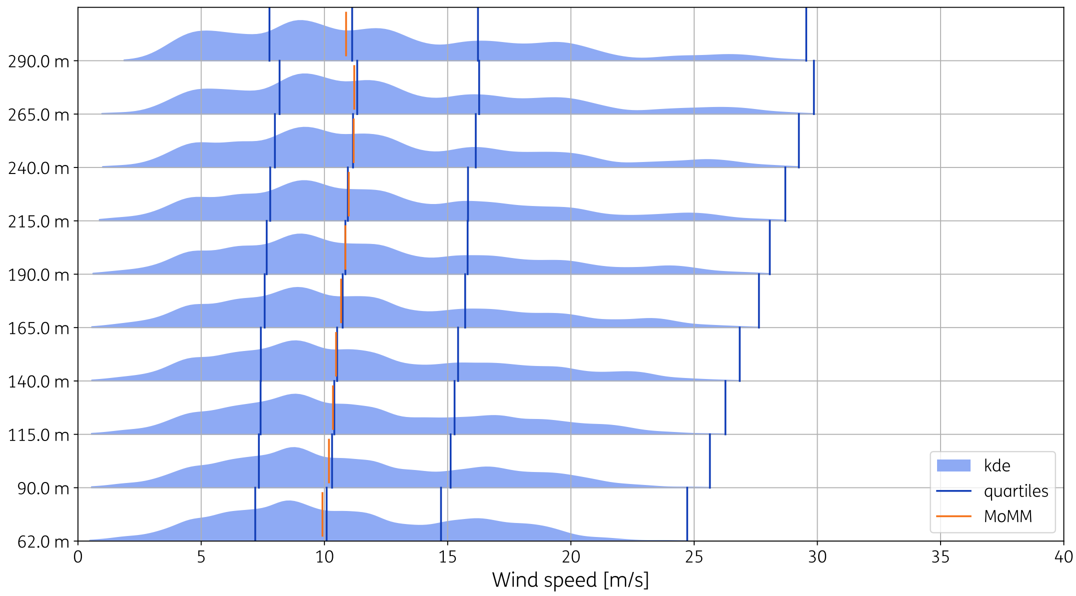

Figure B.11: Wind speed distributions for 2014

Table B.2: Wind speed and wind direction statistics for 2015

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	°
62	28 220	6.89	10.01	13.65	26.56	10.02	212.6
90	28 222	7.02	10.39	14.31	27.58	10.39	213.3
115	27 876	7.18	10.70	14.85	28.31	10.70	214.9
140	27 550	7.35	10.98	15.32	29.48	11.02	216.5
165	27 148	7.46	11.22	15.72	30.79	11.26	218.0
190	26 209	7.57	11.47	16.10	31.91	11.49	218.9
215	24 355	7.73	11.76	16.46	32.78	11.73	221.4
240	21 216	7.68	11.93	16.72	33.77	11.79	225.7
265	17 593	7.60	12.11	16.91	34.52	11.84	230.6
290	14 120	7.32	12.12	17.16	34.68	11.74	233.6

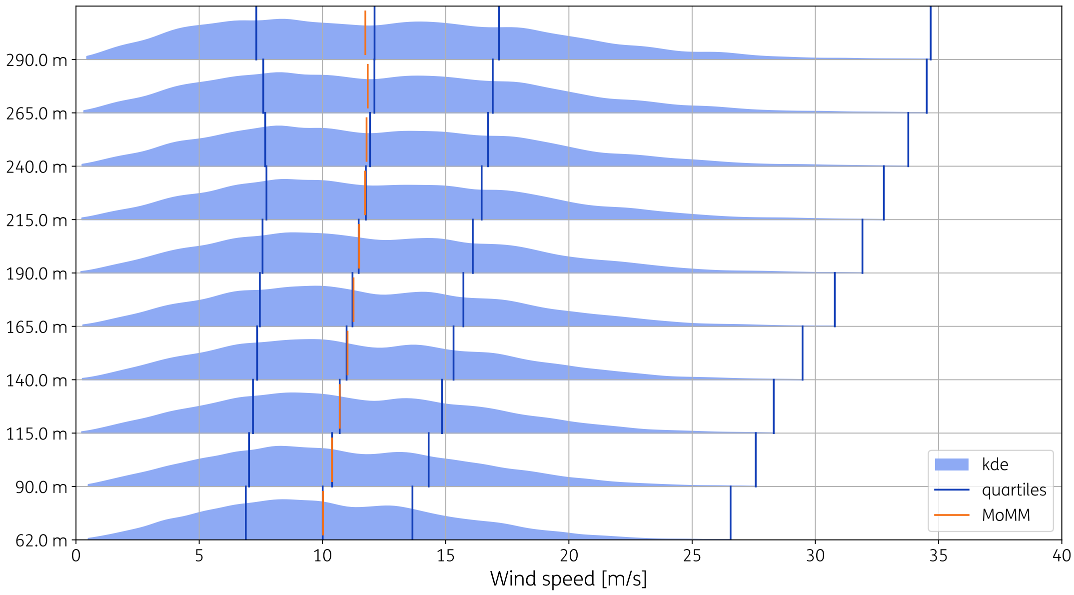

Figure B.12: Wind speed distributions for 2015

Table B.3: 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	°
62	49 198	5.86	8.61	11.70	32.07	8.92	235.7
90	49 461	5.90	8.75	12.01	33.46	9.12	235.4
115	49 478	5.91	8.86	12.23	34.07	9.28	235.3
140	48 610	6.00	8.99	12.41	34.74	9.44	235.8
165	46 863	6.10	9.15	12.62	35.46	9.61	237.4
190	43 694	6.26	9.33	12.85	35.81	9.78	240.0
215	39 223	6.39	9.51	13.07	36.25	9.96	243.7
240	33 501	6.53	9.66	13.26	36.55	10.10	247.6
265	26 567	6.70	9.88	13.57	36.99	10.31	251.2
290	19 835	6.79	10.11	13.95	35.96	10.48	255.4

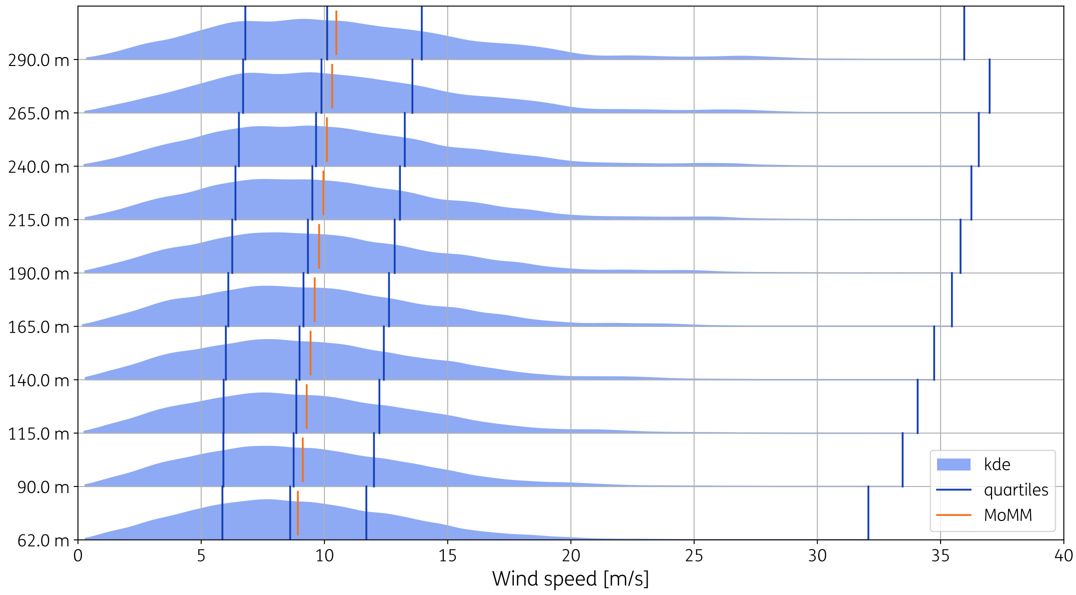

Figure B.13: Wind speed distributions for 2016

Table B.4: 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	°
62	32 240	6.71	9.46	12.38	27.52	9.23	242.2
90	32 484	6.79	9.68	12.86	29.06	9.52	242.1
115	32 382	6.81	9.89	13.20	30.06	9.76	242.5
140	31 696	6.95	10.11	13.52	30.90	9.99	243.5
165	30 208	7.11	10.30	13.83	31.51	10.20	245.2
190	27 741	7.28	10.48	14.06	32.14	10.37	247.0
215	24 908	7.41	10.58	14.27	32.57	10.47	249.2
240	21 400	7.55	10.87	14.53	32.98	10.65	250.9
265	6685	7.02	9.87	13.72	33.31	10.69	249.9
290	4695	6.89	9.83	13.78	32.98	10.92	250.9

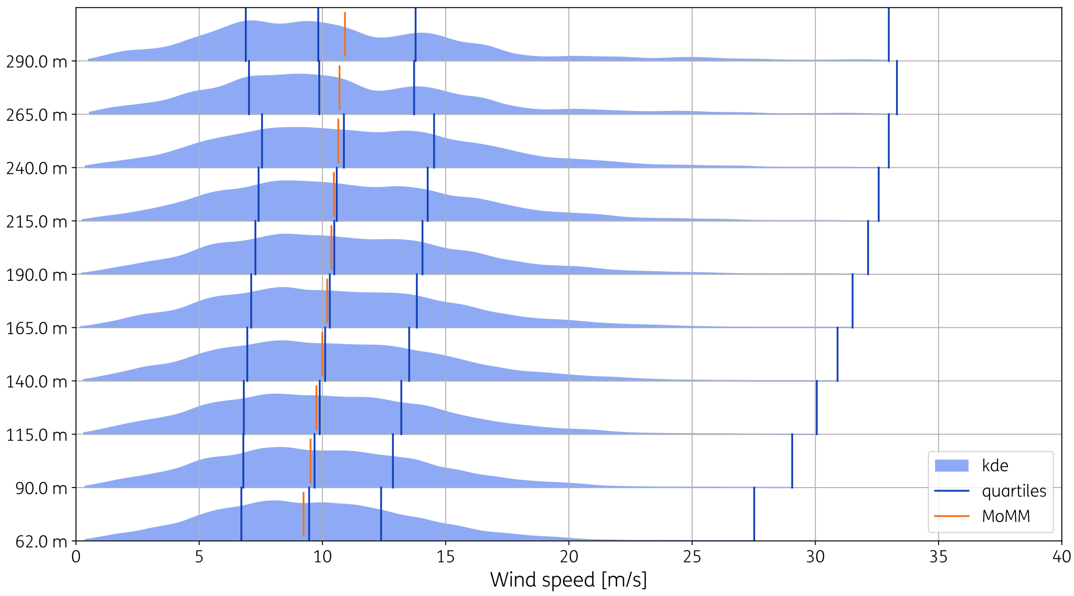

Figure B.14: Wind speed distributions for 2017

Table B.5: 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	°
62	49 305	6.01	8.64	11.47	33.02	8.87	221.2
90	48 597	6.14	8.89	11.95	32.32	9.18	222.3
115	48 407	6.19	9.02	12.23	32.93	9.37	222.9
140	47 598	6.30	9.20	12.52	33.43	9.57	224.0
165	45 656	6.45	9.39	12.76	36.97	9.74	226.4
190	42 493	6.57	9.53	12.92	37.50	9.84	231.5
215	38 291	6.69	9.66	13.09	37.91	9.96	237.2
240	33 099	6.83	9.86	13.37	38.27	10.13	242.9
265	0						
290	0						

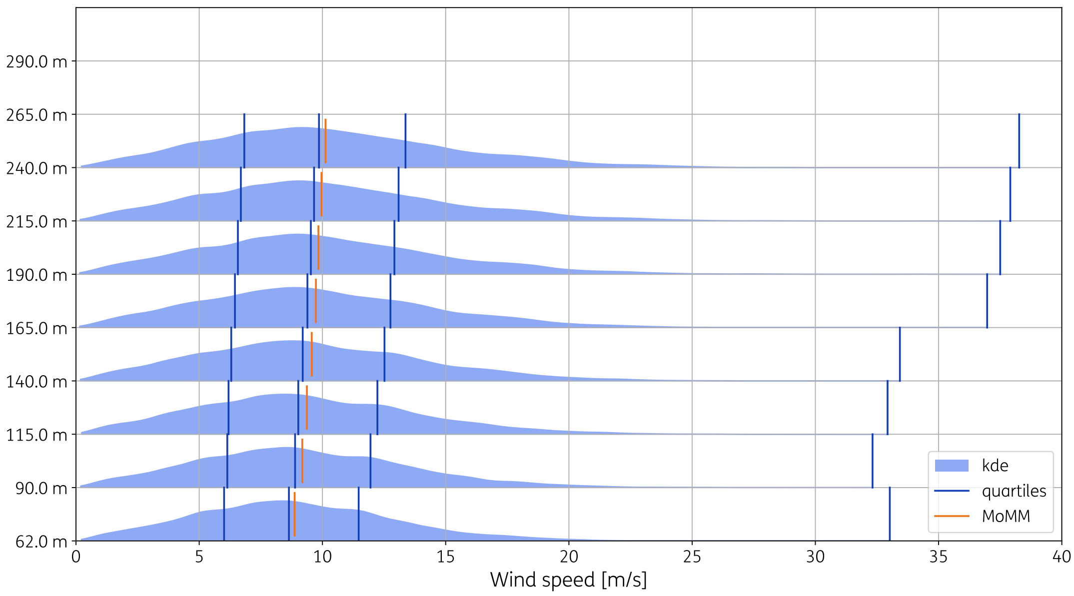

Figure B.15: Wind speed distributions for 2018

Table B.6: 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	°
62	42 085	6.04	8.52	11.44	26.65	9.03	231.0
90	41 382	6.14	8.76	11.95	27.53	9.34	232.6
115	41 230	6.17	8.86	12.23	28.15	9.53	232.9
140	40 642	6.22	9.01	12.51	28.89	9.70	233.8
165	39 142	6.30	9.13	12.78	29.61	9.88	235.0
190	36 404	6.45	9.27	13.03	30.24	10.07	237.6
215	31 364	6.70	9.54	13.44	30.74	10.33	242.1
240	24 874	7.03	9.99	13.99	31.13	10.66	247.1
265	6606	8.02	11.14	15.58	29.28	11.77	218.7
290	5269	8.29	11.66	16.07	27.47	12.06	228.1

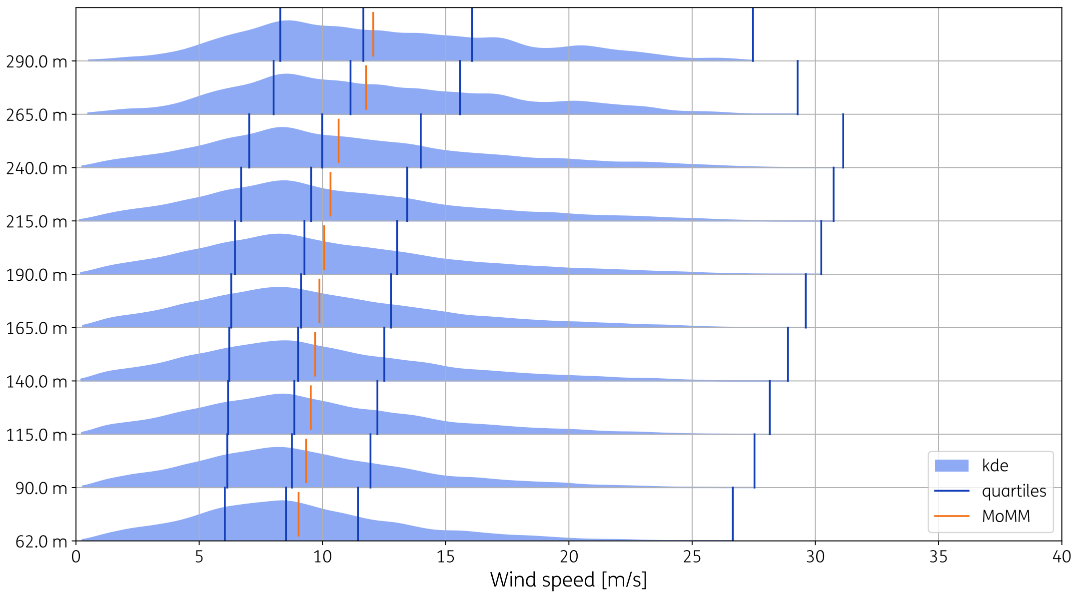

Figure B.16: Wind speed distributions for 2019

Table B.7: 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	°
62	50 774	6.10	9.35	12.62	27.18	9.62	226.8
90	50 840	6.17	9.57	13.07	28.25	9.92	226.6
115	50 524	6.18	9.68	13.38	29.48	10.11	226.6
140	50 032	6.22	9.81	13.72	30.37	10.31	226.9
165	49 168	6.30	9.95	14.00	31.40	10.49	227.1
190	46 854	6.42	10.12	14.27	32.46	10.68	228.2
215	42 648	6.57	10.30	14.60	33.58	10.86	230.8
240	36 575	6.83	10.61	15.04	34.66	11.07	234.6
265	29 282	7.19	11.07	15.51	35.43	11.32	238.7
290	22 344	7.51	11.65	16.03	36.43	11.62	242.0

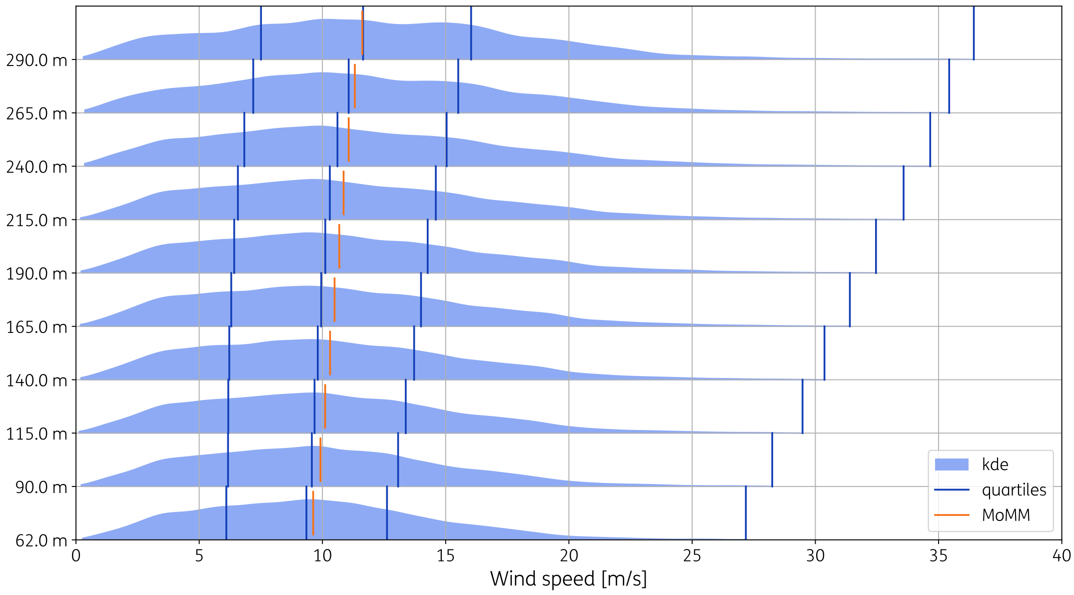

Figure B.17: Wind speed distributions for 2020

Table B.8: 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	°
62	46 121	5.59	8.34	11.28	26.41	8.70	247.6
90	45 929	5.68	8.53	11.62	27.84	8.95	247.1
115	45 638	5.72	8.61	11.80	28.80	9.09	246.7
140	45 255	5.78	8.72	11.98	29.74	9.24	246.2
165	44 337	5.83	8.83	12.12	30.53	9.39	246.0
190	42 518	5.90	8.93	12.22	31.25	9.51	247.6
215	39 444	6.00	9.08	12.35	31.93	9.62	252.1
240	35 038	6.16	9.23	12.43	32.62	9.76	256.6
265	29 587	6.38	9.48	12.66	33.63	9.98	261.2
290	24 558	6.58	9.77	12.91	34.43	10.24	263.7

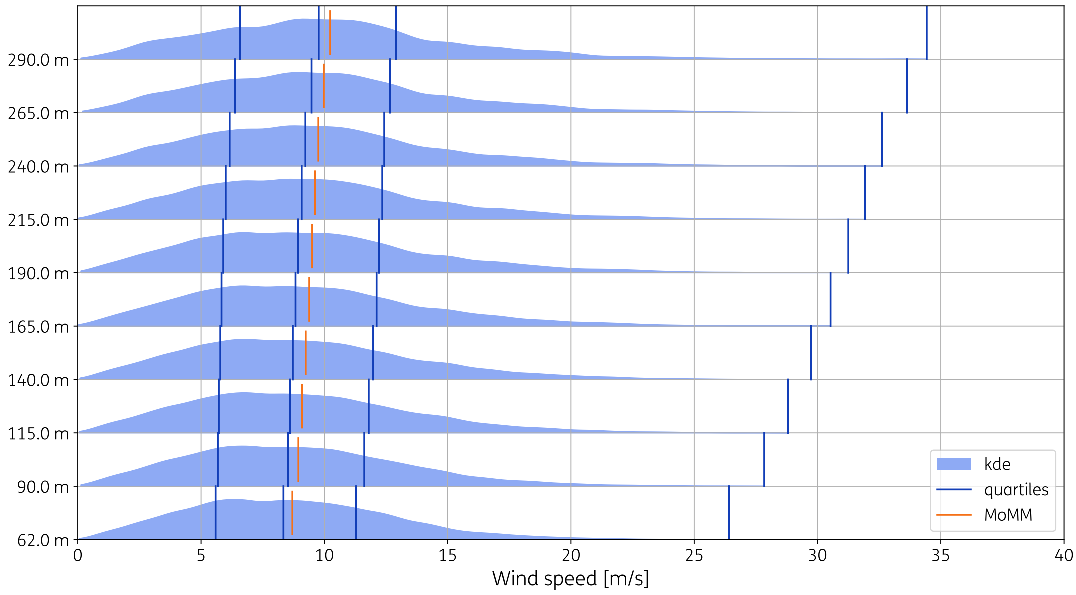

Figure B.18: Wind speed distributions for 2021

Table B.9: 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	°
62	50 694	5.50	8.20	11.42	31.97	8.70	234.2
90	50 327	5.60	8.46	11.90	33.33	9.02	233.6
115	49 920	5.65	8.61	12.14	34.21	9.22	233.9
140	49 757	5.69	8.75	12.39	34.99	9.41	234.7
165	49 507	5.74	8.86	12.65	35.64	9.59	236.0
190	49 125	5.78	8.92	12.86	36.35	9.73	237.1
215	48 191	5.78	8.96	12.99	37.11	9.83	238.7
240	46 418	5.82	9.00	13.08	37.78	9.92	240.7
265	43 845	5.86	9.04	13.20	38.30	10.01	243.0
290	41 232	5.84	9.00	13.19	38.62	10.02	246.7

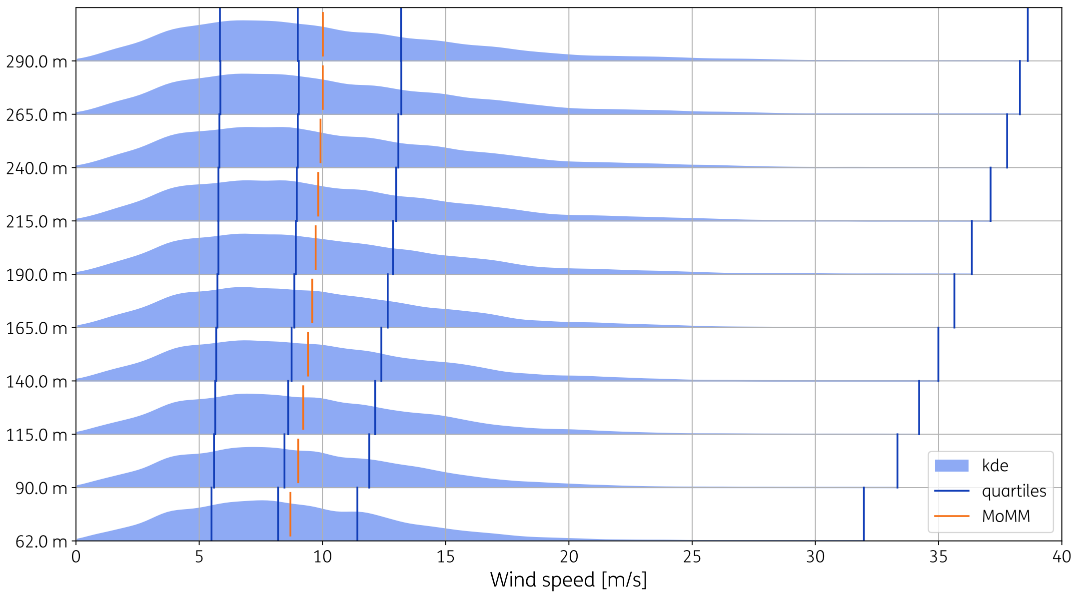

Figure B.19: Wind speed distributions for 2022

Table B.10: 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	°
62	49 338	5.92	8.98	12.11	30.19	9.22	240.1
90	48 544	6.04	9.23	12.52	30.28	9.52	240.9
115	47 709	6.09	9.39	12.72	30.92	9.70	241.3
140	47 508	6.20	9.58	12.97	31.90	9.92	241.5
165	47 319	6.26	9.68	13.18	33.32	10.09	241.9
190	46 807	6.31	9.75	13.33	33.71	10.22	242.5
215	45 731	6.36	9.80	13.45	33.90	10.31	243.2
240	43 792	6.46	9.90	13.59	34.09	10.42	244.2
265	40 928	6.57	10.04	13.80	34.37	10.55	246.0
290	38 715	6.60	10.10	13.87	34.65	10.60	247.7

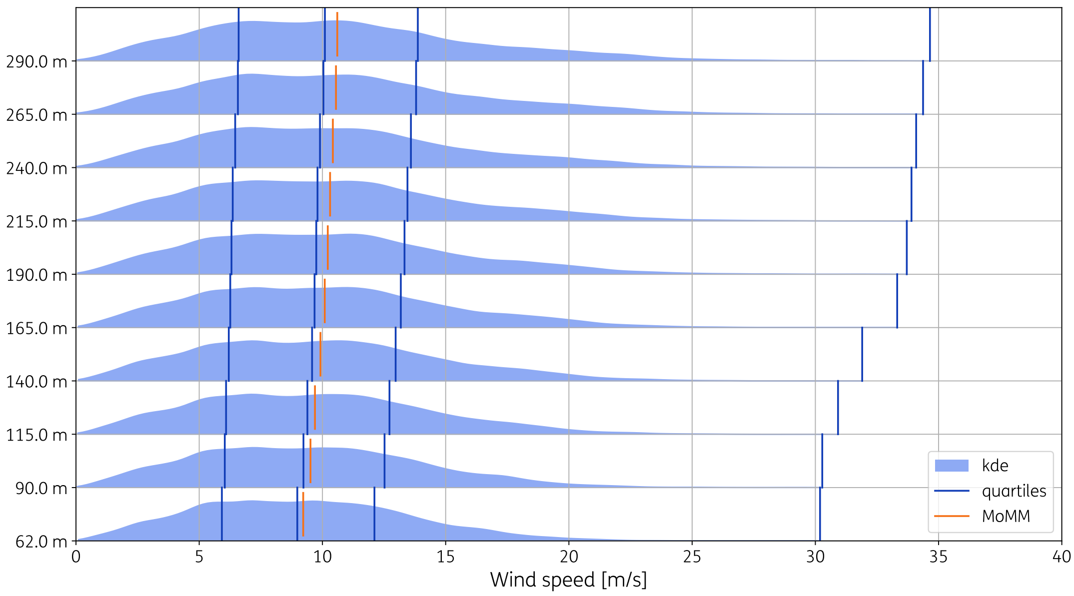

Figure B.20: Wind speed distributions for 2023

B.3 Wind speed distribution

Table B.11: Weibull parameters for 2014

Height	Shape (k)	Scale (c)
m	–	m/s
62	2.468	12.22
90	2.401	12.60
115	2.336	12.81
140	2.277	12.99
165	2.247	13.26
190	2.226	13.44
215	2.213	13.59
240	2.221	13.87
265	2.245	14.01
290	2.222	13.76

Table B.12: Weibull parameters for 2015

Height	Shape (k)	Scale (c)
m	–	m/s
62	2.395	11.77
90	2.319	12.21
115	2.284	12.61
140	2.273	12.98
165	2.246	13.27
190	2.220	13.55
215	2.201	13.84
240	2.152	14.01
265	2.117	14.12
290	2.048	14.14

Table B.13: Weibull parameters for 2016

Height	Shape (k)	Scale (c)
m	–	m/s
62	2.274	10.10
90	2.204	10.33
115	2.148	10.50
140	2.125	10.68
165	2.112	10.89
190	2.106	11.14
215	2.101	11.38
240	2.100	11.62
265	2.111	11.91
290	2.107	12.18

Table B.14: Weibull parameters for 2017

Height	Shape (k)	Scale (c)
m	–	m/s
62	2.523	10.89
90	2.445	11.21
115	2.385	11.46
140	2.363	11.75
165	2.355	12.03
190	2.363	12.28
215	2.355	12.47
240	2.366	12.72
265	2.162	12.01
290	2.088	12.05

Table B.15: Weibull parameters for 2018

Height	Shape (k)	Scale (c)
m	–	m/s
62	2.355	10.01
90	2.309	10.36
115	2.264	10.56
140	2.238	10.79
165	2.228	11.04
190	2.205	11.23
215	2.204	11.43
240	2.226	11.68
265		
290		

Table B.16: Weibull parameters for 2019

Height	Shape (k)	Scale (c)
m	–	m/s
62	2.240	10.15
90	2.188	10.49
115	2.137	10.69
140	2.101	10.89
165	2.081	11.12
190	2.080	11.38
215	2.095	11.76
240	2.116	12.26
265	2.413	13.52
290	2.513	13.97

Table B.17: Weibull parameters for 2020

Height	Shape (k)	Scale (c)
m	–	m/s
62	2.198	10.86
90	2.137	11.18
115	2.091	11.38
140	2.057	11.61
165	2.033	11.83
190	2.023	12.06
215	2.021	12.32
240	2.026	12.66
265	2.062	13.06
290	2.090	13.52

Table B.18: Weibull parameters for 2021

Height	Shape (k)	Scale (c)
m	–	m/s
62	2.236	9.74
90	2.184	10.02
115	2.140	10.18
140	2.113	10.36
165	2.086	10.52
190	2.072	10.65
215	2.081	10.79
240	2.103	10.95
265	2.133	11.22
290	2.147	11.51

Table B.19: Weibull parameters for 2022

Height	Shape (k)	Scale (c)
m	–	m/s
62	2.114	9.80
90	2.076	10.15
115	2.045	10.37
140	2.017	10.59
165	1.981	10.79
190	1.950	10.95
215	1.926	11.07
240	1.917	11.15
265	1.904	11.24
290	1.886	11.25

Table B.20: Weibull parameters for 2023

Height	Shape (k)	Scale (c)
m	–	m/s
62	2.272	10.39
90	2.228	10.70
115	2.199	10.89
140	2.168	11.14
165	2.139	11.34
190	2.118	11.48
215	2.100	11.60
240	2.091	11.76
265	2.085	11.95
290	2.073	12.05

B.4 Wind shear and veer

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

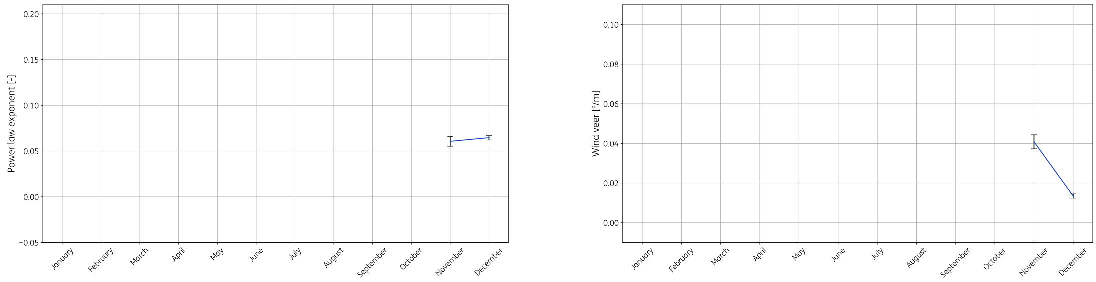

Figure B.21: Wind shear and veer as function of the month-of-year for 2014

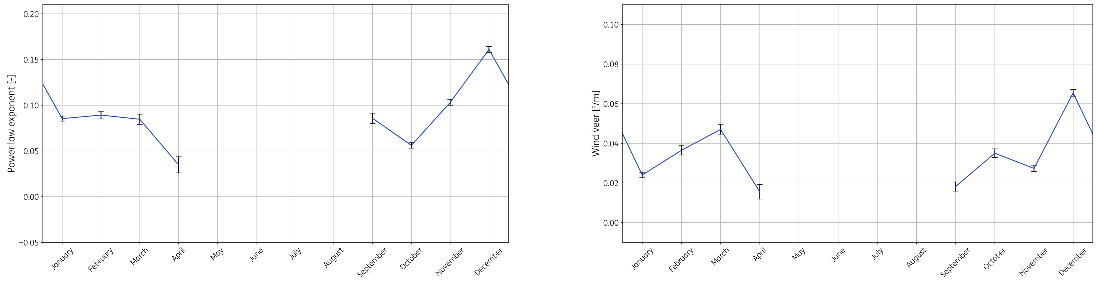

Figure B.22: Wind shear and veer as function of the month-of-year for 2015

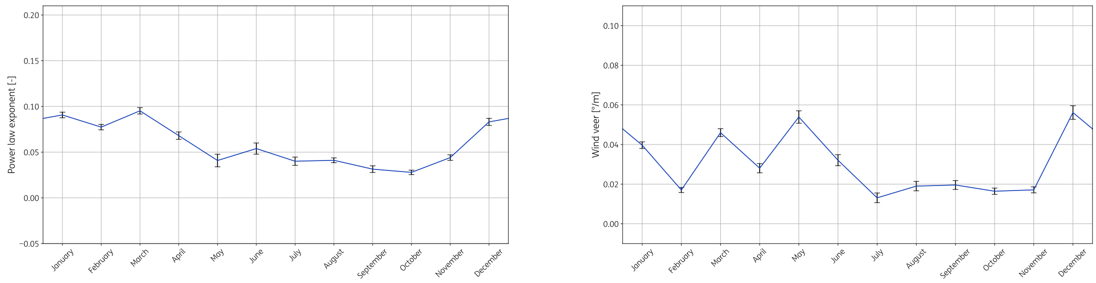

Figure B.23: Wind shear and veer as function of the month-of-year for 2016

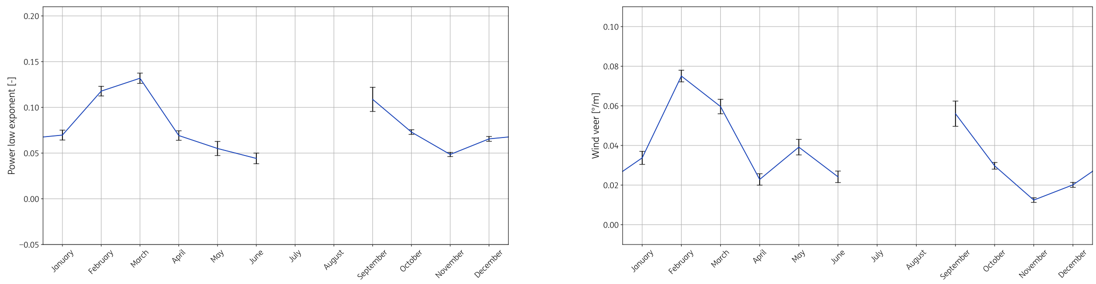

Figure B.24: Wind shear and veer as function of the month-of-year for 2017

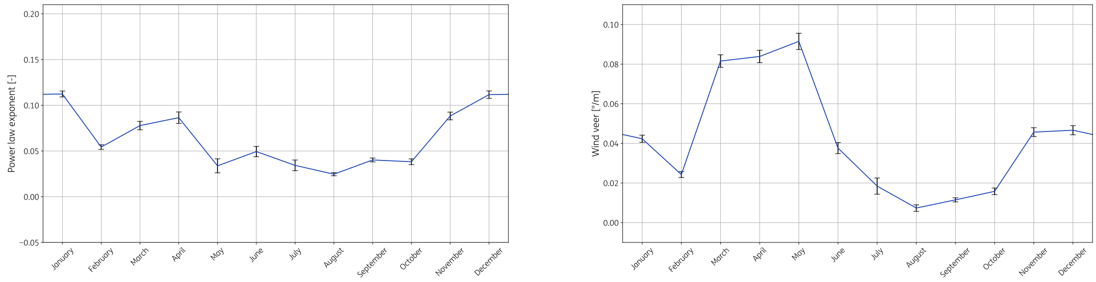

Figure B.25: Wind shear and veer as function of the month-of-year for 2018

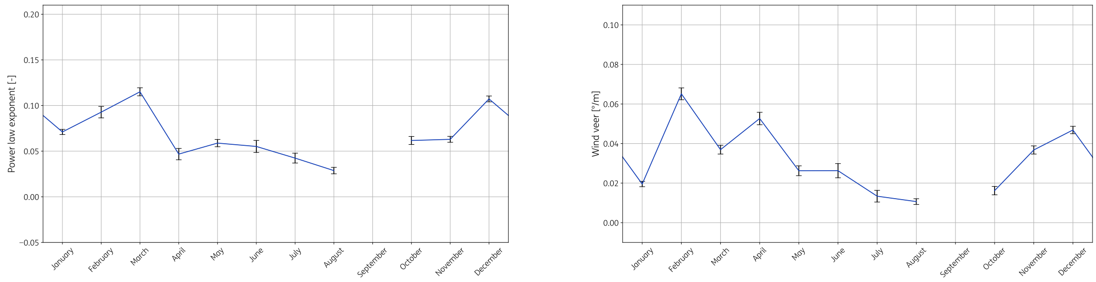

Figure B.26: Wind shear and veer as function of the month-of-year for 2019

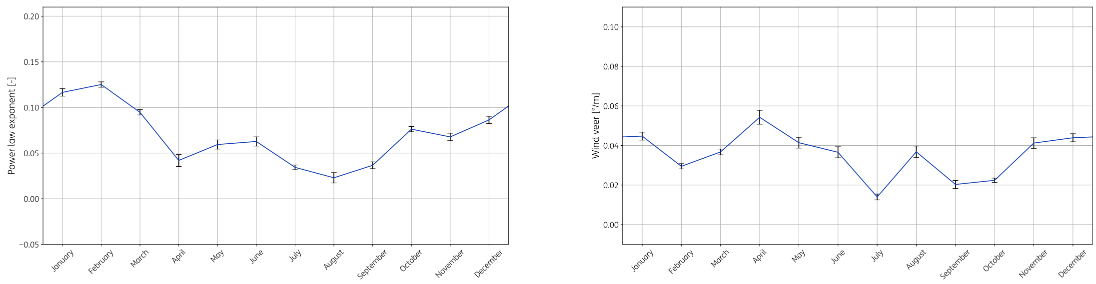

Figure B.27: Wind shear and veer as function of the month-of-year for 2020

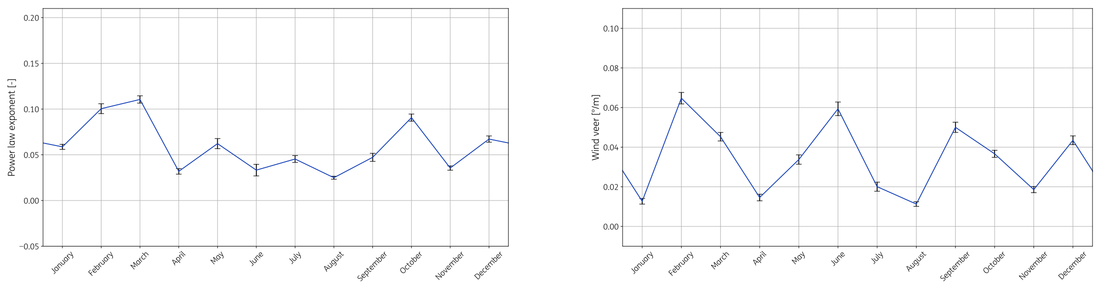

Figure B.28: Wind shear and veer as function of the month-of-year for 2021

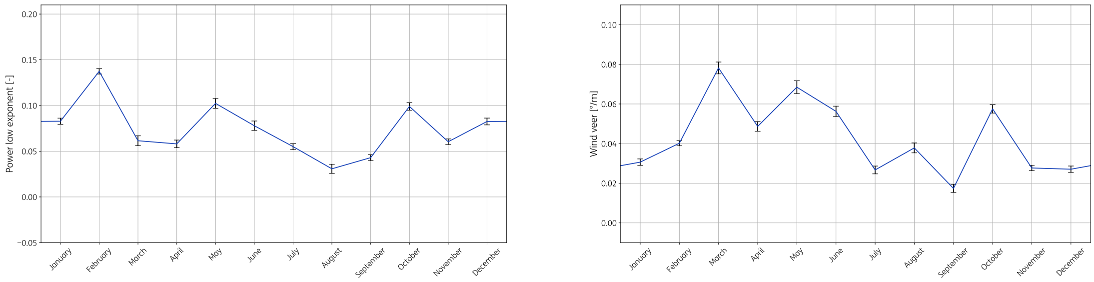

Figure B.29: Wind shear and veer as function of the month-of-year for 2022

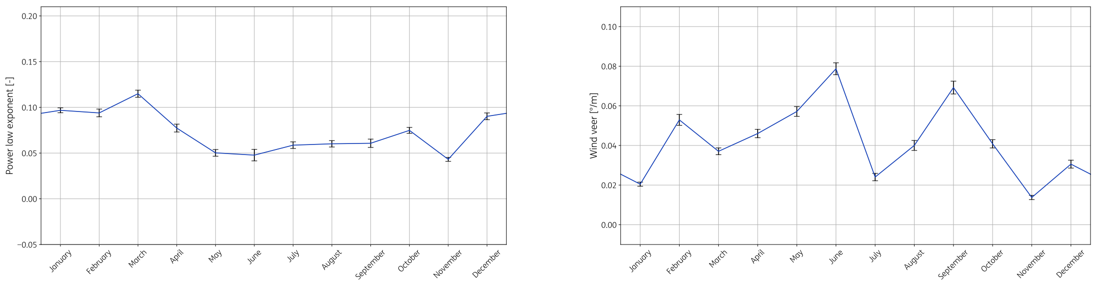

Figure B.30: Wind shear and veer as function of the month-of-year for 2023

B.4.2 Wind shear and veer as function of hour

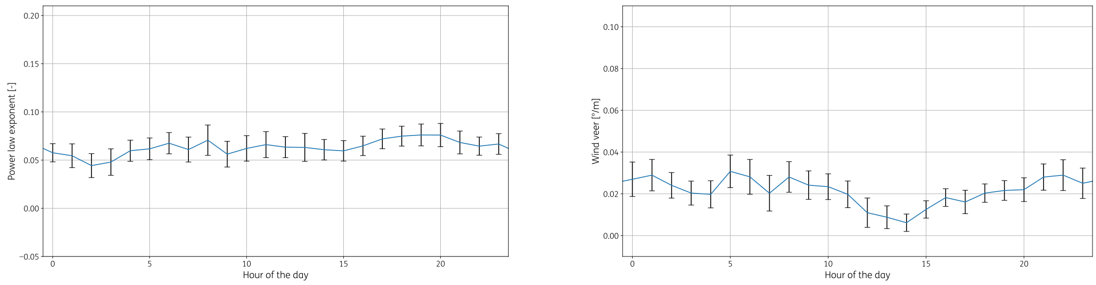

Figure B.31: Wind shear and veer as function the hour-of-day for 2014

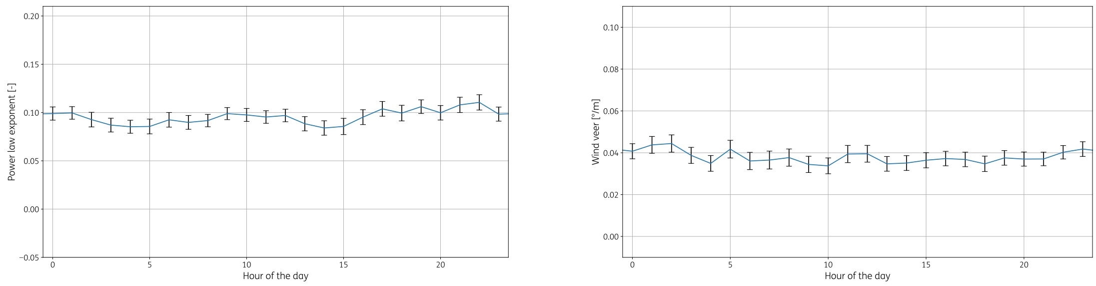

Figure B.32: Wind shear and veer as function the hour-of-day for 2015

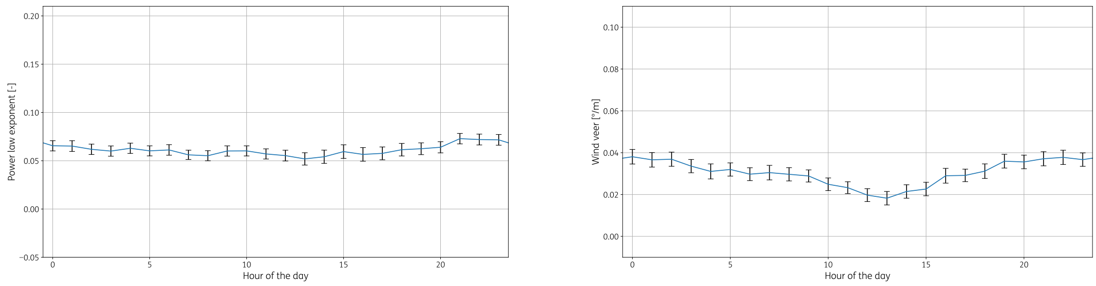

Figure B.33: Wind shear and veer as function the hour-of-day for 2016

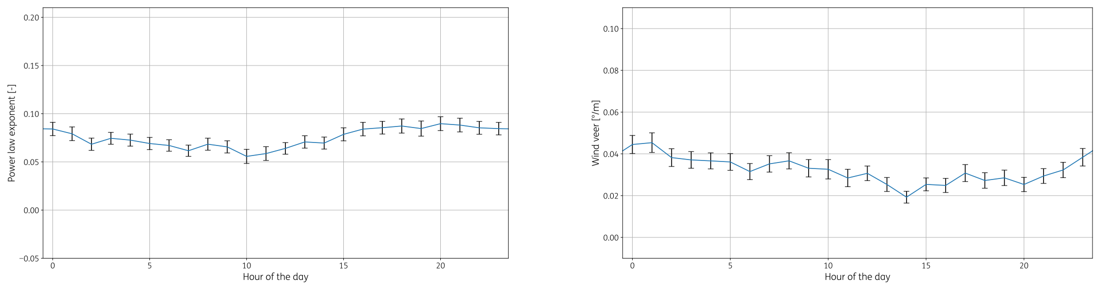

Figure B.34: Wind shear and veer as function the hour-of-day for 2017

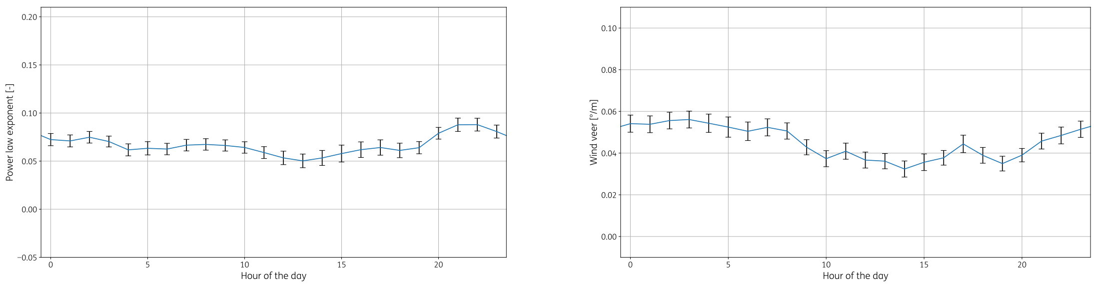

Figure B.35: Wind shear and veer as function the hour-of-day for 2018

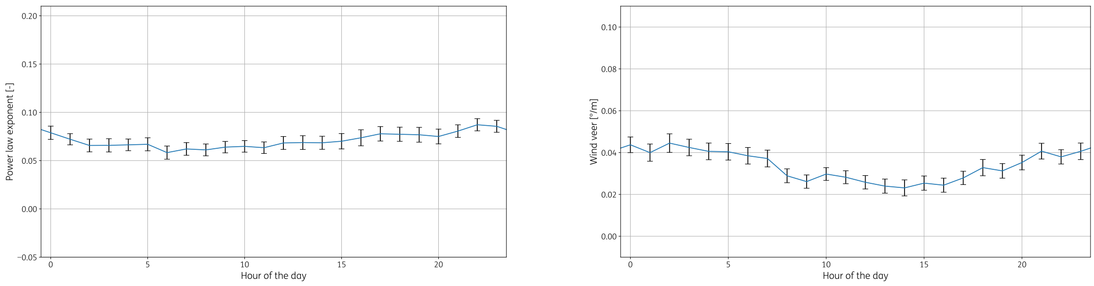

Figure B.36: Wind shear and veer as function the hour-of-day for 2019

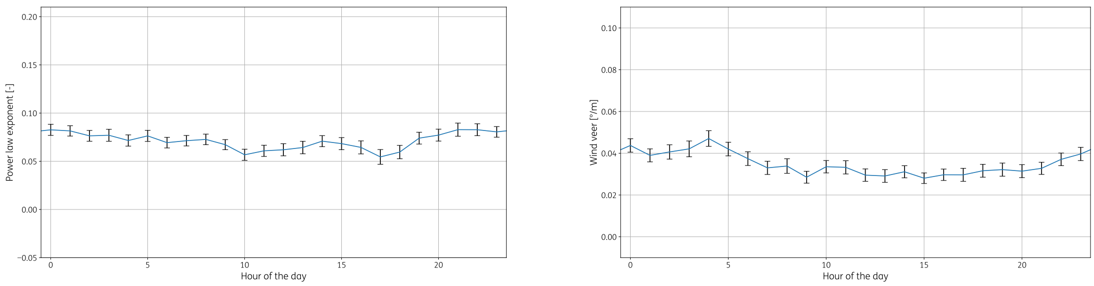

Figure B.37: Wind shear and veer as function the hour-of-day for 2020

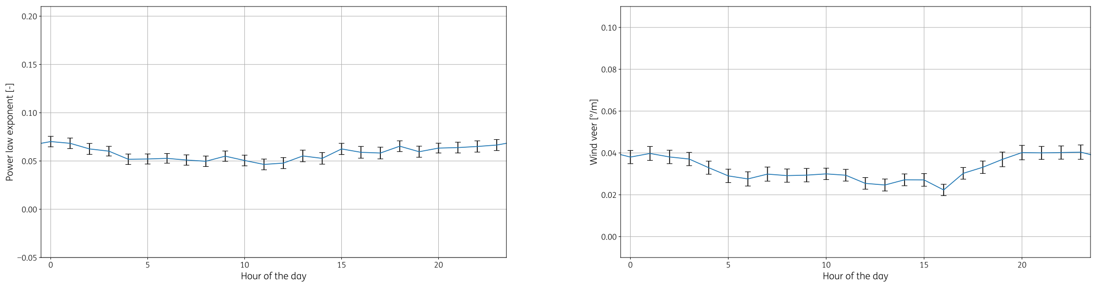

Figure B.38: Wind shear and veer as function the hour-of-day for 2021

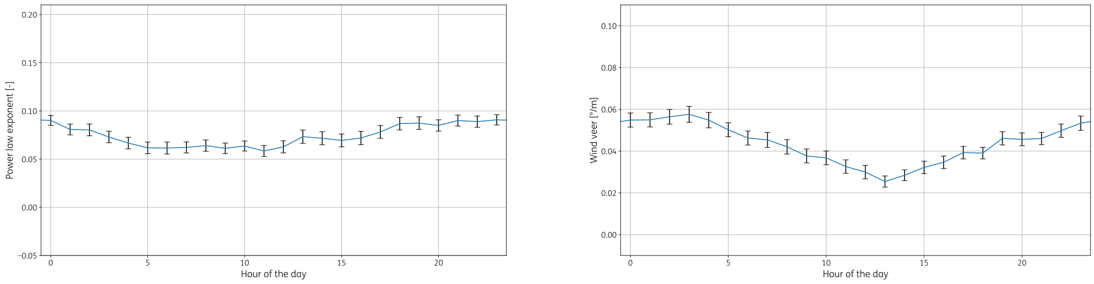

Figure B.39: Wind shear and veer as function the hour-of-day for 2022

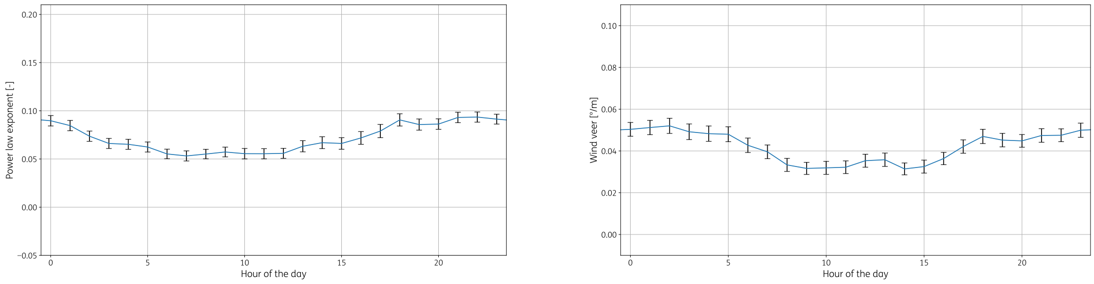

Figure B.40: Wind shear and veer as function the hour-of-day for 2023

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

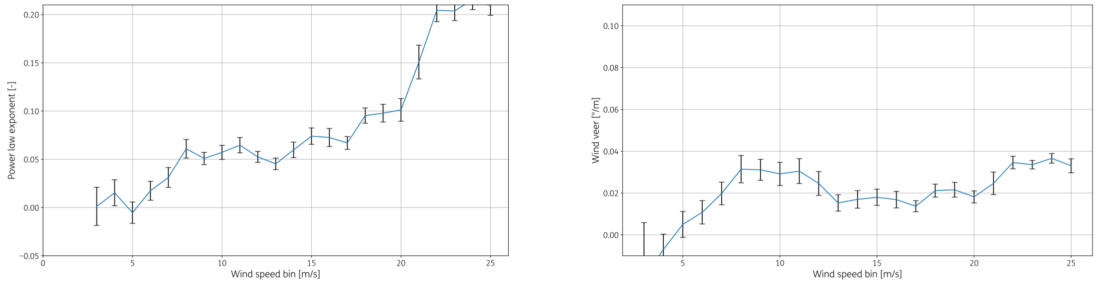

Figure B.41: Wind shear and veer as function of wind speed for 2014

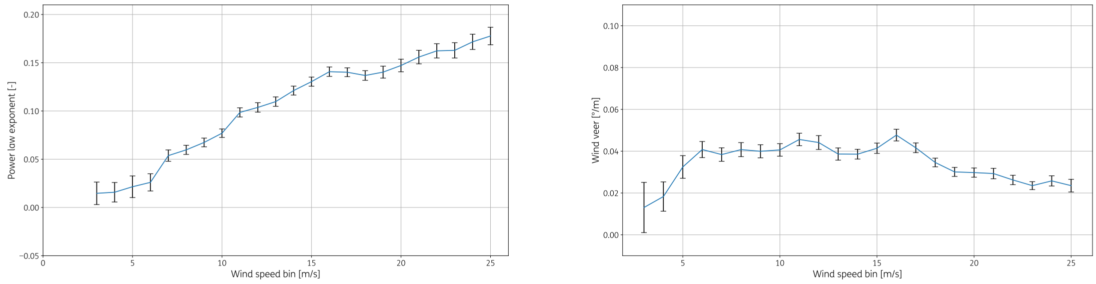

Figure B.42: Wind shear and veer as function of wind speed for 2015

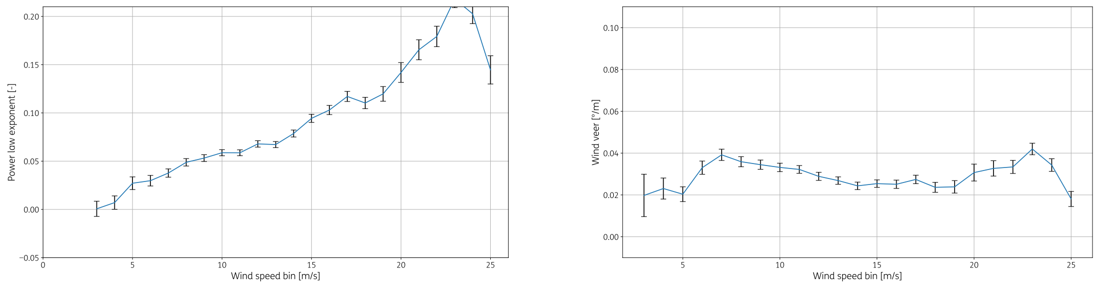

Figure B.43: Wind shear and veer as function of wind speed for 2016

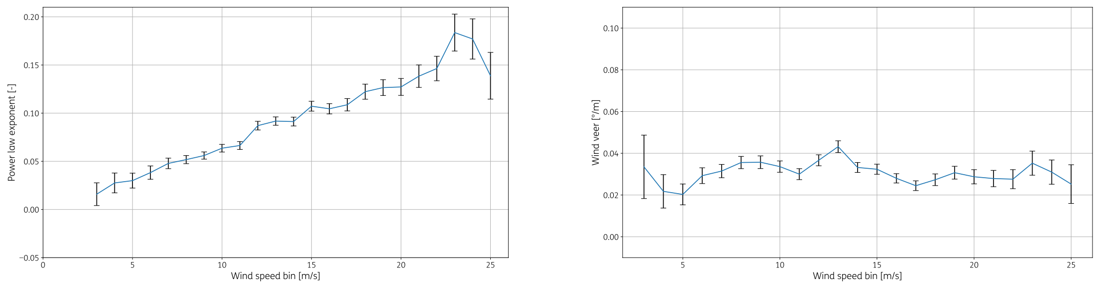

Figure B.44: Wind shear and veer as function of wind speed for 2017

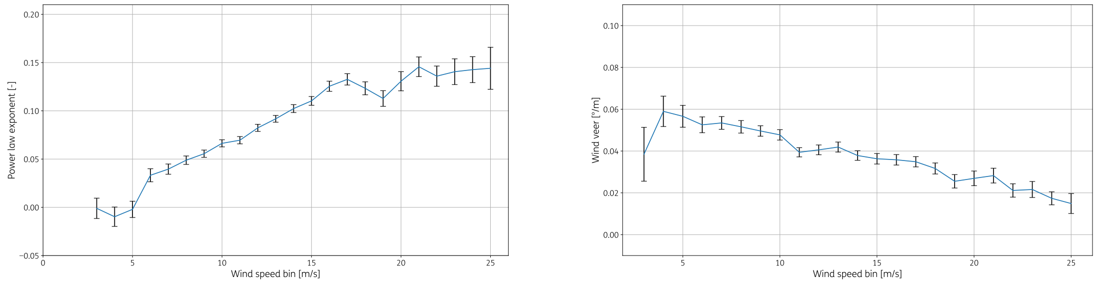

Figure B.45: Wind shear and veer as function of wind speed for 2018

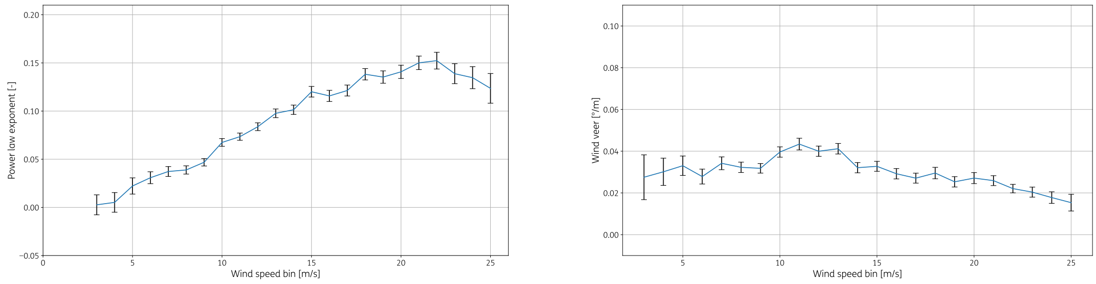

Figure B.46: Wind shear and veer as function of wind speed for 2019

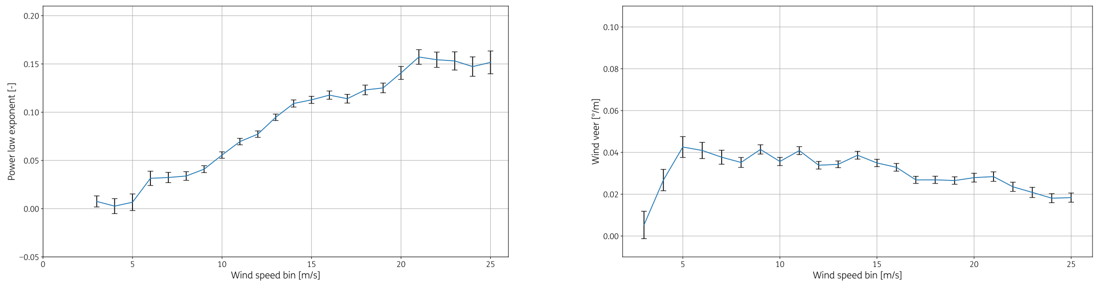

Figure B.47: Wind shear and veer as function of wind speed for 2020

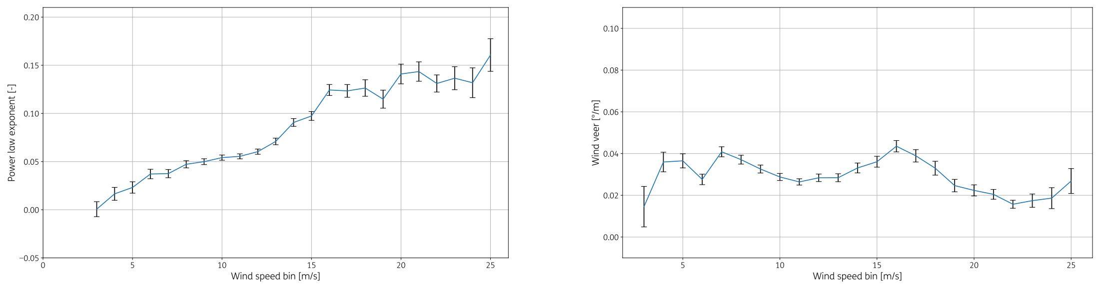

Figure B.48: Wind shear and veer as function of wind speed for 2021

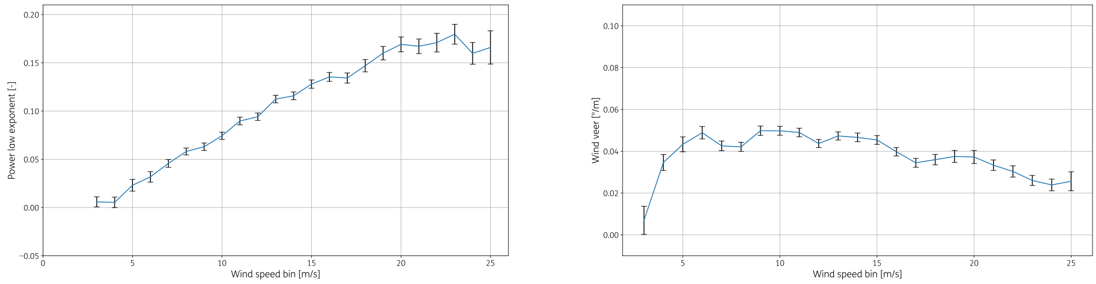

Figure B.49: Wind shear and veer as function of wind speed for 2022

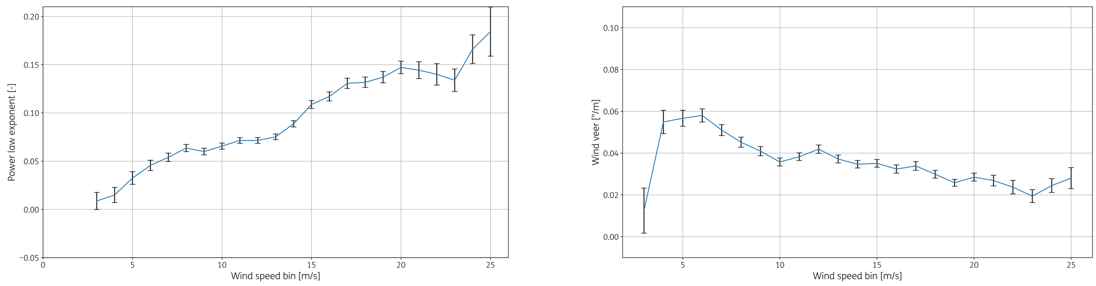

Figure B.50: Wind shear and veer as function of wind speed for 2023

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

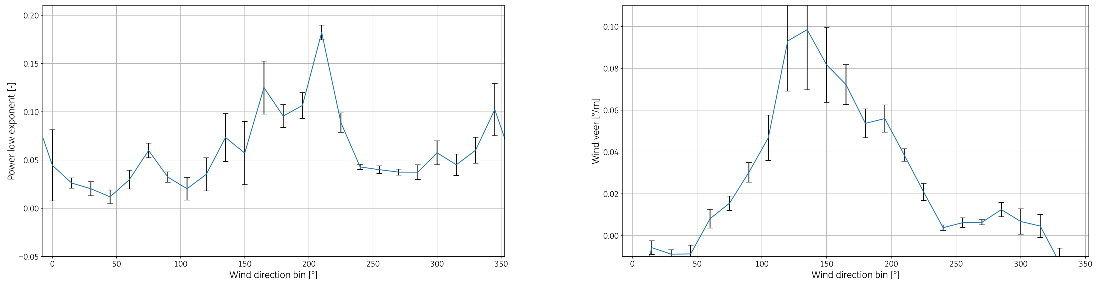

Figure B.51: Wind shear and veer as function of wind direction for 2014

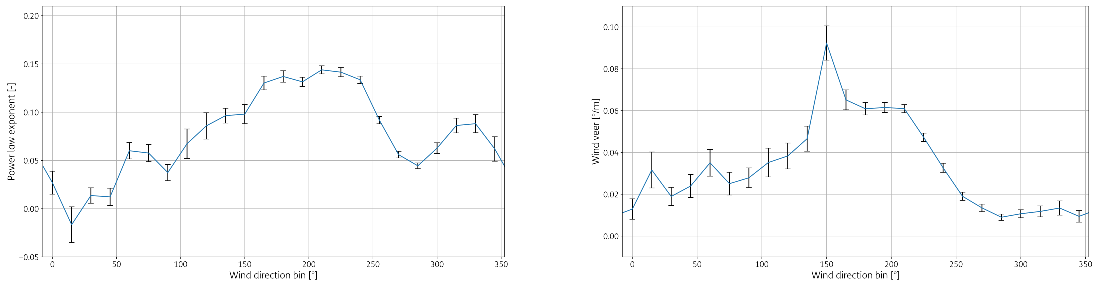

Figure B.52: Wind shear and veer as function of wind direction for 2015

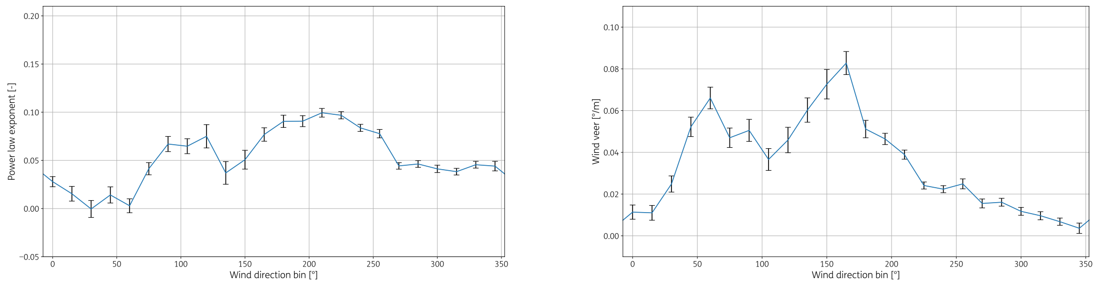

Figure B.53: Wind shear and veer as function of wind direction for 2016

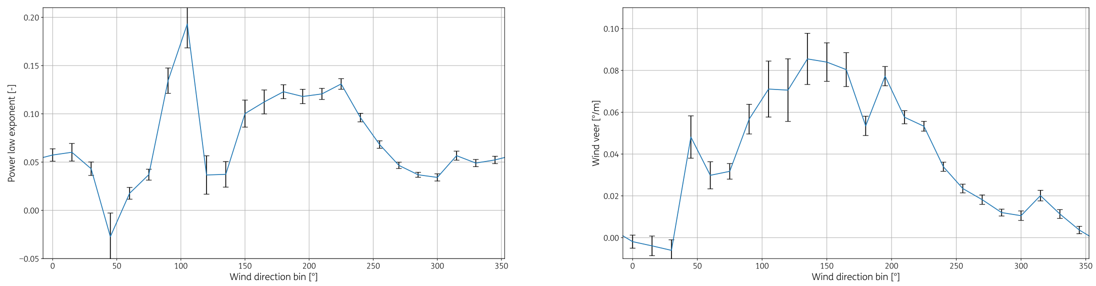

Figure B.54: Wind shear and veer as function of wind direction for 2017

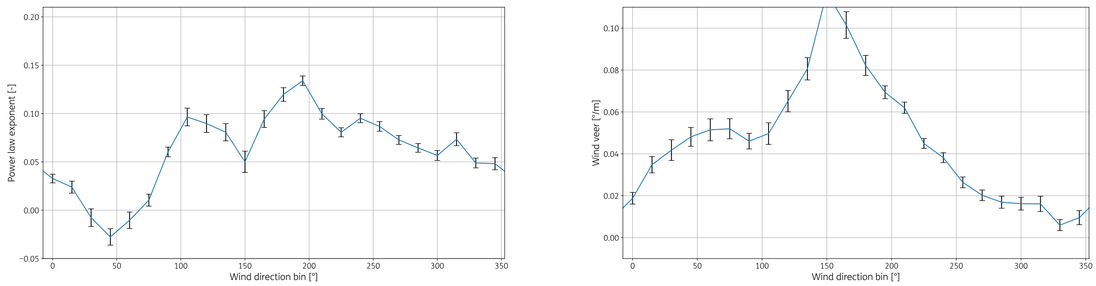

Figure B.55: Wind shear and veer as function of wind direction for 2018

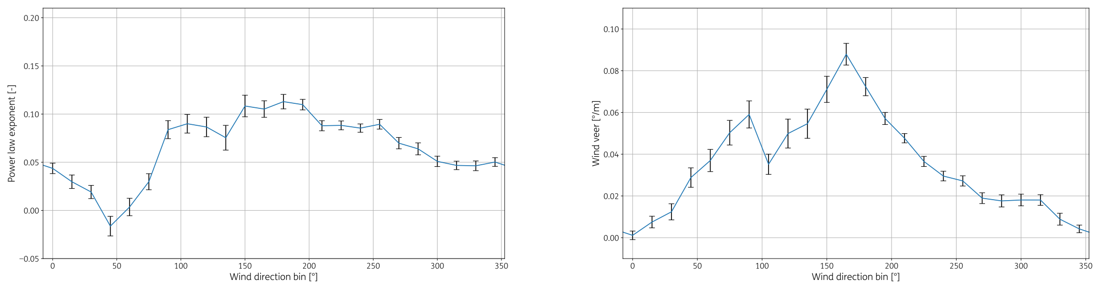

Figure B.56: Wind shear and veer as function of wind direction for 2019

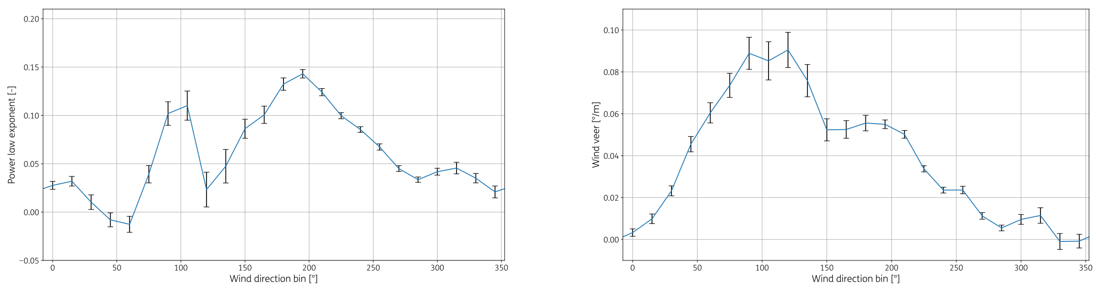

Figure B.57: Wind shear and veer as function of wind direction for 2020

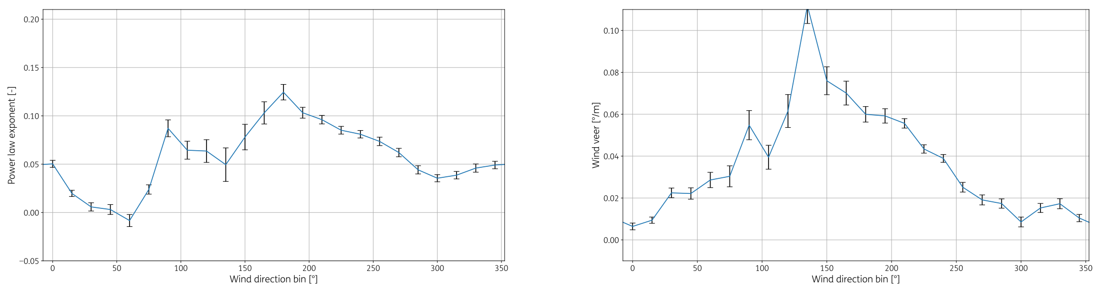

Figure B.58: Wind shear and veer as function of wind direction for 2021

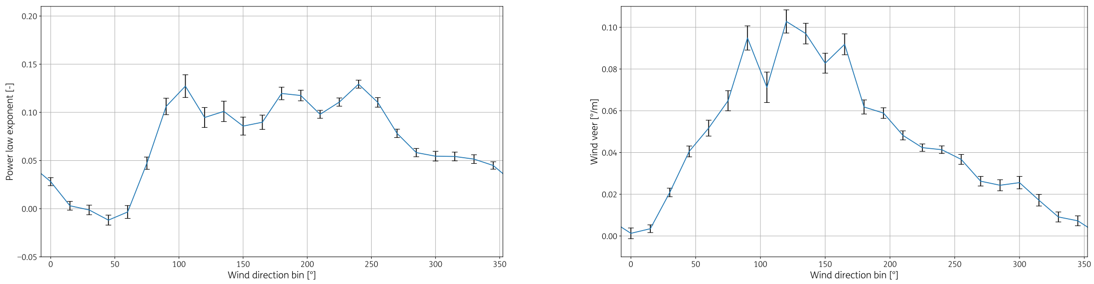

Figure B.59: Wind shear and veer as function of wind direction for 2022

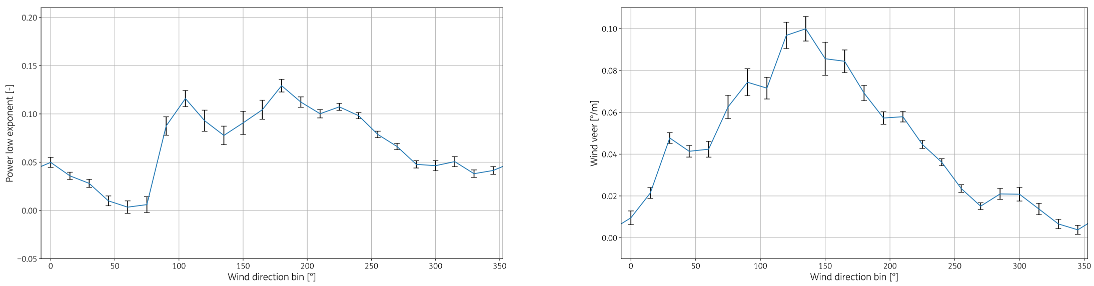

Figure B.60: Wind shear and veer as function of wind direction for 2023

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

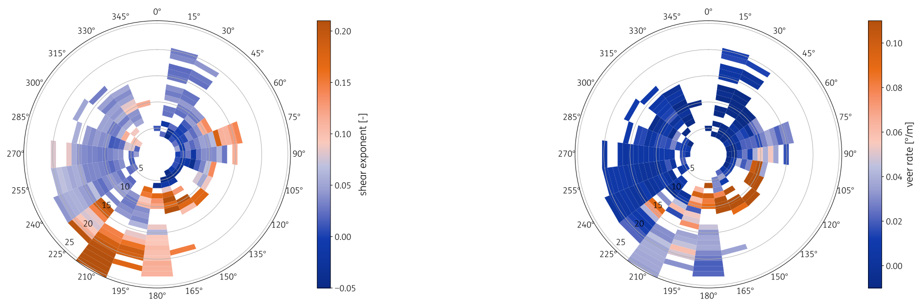

Figure B.61: Wind shear and veer as function of wind speed and direction for 2014

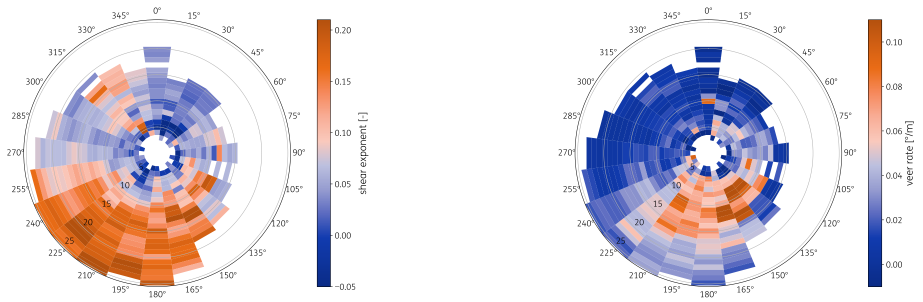

Figure B.62: Wind shear and veer as function of wind speed and direction for 2015

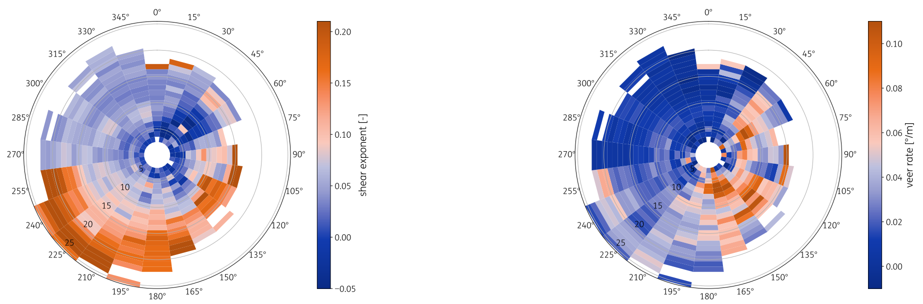

Figure B.63: Wind shear and veer as function of wind speed and direction for 2016

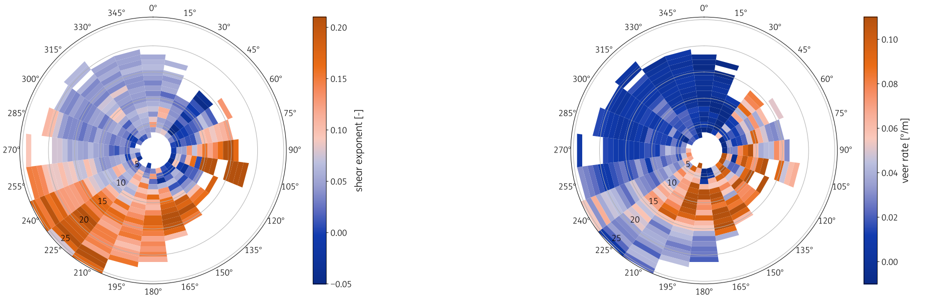

Figure B.64: Wind shear and veer as function of wind speed and direction for 2017

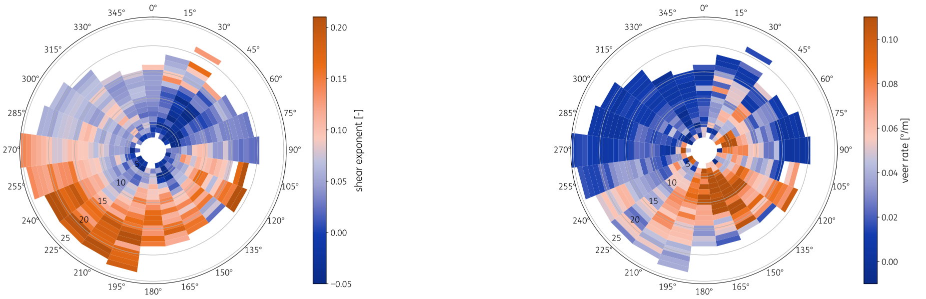

Figure B.65: Wind shear and veer as function of wind speed and direction for 2018

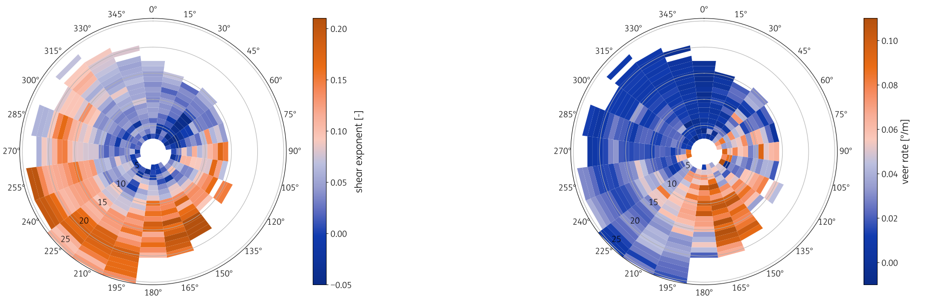

Figure B.66: Wind shear and veer as function of wind speed and direction for 2019

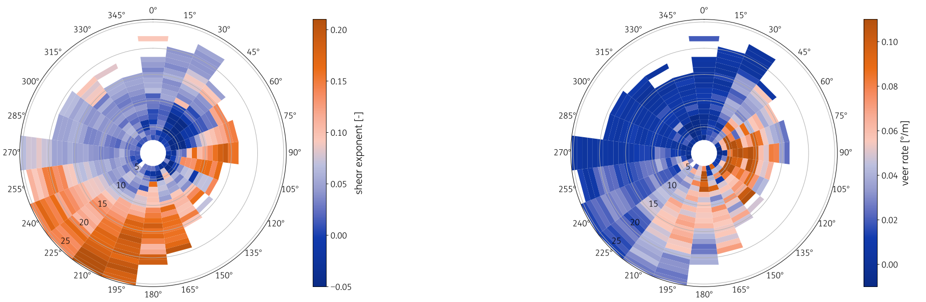

Figure B.67: Wind shear and veer as function of wind speed and direction for 2020

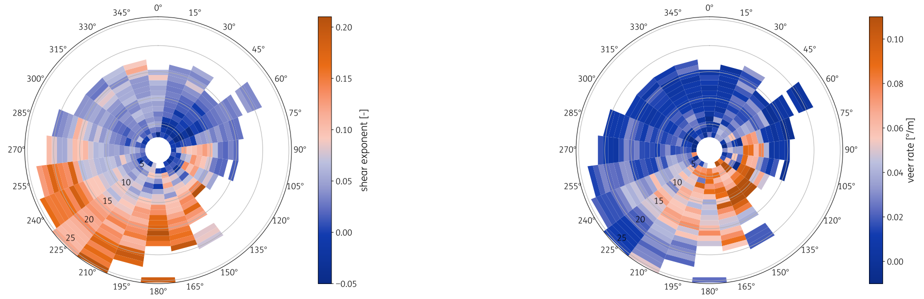

Figure B.68: Wind shear and veer as function of wind speed and direction for 2021

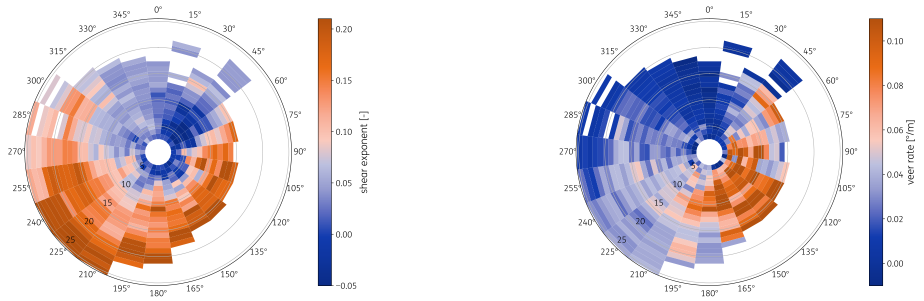

Figure B.69: Wind shear and veer as function of wind speed and direction for 2022

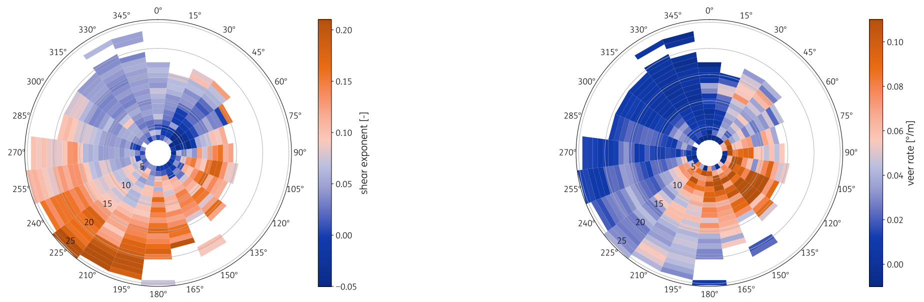

Figure B.70: Wind shear and veer as function of wind speed and direction for 2023

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