TNO innovation for life

Lichteiland Goeree, 2014–2024

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 expand to 21 GW by 2032. By the end of 2023 an installed capacity of 4.7 GW was already achieved, surpassing the original goal of 4.5 GW. Several wind farms with a combined capacity of 6.5 GW are currently under construction in the wind farm sites *Hollandse Kust West* and *IJmuiden Ver*. The Netherlands is moving ahead with almost yearly tendering rounds for upcoming development areas. Tenders for the *Nederwiek* wind farm site are expected to start in late 2025.

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-metre meteorological mast and a co-located lidar situated 75 km west of IJmuiden. From 2014 onwards, TNO has further organised wind measurement campaigns with lidars on offshore platforms for the Dutch Ministry of Economic Affairs and Climate Policy (now for the Ministry of Climate Policy and Green Growth). These campaigns are part of the *Wind op Zee* project to support the Dutch offshore wind 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. Currently TNO is investigating possible options for a fifth measurement platform, where measurements could start in the beginning of 2026. TNO is accredited for performing the aforementioned measurements in accordance with IEC 61400-50-2.

This report refers to the measurement campaign at the LEG platform where a Vaisala WindCube lidar has been deployed, providing high quality data since 2014[1]. The data are publicly available to be used for further purposes (offshorewind-measurements.tno.nl).

At the LEG platform, the wind analysis for the 2014–2024 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 235.3° to 246.6° across the different sensor heights (62 m to 290 m). The average wind speed ranges from 9.04 m/s at the lowest measurement height of 62 m up to 10.51 m/s at 290 m. The Weibull distribution, indicating the variability of the wind regime throughout the measurement period, shows a wind speed distribution with typical offshore scale (k) and shape (c) parameters (k = 2.12 and c = 11.09 m/s at 140 m height).

[1]Before 2024 we were using a single WindCube V2 lidar, but since 2024 a pair of WindCube V2.1 lidars is installed.

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Abbreviations

CNR	carrier-to-noise ratio
EEZ	exclusive economic zone
EPL	Europlatform
GWO	Global Wind Organisation
HUET	helicopter underwater escape training
IEC	International Electrotechnical Commission
IECRE WE	IEC system for certification to standards relating to equipment for use in Renewable Energy applications – Wind Energy
ILAC MRA	International Laboratory Accreditation Cooperation Mutual Recognition Arrangement
ISO	International Organisation for Standardisation
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
NAO	North Atlantic Oscillation
OWEZ	Offshore Windpark Egmond aan Zee (Offshore wind farm Egmond aan Zee)
pdf	probability density function
RETL	Renewable Energy Testing Laboratory
RI&E	risico-inventarisatie en evaluatie (risk-assessment and evaluation)
RvA	Raad voor Accreditatie (Dutch Accreditation Council)
TI	Turbulence Intensity
TNO	Nederlandse Organisatie voor toegepast-natuurwetenschappelijk onderzoek (Netherlands Organisation for applied scientific research)
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 aiming to expand to 21 GW by 2032 [2]. By the end of 2023 an installed capacity of 4.7 GW was already achieved, surpassing the original goal of 4.5 GW [3]. Several wind farms with a combined capacity of 6.5 GW are currently under construction in the wind farm sites *Hollandse Kust West* and *IJmuiden Ver*. The Netherlands is moving ahead with almost yearly tendering rounds for upcoming development areas. Tenders for the *Nederwiek* wind farm site are expected to start in late 2025 [4].

To achieve such an ambitious realisation of operational offshore wind farms in the Dutch part of the North Sea, importance must be given to both spatial planning, and characterisation of the precious, valuable and volatile wind 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 therefore 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-metre meteorological mast and a co-located lidar situated 75 km west of IJmuiden. From 2014 onwards, TNO has further organised wind measurement campaigns with lidars on offshore platforms for the Dutch Ministry of Economic Affairs and Climate Policy (now for the Ministry of Climate Policy and Green Growth). 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). Discussions with platform operators are currently ongoing with the aim of finding a fifth suitable measurement location in the vicinity of the wind farm development search area *Ten noorden van de Waddeneilanden*. TNO is accredited for performing the aforementioned wind measurements in accordance with IEC 61400-50-2 [5].

This report will focus on the wind conditions characterisation of the LEG platform, located about 30 km south-west from the coast of Hoek van Holland.

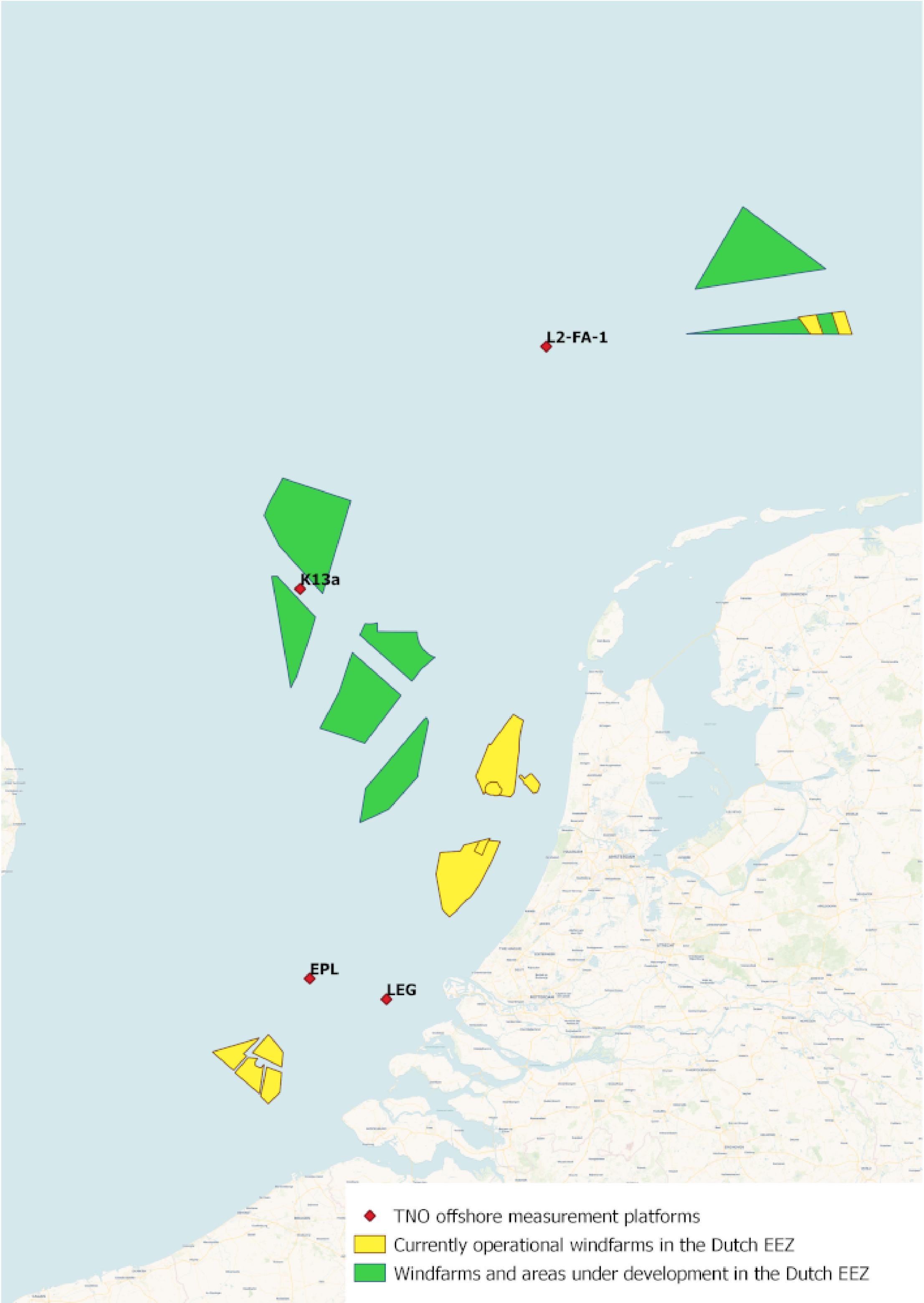


Figure 1.1: TNO's long-term offshore wind measurement campaign locations at Lichteiland Goeree (LEG), Europlatform (EPL), Wintershall platform K13-A (K13a) and L2-FA-1, along with wind farm development zones in the Dutch North Sea.

2 Wind measurement campaigns at the North Sea

2.1 TNO's leading role in wind condition measurement 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 have also been 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 each part of the process: from selection of the instrumentation and planning the installation, to the purchase, validation, installation, and maintenance of the lidar, as well as analysing, 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, see table 2.1. These reports are available at offshorewind-measurements.tno.nl. This report includes the specific wind conditions for the period 2014–2024 at the LEG platform. The present 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 LEG

Period	Report
2014–2019	TNO 2020 R10511 [6]
2014–2020	TNO 2021 R11202 [7]
2014–2021	TNO 2022 R10649 [8]
2014–2022	TNO 2023 R10579 [9]
2014–2023	TNO 2024 R11674 [10]

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* measurement 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.},
institution = {TNO},
title       = {Lichteiland Goeree lidar measurement campaign},
subtitle    = {Instrumentation Report 2024},
number      = {TNO 2024 R11578},
date        = {2024-10-10},
url         = {https://publications.tno.nl/publication/34643285/zQw9Y2mw/TNO-2024-R11578.pdf},
```

2. citation to this report:

```
author      = {Wouters, D. A. J. and van Dooren, M. F. and Fritz, E. K.
    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    = {Lichteiland Goeree, 2014\textendash2024},
number      = {TNO 2025 R11109},
date        = {2025-05-27},
```

The publication date on which the data have last been accessed must be indicated along the citations, e.g. "Last accessed May 2025".

The data are 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. From 1971 (year of construction) until 2020 the platform was 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.

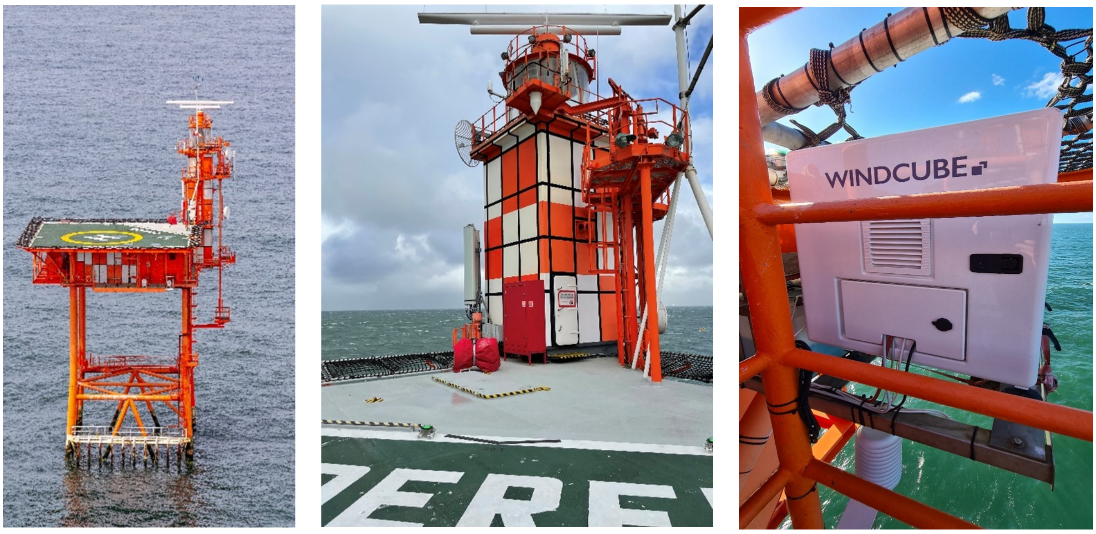
Since October 2014, TNO has been conducting an ongoing measurement campaign at LEG, and has accumulated meteorological data, knowledge about installation practices, maintenance, replacement, and observations of weather conditions that have occurred at the site. Figure 3.1(c) shows the lidar at its location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

On this platform, the 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 current instrumentation at LEG is a pair of two Vaisala WindCube V2.1 lidars. The redundancy ensures that the highest data availability is achieved, especially for the many floating lidar system verification campaigns that also take place around the platform. Each lidar measures wind profiles up to ten different heights by sending infrared pulses into the atmosphere (see [11] for the lidar specifications). Before each lidar was installed at the LEG platform, it was first calibrated, see the latest calibration reports [12, 13]. The lidars are both mounted 22 m above mean sea level (MSL) and provide both wind speed and direction measurements at ten different heights between 62 m and 290 m above MSL. To ensure good quality measurements it is crucial to select the right location for the lidars on the platform. More detailed information about the positioning and installation of the lidars on the LEG platform is available in the instrumentation report [14].

The lidar measurement height and data acquisition configuration is chosen to be the same as at other measurement locations, i.e. the EPL, K13-A 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 [11]. 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, each lidar should be serviced after one year of operation and replaced every two years. These periodic lidar replacements are logged in table 3.1. All operational aspects with respect to installing and maintaining the lidar are recorded in a logbook by the team responsible for the measurement campaign. These occurrences during the year 2024 are summarised in table 3.2.



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

Figure 3.1: Lichteiland Goeree platform

Table 3.1: Replacements of lidars at the LEG platform

Lidar ID	Operational period	Reason for replacement
WLS7-127	06-10-2014 to 10-04-2015	First installation, 3G communication switch
WLS7-258	10-04-2015 to 28-09-2015	Switched from satellite to GSM to improve communications
WLS7-127	28-09-2015 to 05-10-2017	Periodic replacement
WLS7-577	05-10-2017 to 24-10-2019	Periodic replacement
WLS7-258	24-10-2019 to 06-09-2021	Periodic replacement
WLS7-127	06-09-2021 to 07-05-2024	Upgrade to WindCube V2.1
WLS866-0183	18-12-2023 to present	
WLS866-0184	07-05-2024 to present	

Table 3.2: Down-time periods and actions taken at LEG platform during the year 2024

Date ID	Reason
16-01-2024	Power cut resulting in a loss of data for a duration of 12 h
24-04-2024 to 26-04-2024	Loss of connection, which fortunately did not cause any data loss
07-05-2024	Replacement of lidar WLS7-127 with lidar WLS866-0184
14-05-2024	Correction of lowest measurement height for both lidars from 63 m to 62 m

3.2 Health and safety measures

Health, safety and environment are main priorities at TNO. TNO follows a strict programme 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 are 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.

An overview of the measured and recorded quantities by the lidar at LEG is shown in table 3.3. The data are measured on a 10-minute basis and timestamped at the start of each 10-minute interval. The data collection period started on 17 November 2014 at 13:00 UTC. This report considers the measurement period until 31 December 2024 at 23:50 UTC. The campaign is still ongoing, with future yearly assessments envisioned.

The annual lidar data availability at LEG is indicated in table 3.4. The data availability depends on the height of the measurements, and manufacturers will typically suggest usage of the lidar up to a certain height. On average, the data availability for heights up to 190 m is at least 77.8 %, while farther up to 240 m it decreases to 64.9 %, and finally to 40.5 % at the highest altitude of 290 m. For the year 2024, the data availability for heights up to 190 m is at least 87.6 %, while farther up to 240 m it decreases to 84.5 %, and finally to 78.8 % at the highest altitude of 290 m. The decrease in data availability and coverage with increasing measurement height is typically caused by the optical scattering of the lidar's laser pulses as they travel through the air. The farther the laser pulse travels, the more scattering occurs, resulting in a lower intensity of the laser light reflected back to the lidar. In some situations, the concentration of aerosols in the air, which usually decreases with height, could play an additional role.

During the year 2017 and most of 2016 and 2018, the two highest sensor levels were not configured, explaining the zero and low values, respectively. The analysis of the data availability

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

is based on the available measurements periods. Therefore, the percentages 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 were not available from May to August in 2015.

For a more detailed overview of the lidar availability, the monthly availability is plotted in figure 3.2. Higher monthly data availability is shown by the system when it is 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 signal power suffers from degradation over time, providing a lower data availability at the end of its operational period. This effect is more prevalent at higher altitudes. 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. 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, [15] 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.

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
2024	93.7	92.0	89.9	88.9	88.5	87.6	86.3	84.5	82.1	78.8
Overall	85.2	84.6	83.9	83.0	81.2	77.8	72.4	64.9	46.7	40.5

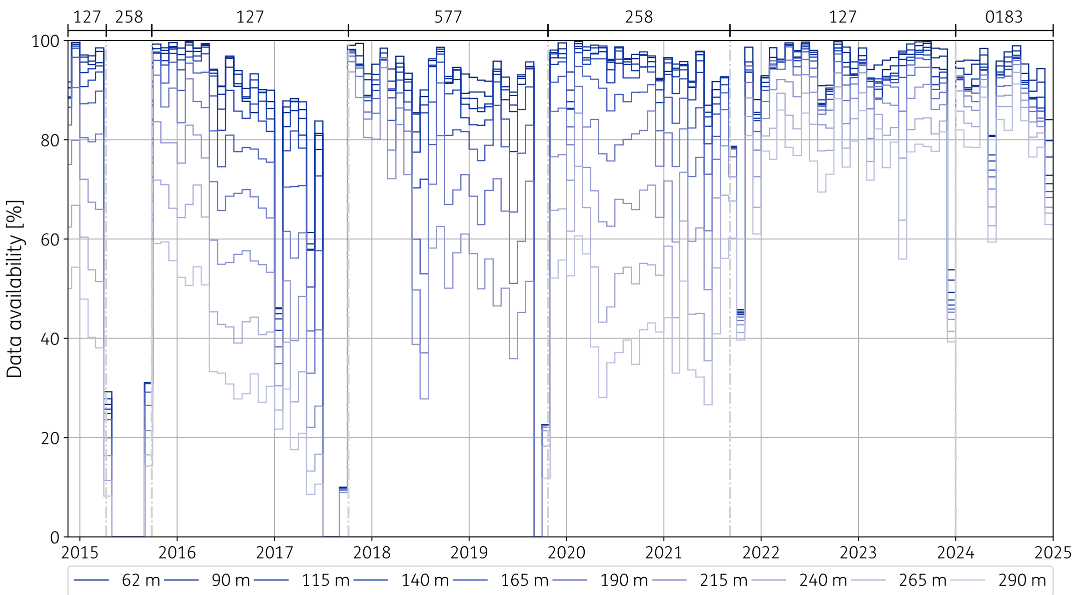


Figure 3.2: Monthly lidar data availability showing the lidar IDs and their operational periods. WLS866-0183 is providing the data since 18-12-2023. Data measured by the most recently installed lidar WLS866-0184 is not used in this report.

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 A.

4.1 Distributions

For the presentation of the wind speed and wind direction distributions no filtering is applied besides 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 A.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 A.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 can be visualised simultaneously in a wind rose, as shown in figure 4.1. Annual results are presented in section A.1.

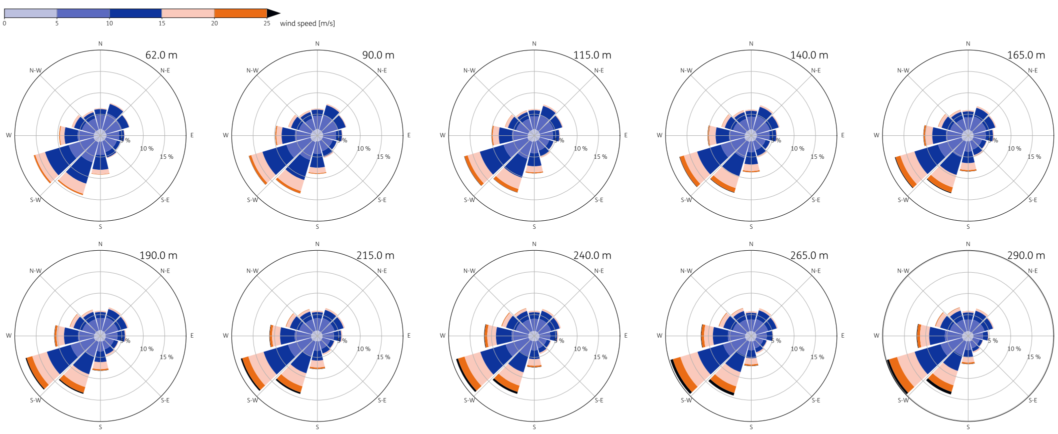


Figure 4.1: Wind roses for the complete measurement campaign

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

[3]First the data are 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	453 561	5.97	8.80	11.93	33.02	9.04	235.3
90	450 444	6.06	9.04	12.39	33.46	9.33	235.3
115	446 711	6.11	9.17	12.66	34.21	9.51	235.3
140	441 675	6.18	9.33	12.93	34.99	9.70	235.7
165	432 085	6.26	9.48	13.18	36.97	9.88	236.6
190	413 984	6.35	9.60	13.40	37.50	10.03	238.2
215	385 310	6.44	9.72	13.61	37.91	10.18	240.6
240	345 460	6.55	9.87	13.83	38.27	10.32	243.3
265	248 541	6.54	9.94	14.02	38.30	10.43	243.9
290	215 675	6.53	10.01	14.18	38.62	10.51	246.6

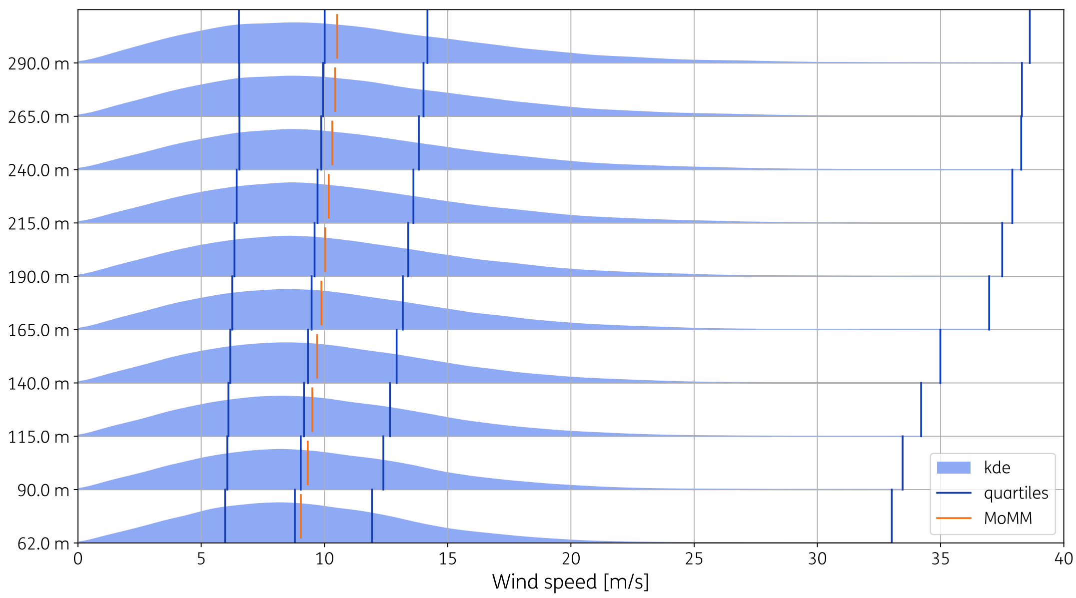


Figure 4.2: Wind speed distributions. The kde is shown with blue markers for the quartiles (Q_1, median, Q_3 and maximum) and an orange marker for the MoMM, as listed in table 4.1.

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

Height	Shape (k)	Scale (c)
m	–	m/s
62	2.246	10.33
90	2.192	10.66
115	2.149	10.86
140	2.121	11.09
165	2.096	11.31
190	2.078	11.51
215	2.067	11.70
240	2.061	11.90
265	2.030	12.02
290	2.016	12.13

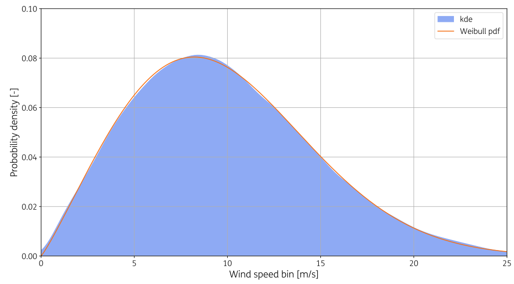


Figure 4.3: Weibull pdf of wind speed distribution at 140 m

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

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 can be estimated from the wind speed data 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 (percent)
- 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.

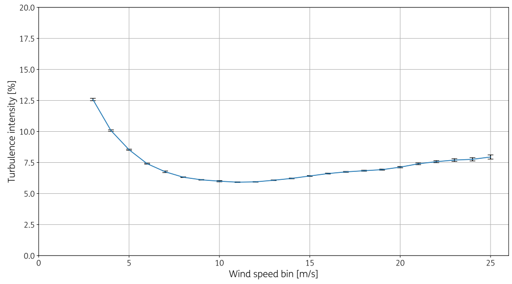


Figure 4.4: Turbulence intensity at 62 m

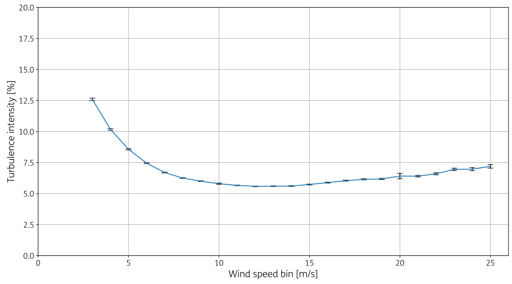


Figure 4.5: Turbulence intensity at 90 m

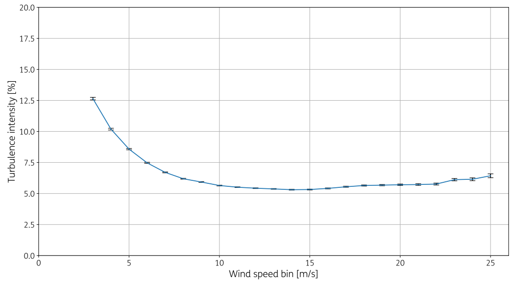


Figure 4.6: Turbulence intensity at 115 m

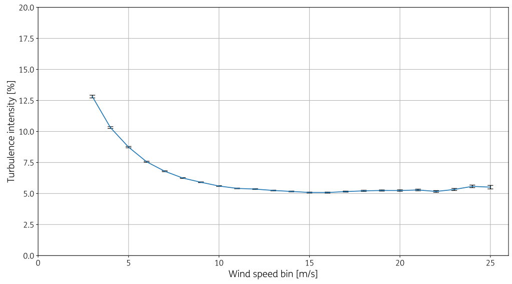


Figure 4.7: Turbulence intensity at 140 m

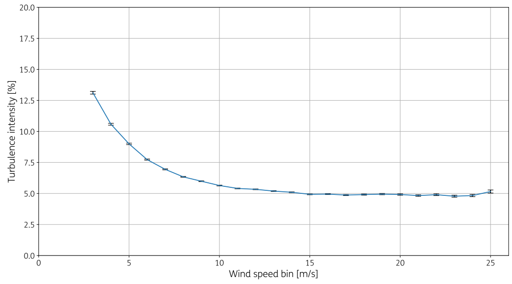


Figure 4.8: Turbulence intensity at 165 m

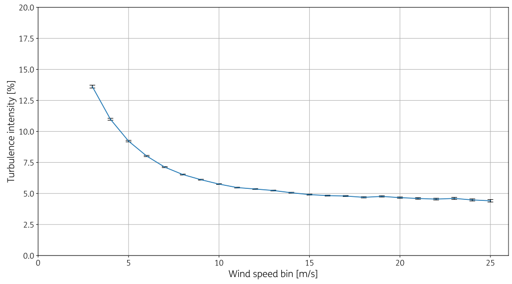


Figure 4.9: Turbulence intensity at 190 m

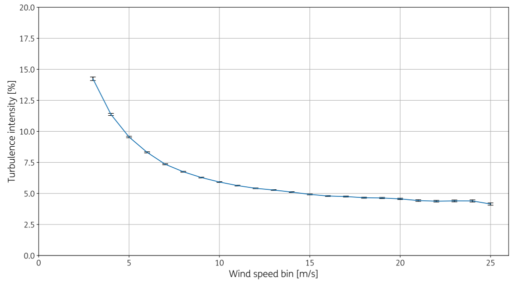


Figure 4.10: Turbulence intensity at 215 m

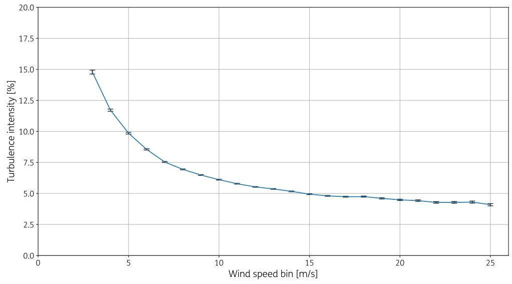


Figure 4.11: Turbulence intensity at 240 m

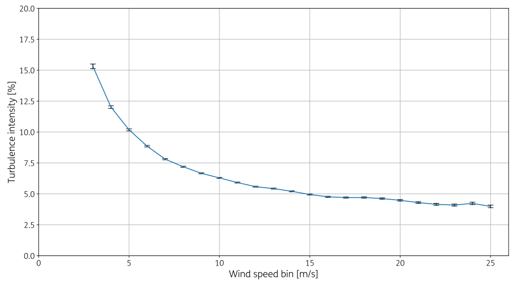


Figure 4.12: Turbulence intensity at 265 m

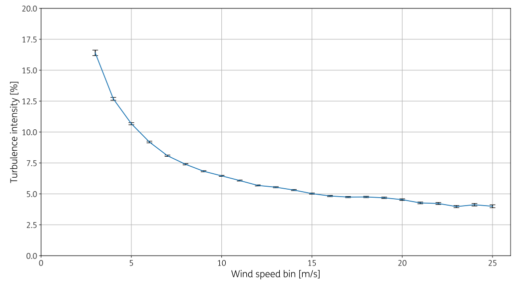


Figure 4.13: Turbulence intensity at 290 m

4.3 Wind shear and veer

When characterising the shear and veer, only the measurements across the swept area of a large offshore turbine rotor are included. For this purpose, a fictive wind turbine with a hub height of 150 m and 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 fictive wind turbine definition.
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. The plot showing the average wind speed per height can be interpreted as an average wind shear profile. The plot showing the average wind direction per height is not representing an average veer profile, because the average wind direction is computed by vector averaging and thus weighted by the wind speed.

4.3.2 Modelling

The wind shear is modelled by the power law in equation (4.3). The wind veer is modelled by a linear profile fitted through the unit-vector averaged wind direction over height. These are typically reasonable representations of the 10-minute average wind profile.

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

[8] This threshold is based on the MEASNET procedure [16, 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.

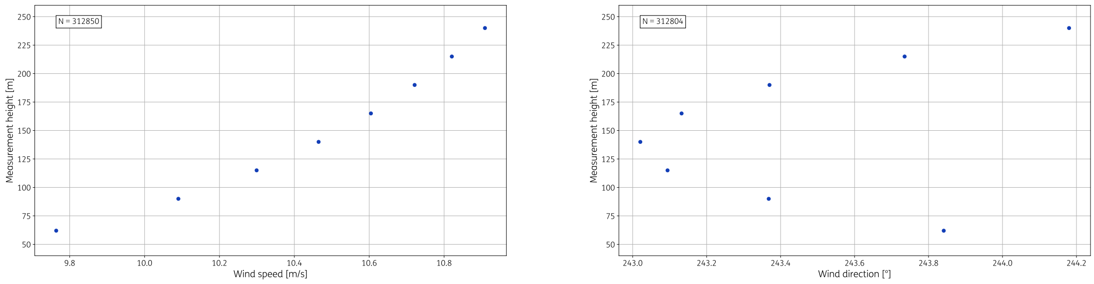


Figure 4.14: Average wind speed and wind direction (MoMM) of the dataset per height. 'N' is the number of 10-minute average samples remaining after filtering used to compute the MoMM values.

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[10], 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 A.4.

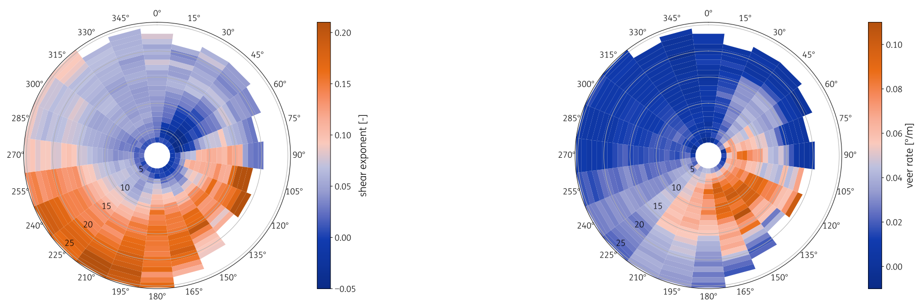


Figure 4.15: Wind shear and veer as function of wind speed and direction. The azimuth indicates the wind direction bin, the radius labels indicate the wind speed bin and the colour represents the mean value for the shear exponent (left) and veer rate (right).

[10]This follows the MEASNET procedure [16, clause 9.4].

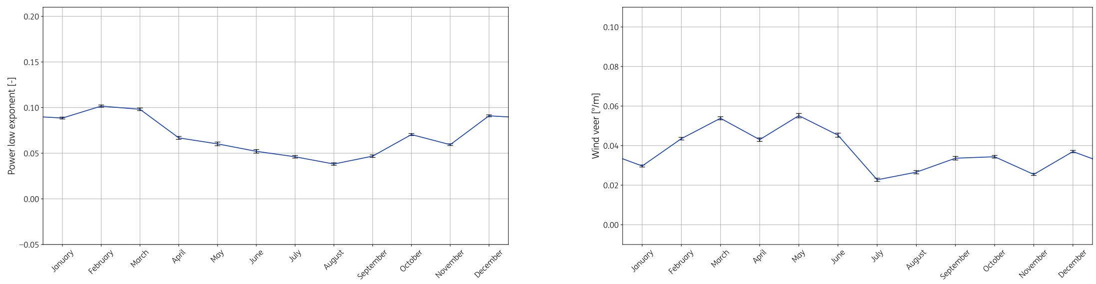


Figure 4.16: Wind shear and veer as function of the month-of-year

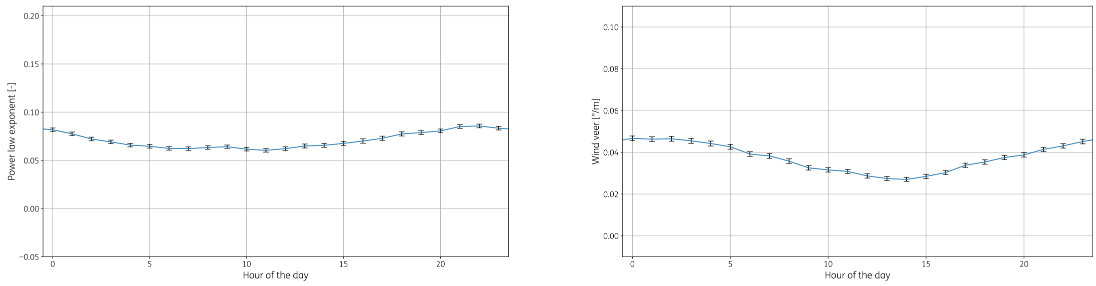


Figure 4.17: Wind shear and veer as function the hour-of-day

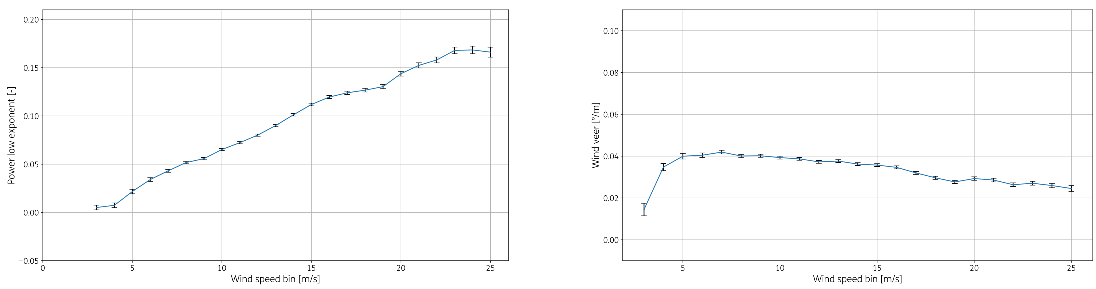


Figure 4.18: Wind shear and veer as function of wind speed

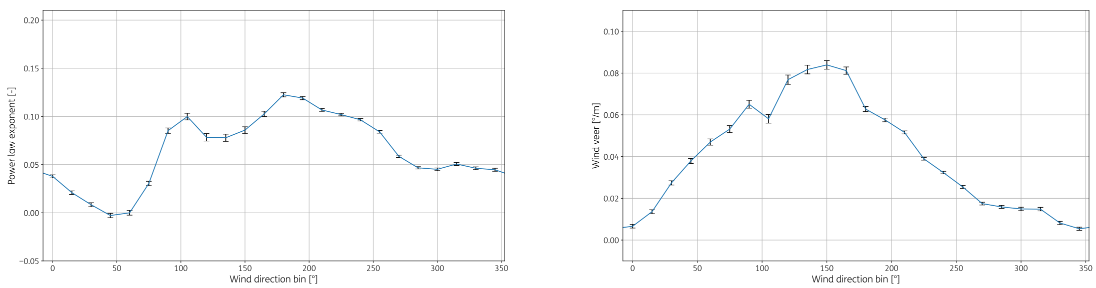


Figure 4.19: Wind shear and veer as function of wind direction

5 Conclusions and recommendations

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

For the year 2024, the data availability for heights up to 190 m is at least 87.6 %, while farther up to 240 m it decreases to 84.5 %, and finally to 78.8 % at the highest altitude of 290 m.

At the LEG platform, the wind analysis for the 2014–2024 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 235.3° to 246.6° across the different sensor heights (62 m to 290 m). The average wind speed ranges from 9.04 m/s at the lowest measurement height of 62 m up to 10.51 m/s at 290 m. The Weibull distribution, indicating the variability of the wind regime throughout the measurement period, shows a wind speed distribution with typical offshore scale (k) and shape (c) parameters (k = 2.12 and c = 11.09 m/s at 140 m height).

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

- developing offshore wind atlases and models by using long-term and accurate wind datasets as reference points.
- serving 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 such power systems crucially depends on the accurate representation of the spatial and temporal characterisation 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.
- studying periodical trends and occurrences in the data.

The present report does not tackle such applications as its aim is to solely present the measurement data from the LEG platform. TNO does, however, publish an additional annual report sketching a broader picture of the North Sea's wind climate, the most recent one being last year's (2023) report [17]. These annual reports provide a more in-depth analysis of the data and (partially) tackle the above-mentioned applications, based on data measured at the LEG, EPL, K13-A and L2-FA-1 platforms. The 2024 version of this overarching report will be released later this year.

Acknowledgements

The measurement campaign at the offshore platform LEG is carried out on the authority of the Ministry of Climate Policy and Green Growth of The Netherlands.

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Appendix A
Annual wind conditions during the campaign at LEG

A.1 Wind rose

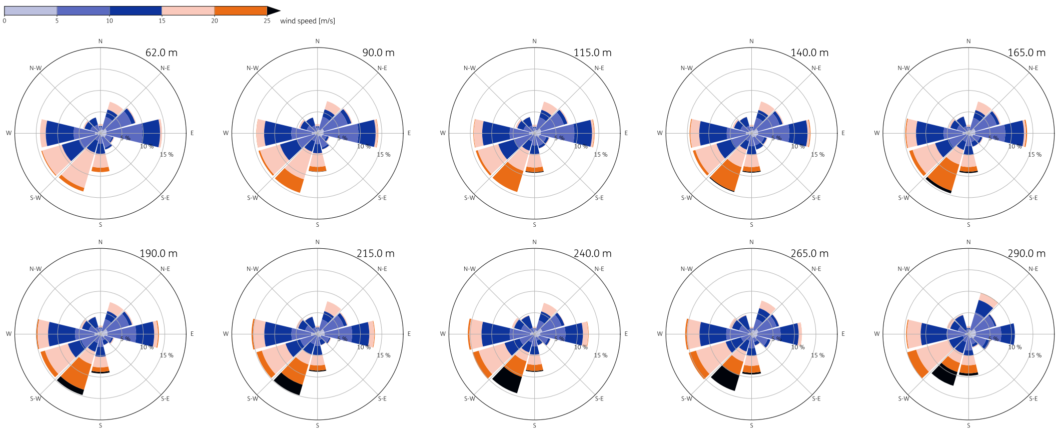

Figure A.1: Wind roses for 2014

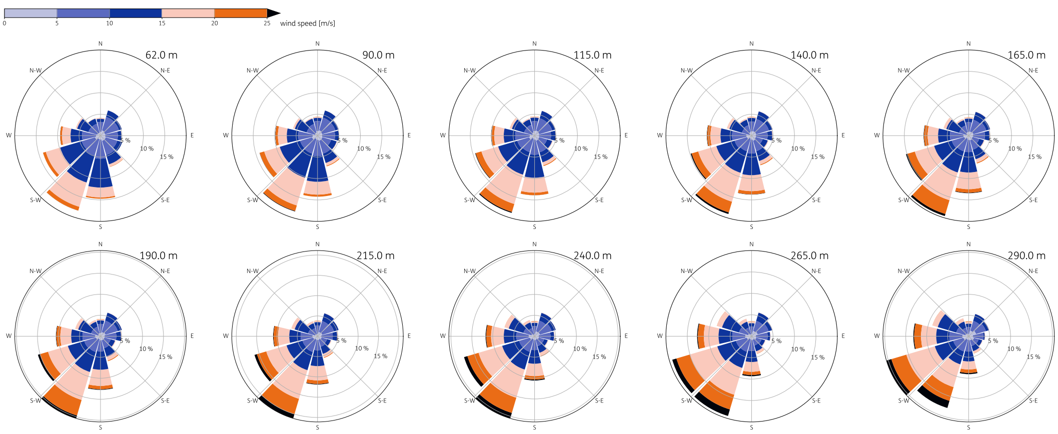

Figure A.2: Wind roses for 2015

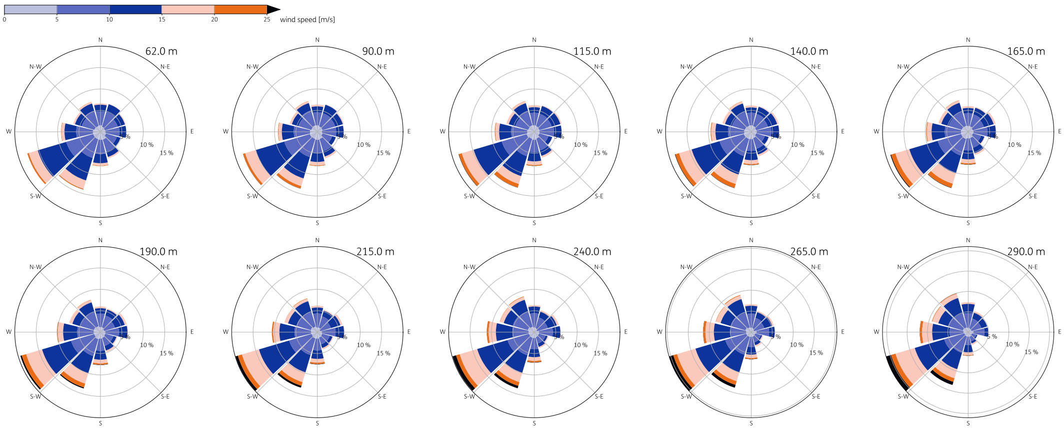

Figure A.3: Wind roses for 2016

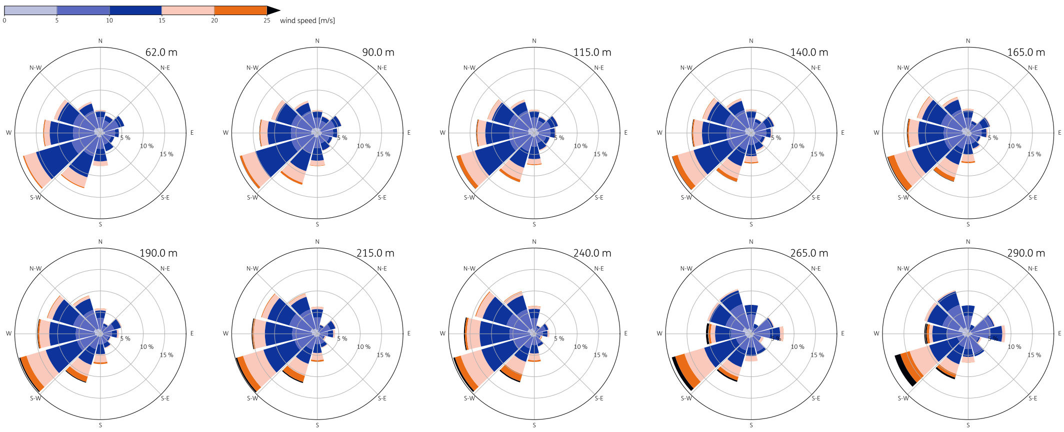

Figure A.4: Wind roses for 2017

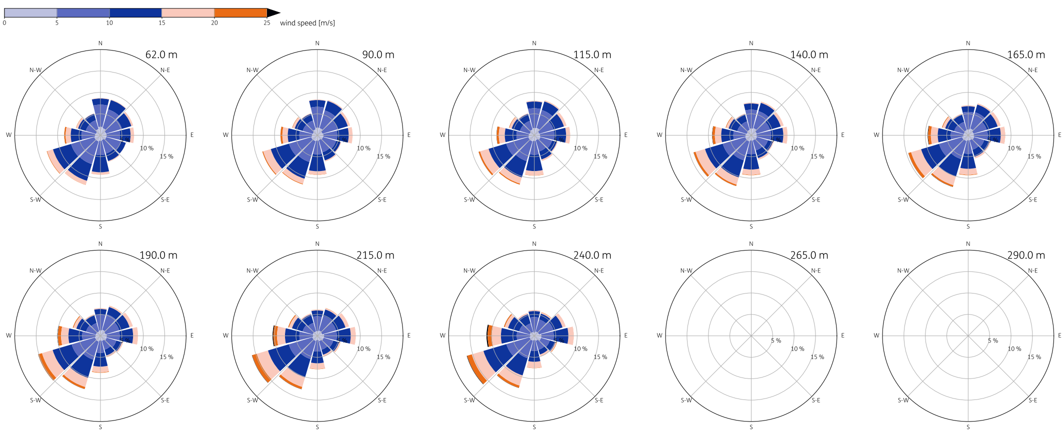

Figure A.5: Wind roses for 2018

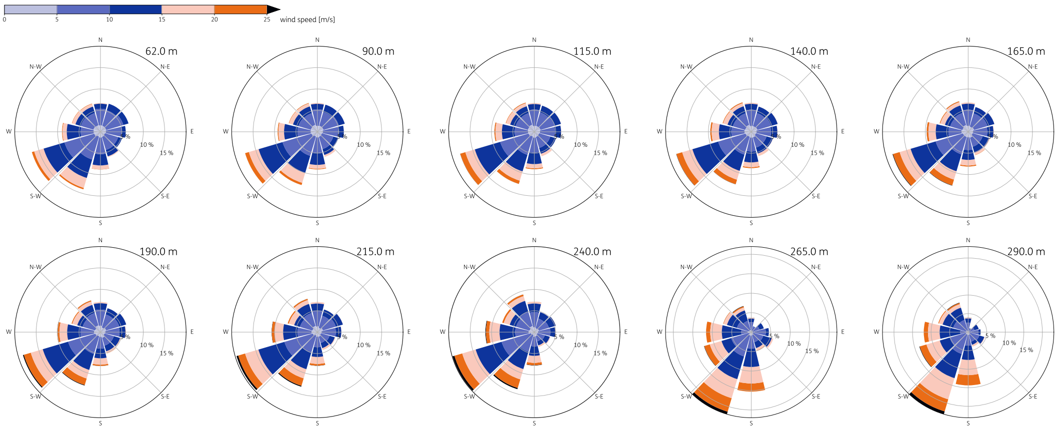

Figure A.6: Wind roses for 2019

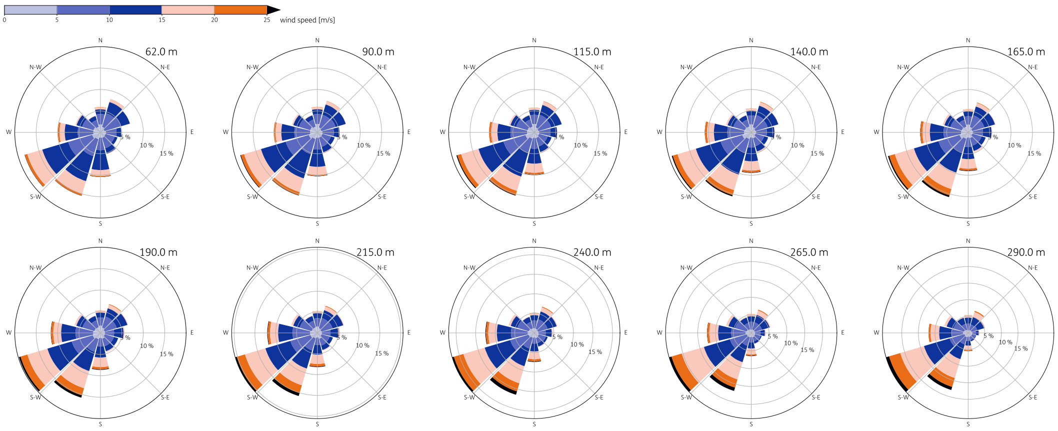

Figure A.7: Wind roses for 2020

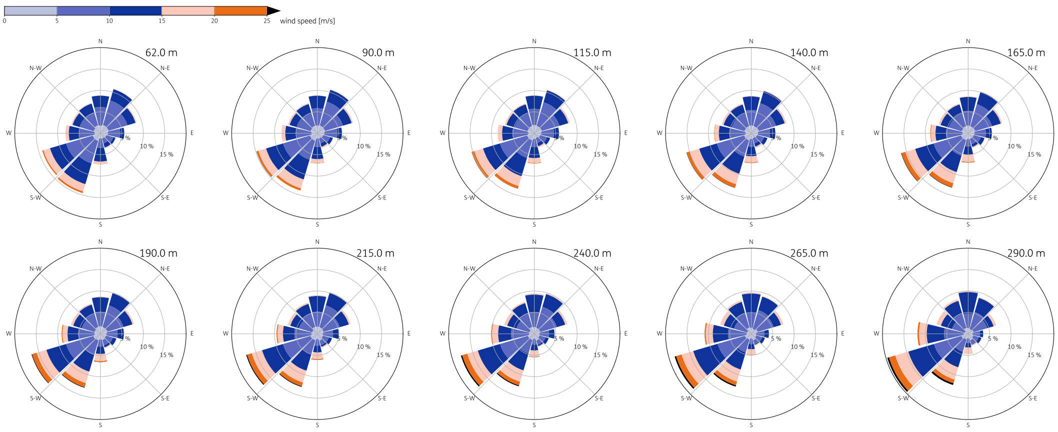

Figure A.8: Wind roses for 2021

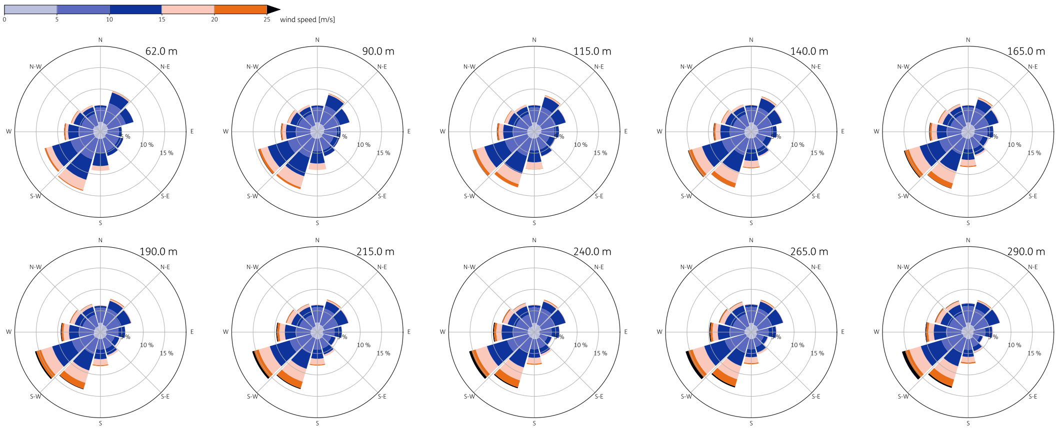

Figure A.9: Wind roses for 2022

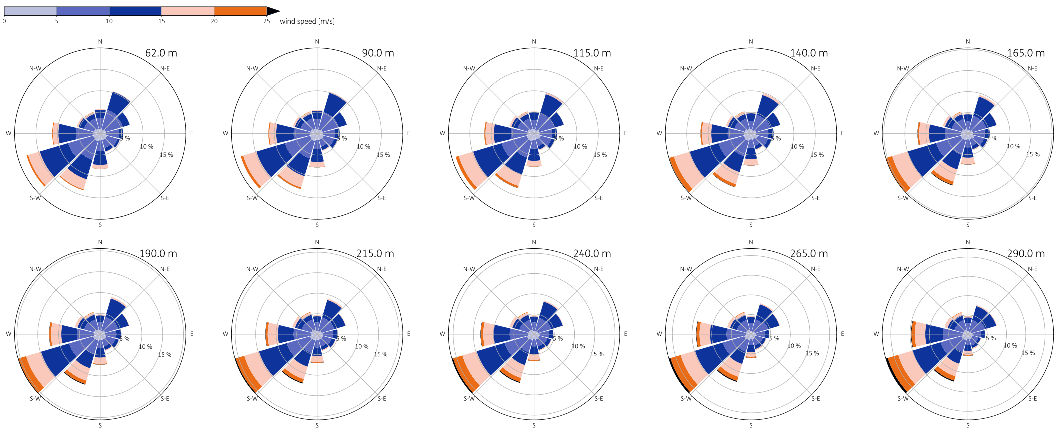

Figure A.10: Wind roses for 2023

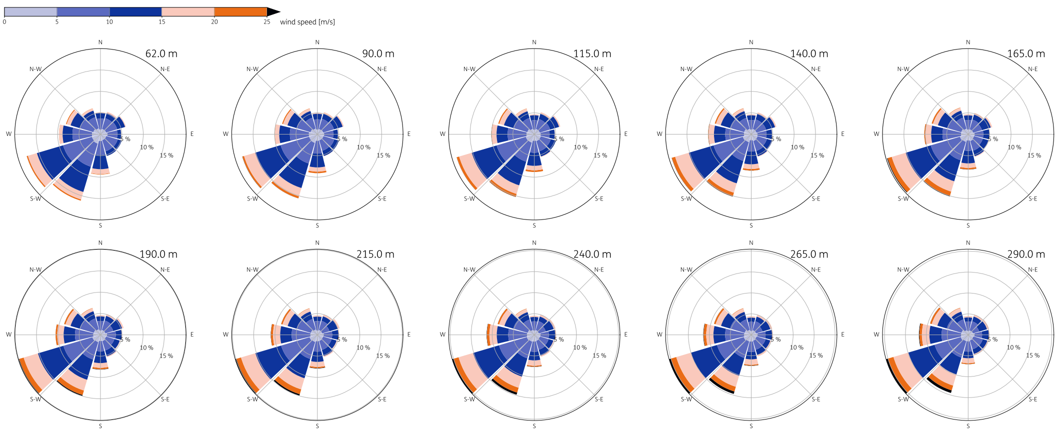

Figure A.11: Wind roses for 2024

A.2 Wind speed and direction statistics

Table A.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

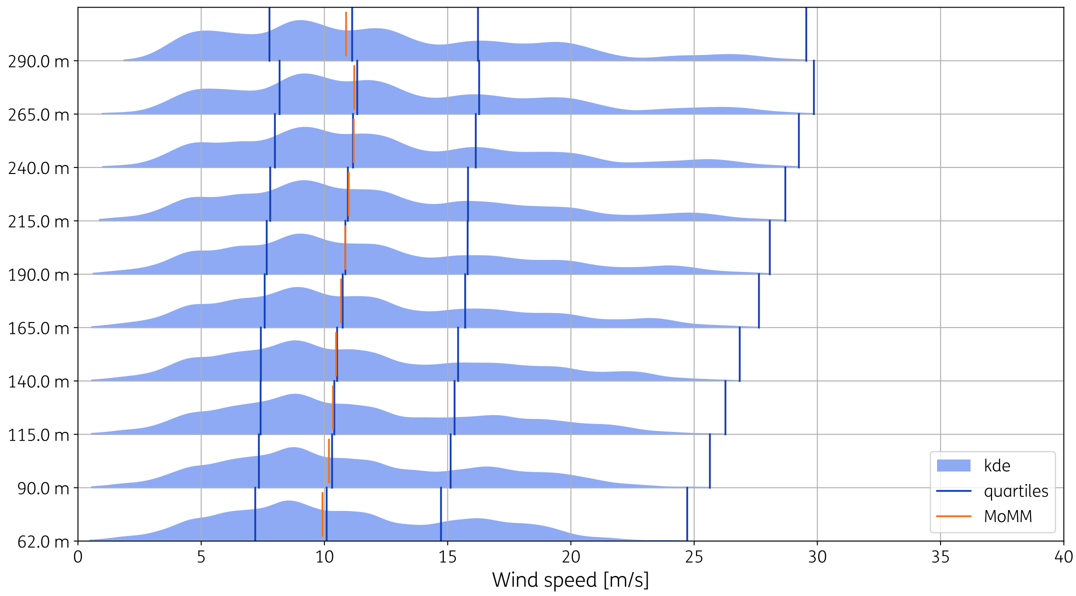

Figure A.12: Wind speed distributions for 2014

Table A.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

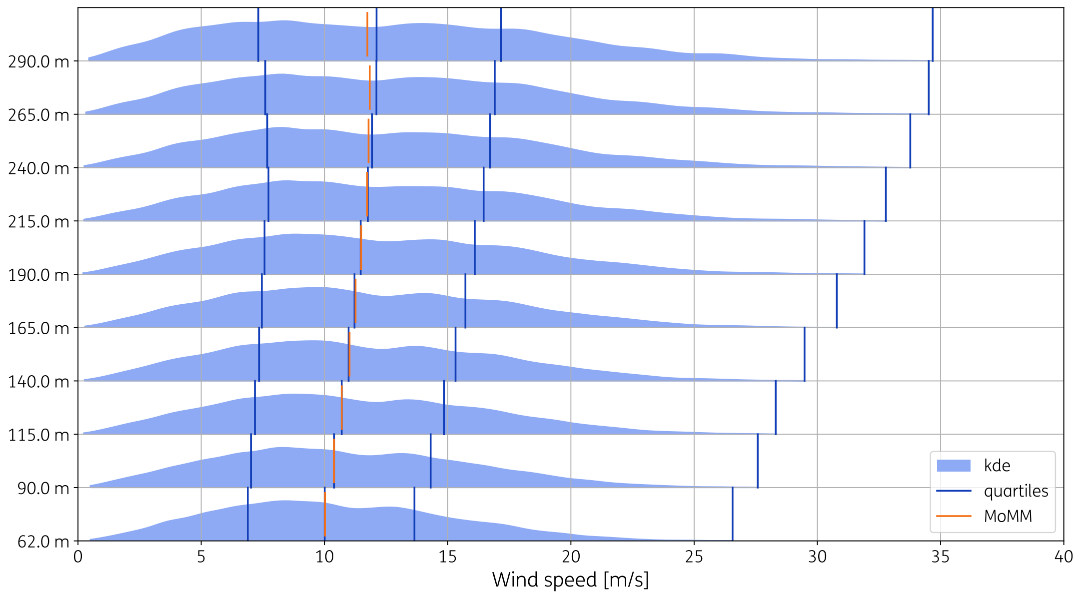

Figure A.13: Wind speed distributions for 2015

Table A.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

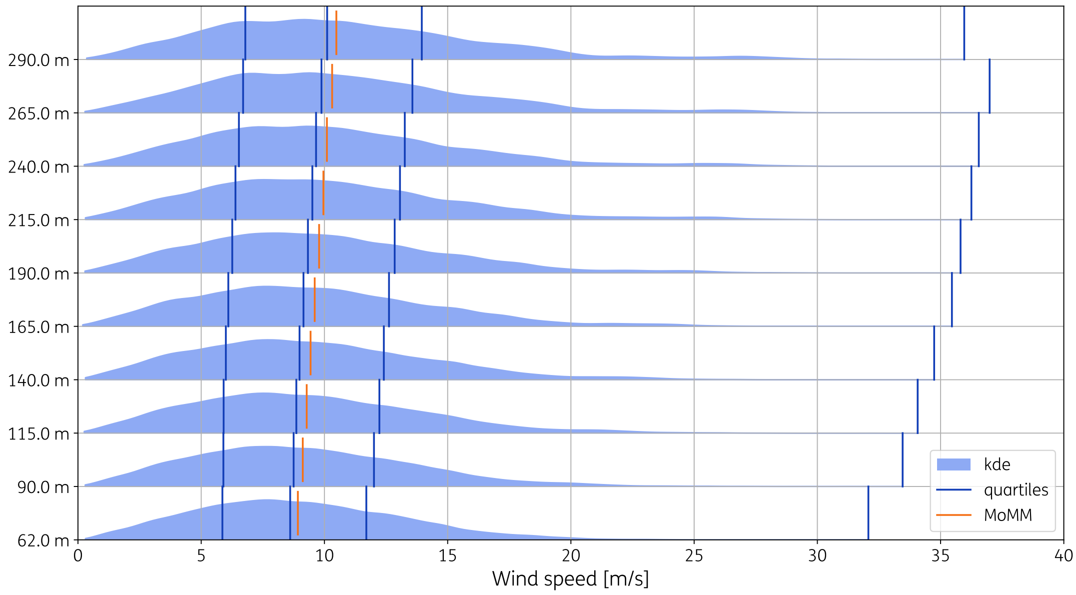

Figure A.14: Wind speed distributions for 2016

Table A.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

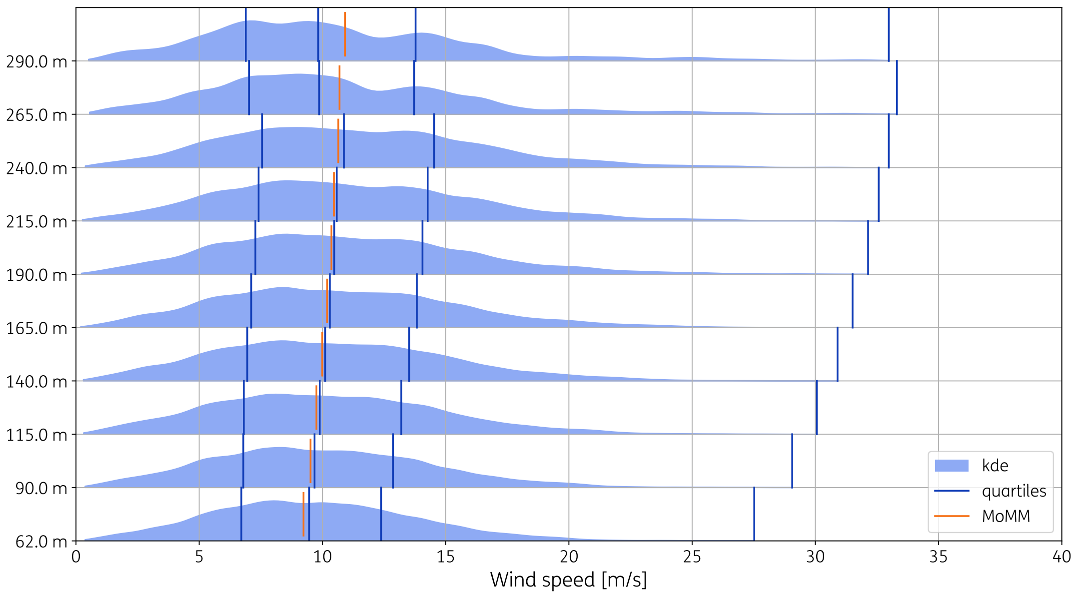

Figure A.15: Wind speed distributions for 2017

Table A.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						

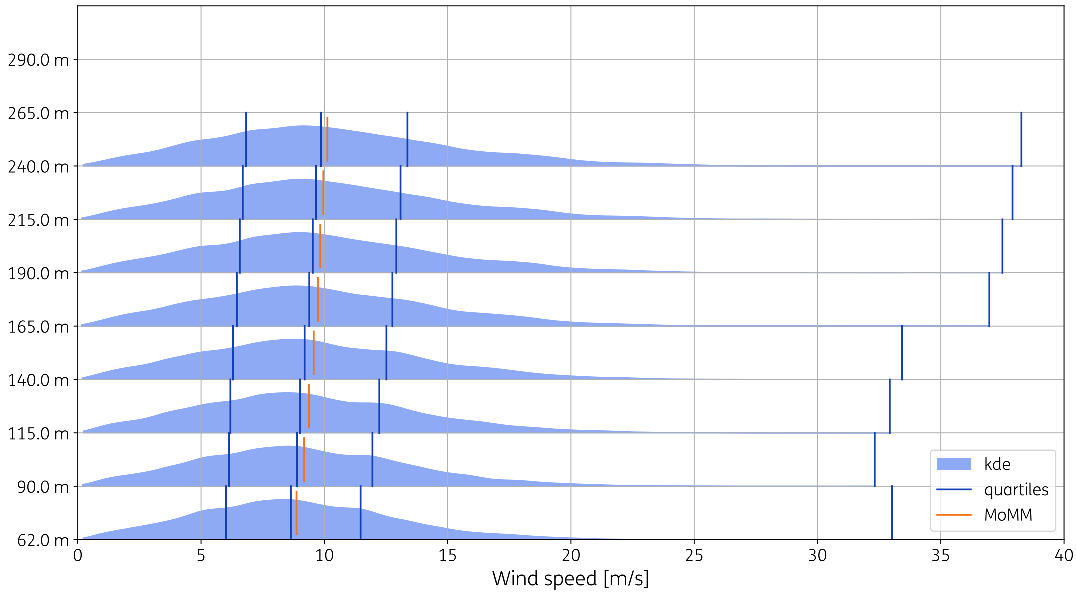

Figure A.16: Wind speed distributions for 2018

Table A.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

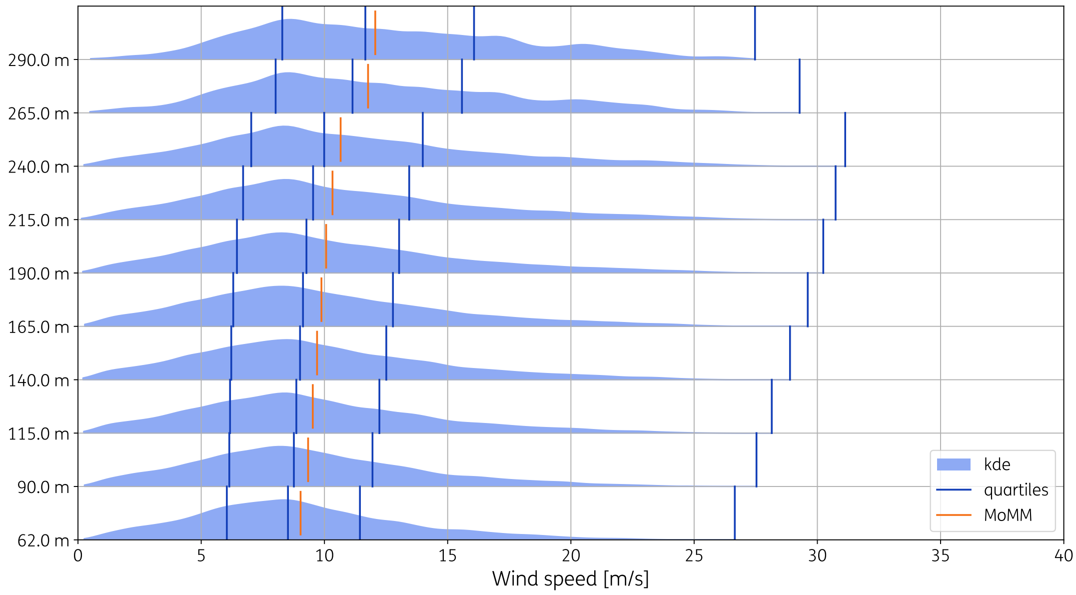

Figure A.17: Wind speed distributions for 2019

Table A.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

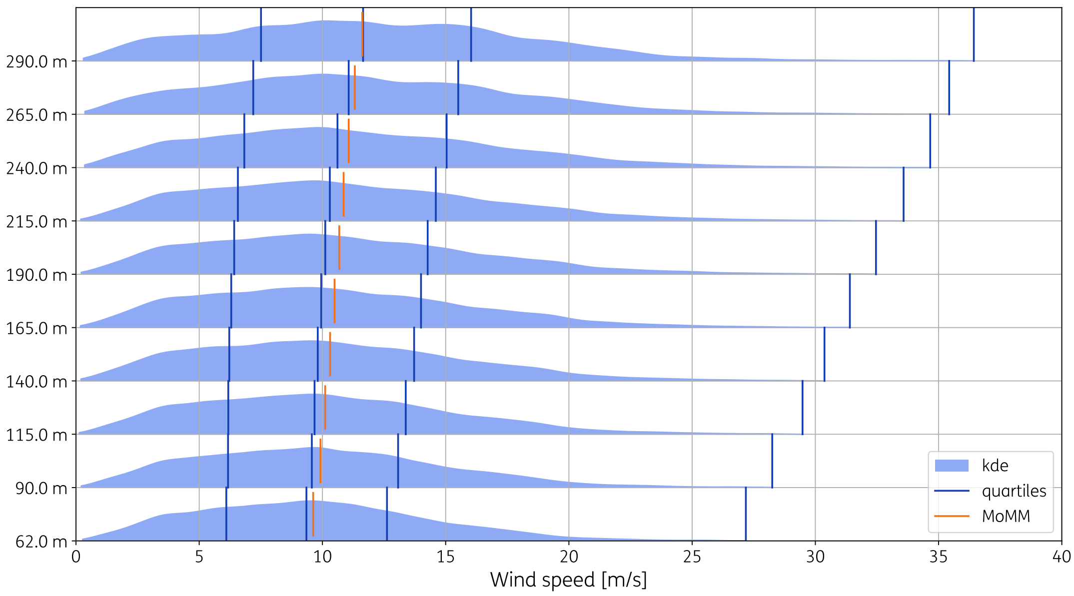

Figure A.18: Wind speed distributions for 2020

Table A.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

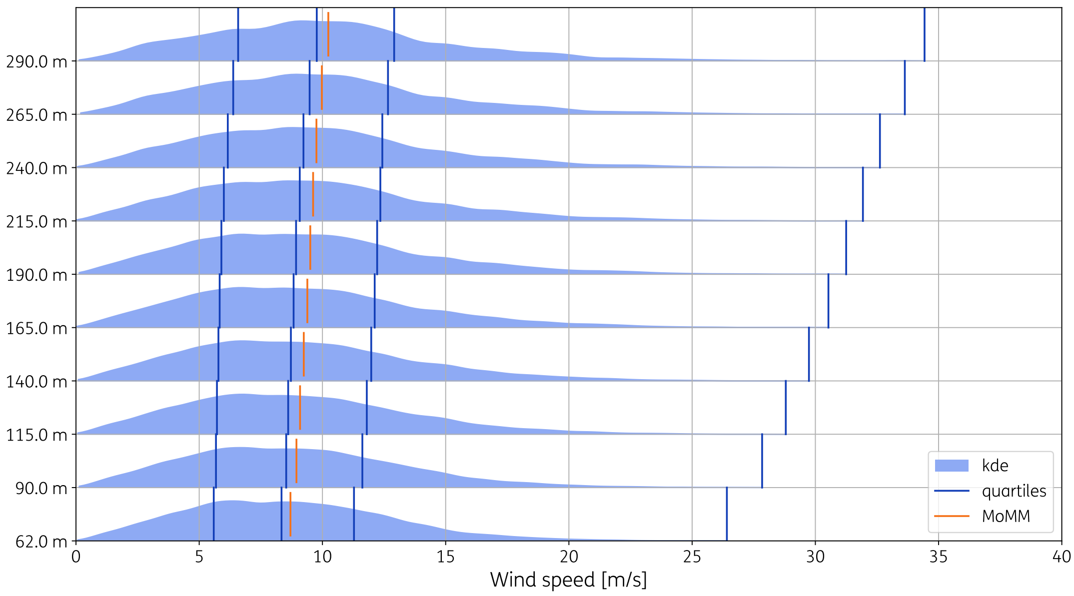

Figure A.19: Wind speed distributions for 2021

Table A.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

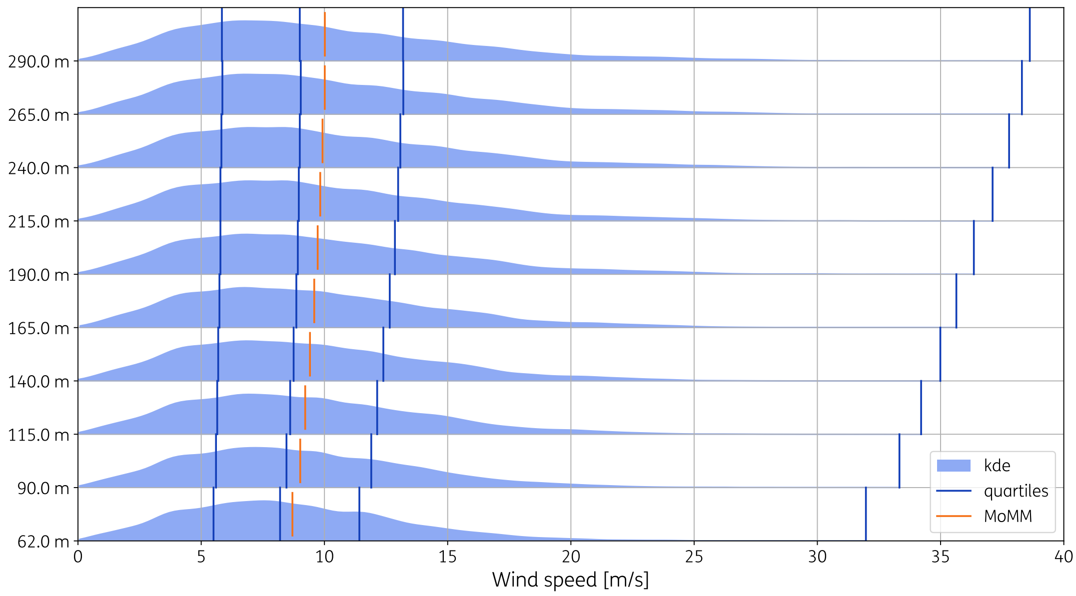

Figure A.20: Wind speed distributions for 2022

Table A.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

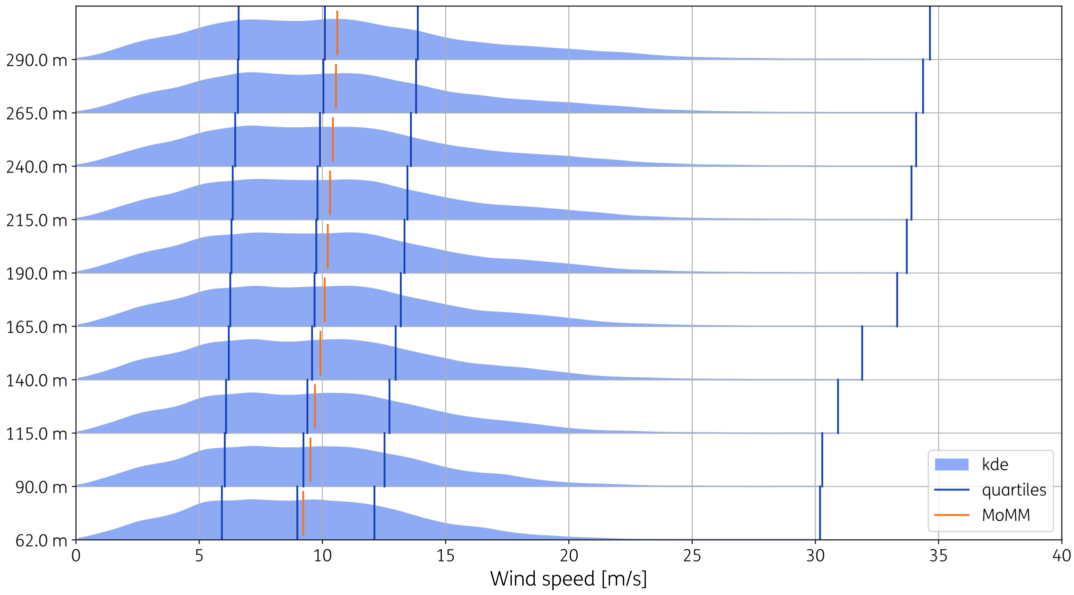

Figure A.21: Wind speed distributions for 2023

Table A.11: Wind speed and wind direction statistics for 2024

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	49 388	5.76	8.64	11.80	26.85	8.97	234.9
90	48 501	5.85	8.86	12.23	28.05	9.26	235.7
115	47 366	5.90	9.00	12.46	27.45	9.44	236.1
140	46 839	5.97	9.15	12.72	29.25	9.64	236.7
165	46 626	6.01	9.27	12.96	32.10	9.81	237.4
190	46 151	6.07	9.37	13.18	32.50	9.96	237.9
215	45 508	6.13	9.45	13.35	33.39	10.09	238.4
240	44 529	6.16	9.49	13.50	33.36	10.19	239.2
265	43 258	6.16	9.51	13.59	33.81	10.26	240.1
290	41 513	6.17	9.52	13.65	34.07	10.32	241.9

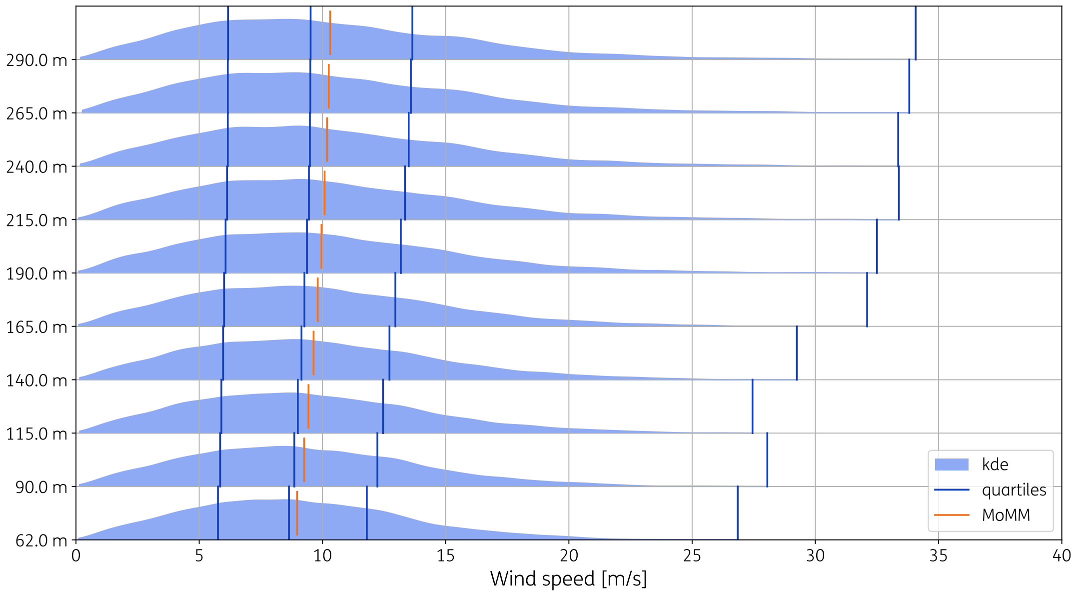

Figure A.22: Wind speed distributions for 2024

A.3 Wind speed distribution

Table A.12: 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 A.13: 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 A.14: 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 A.15: 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 A.16: 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 A.17: 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 A.18: 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 A.19: 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 A.20: 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 A.21: 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

Table A.22: Weibull parameters for 2024

Height	Shape (k)	Scale (c)
m	–	m/s
62	2.191	10.11
90	2.148	10.42
115	2.115	10.61
140	2.088	10.83
165	2.059	11.01
190	2.035	11.19
215	2.016	11.33
240	1.995	11.45
265	1.983	11.52
290	1.979	11.58

A.4 Wind shear and veer

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

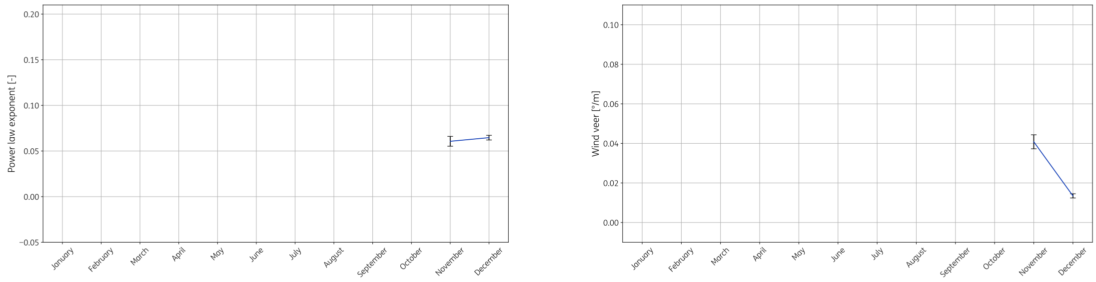

Figure A.23: Wind shear and veer as function of the month-of-year for 2014

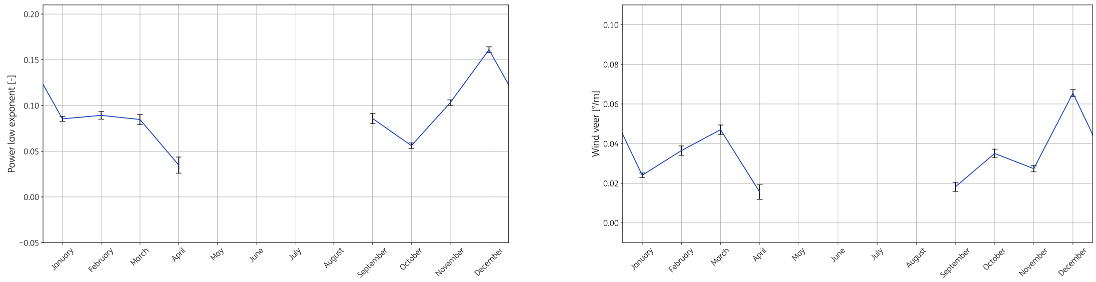

Figure A.24: Wind shear and veer as function of the month-of-year for 2015

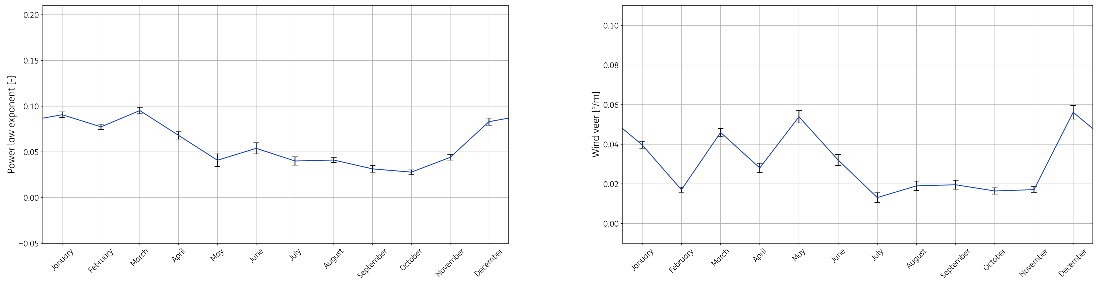

Figure A.25: Wind shear and veer as function of the month-of-year for 2016

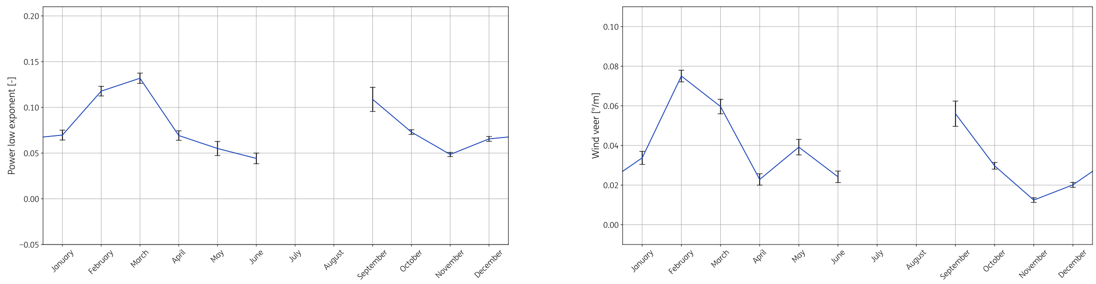

Figure A.26: Wind shear and veer as function of the month-of-year for 2017

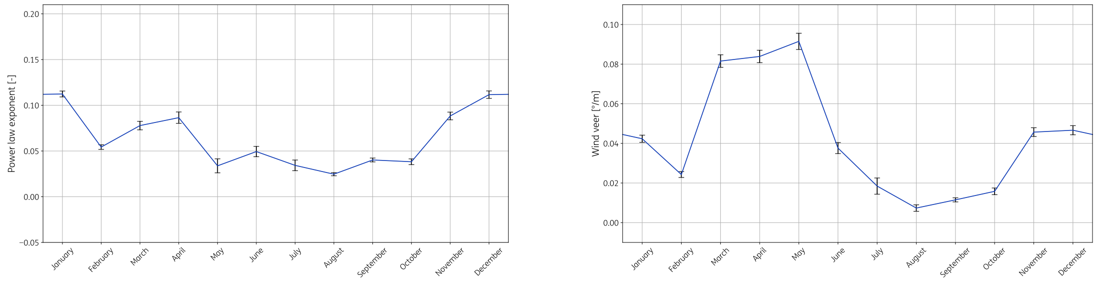

Figure A.27: Wind shear and veer as function of the month-of-year for 2018

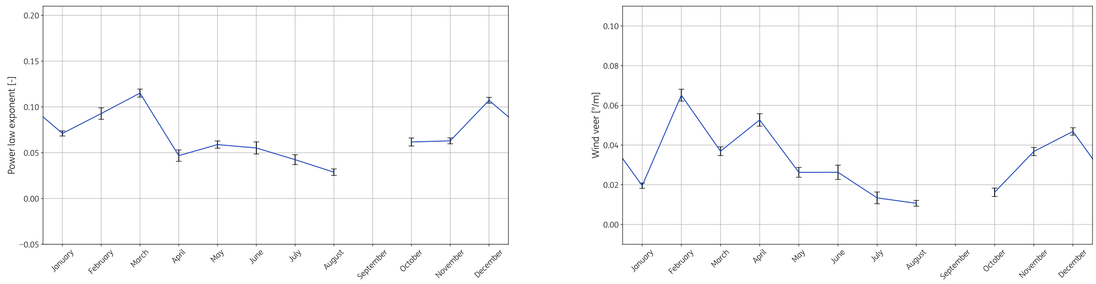

Figure A.28: Wind shear and veer as function of the month-of-year for 2019

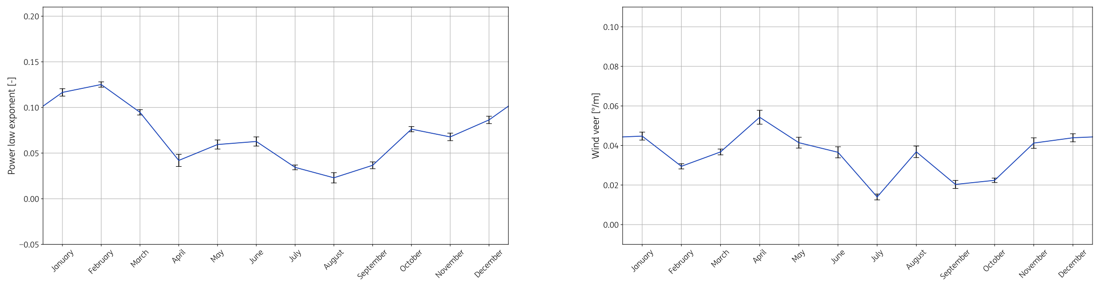

Figure A.29: Wind shear and veer as function of the month-of-year for 2020

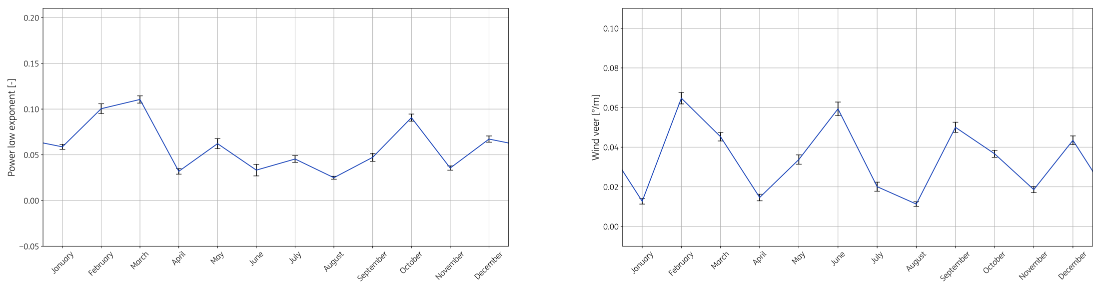

Figure A.30: Wind shear and veer as function of the month-of-year for 2021

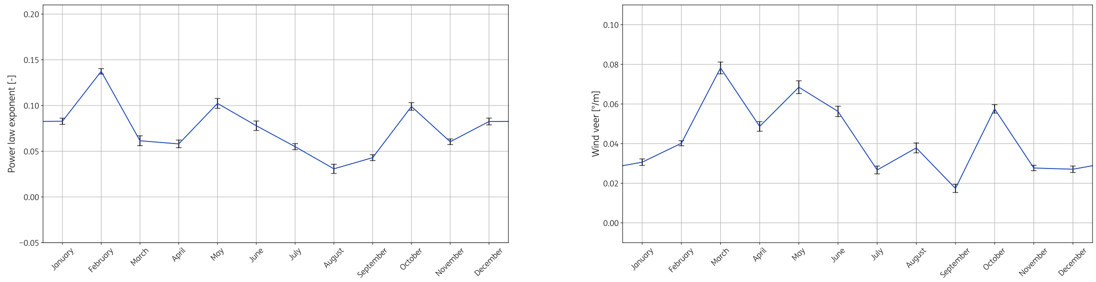

Figure A.31: Wind shear and veer as function of the month-of-year for 2022

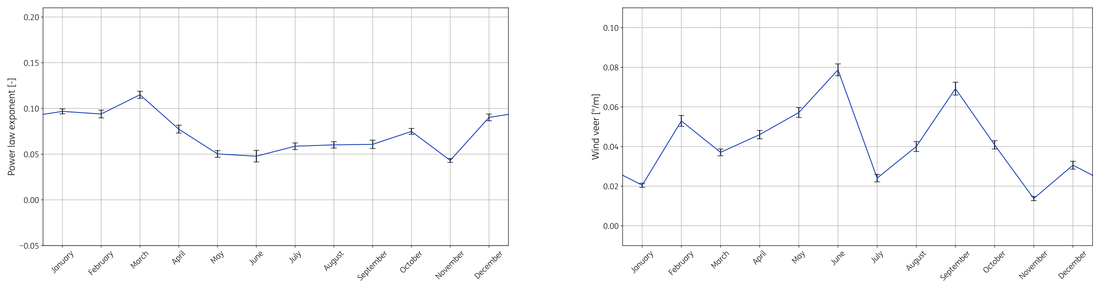

Figure A.32: Wind shear and veer as function of the month-of-year for 2023

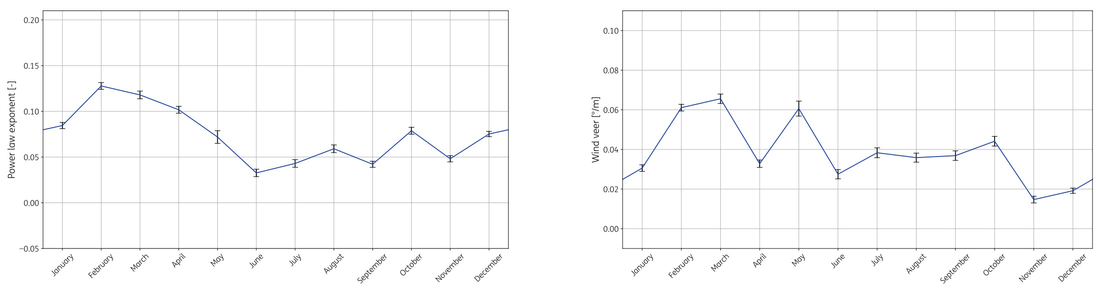

Figure A.33: Wind shear and veer as function of the month-of-year for 2024

A.4.2 Wind shear and veer as function of hour

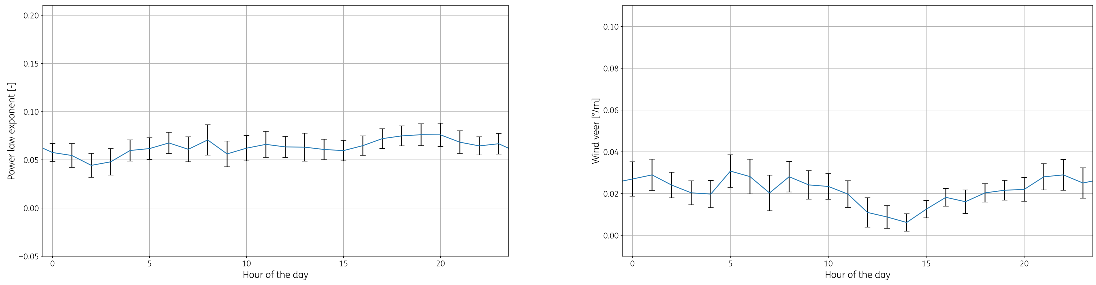

Figure A.34: Wind shear and veer as function the hour-of-day for 2014

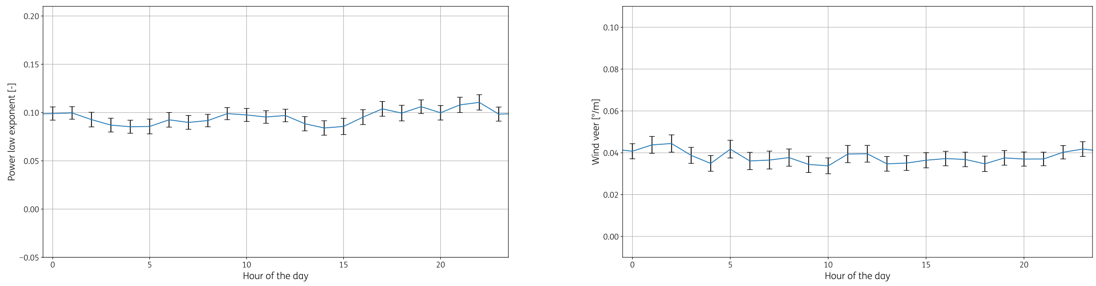

Figure A.35: Wind shear and veer as function the hour-of-day for 2015

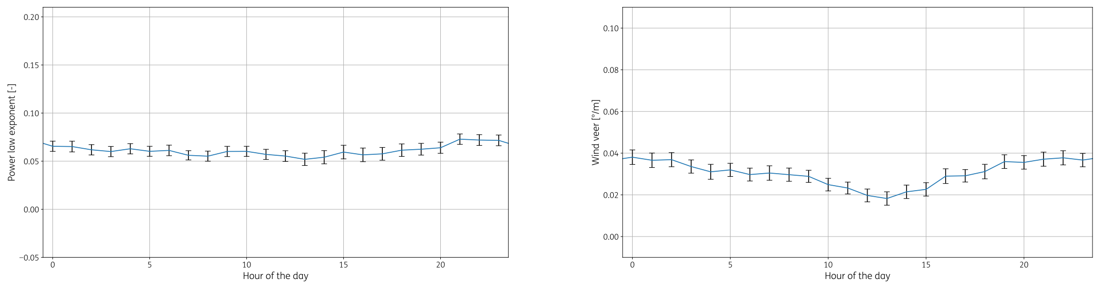

Figure A.36: Wind shear and veer as function the hour-of-day for 2016

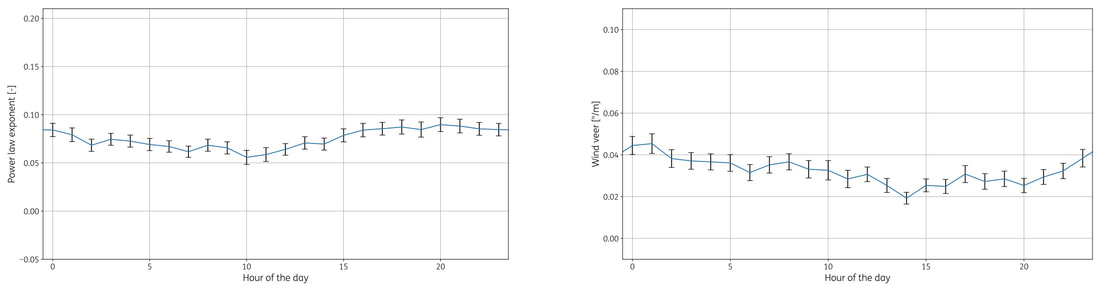

Figure A.37: Wind shear and veer as function the hour-of-day for 2017

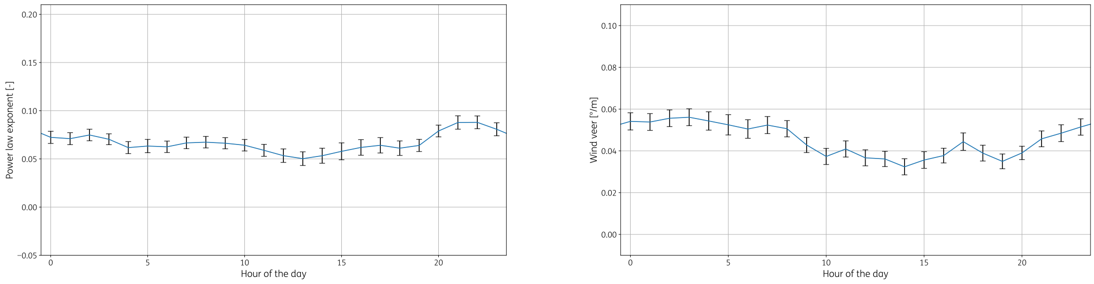

Figure A.38: Wind shear and veer as function the hour-of-day for 2018

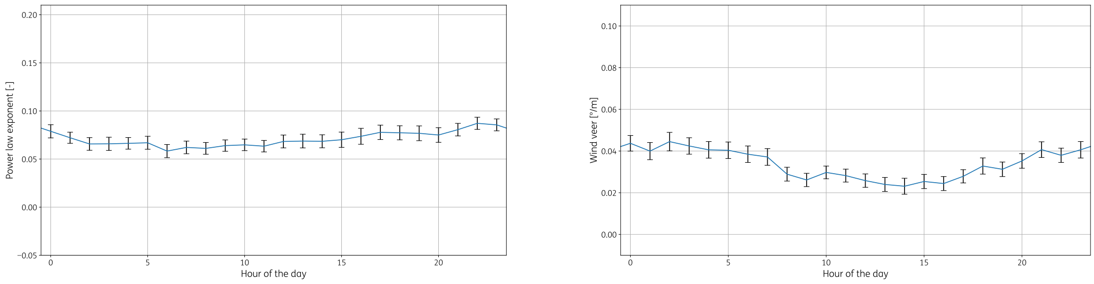

Figure A.39: Wind shear and veer as function the hour-of-day for 2019

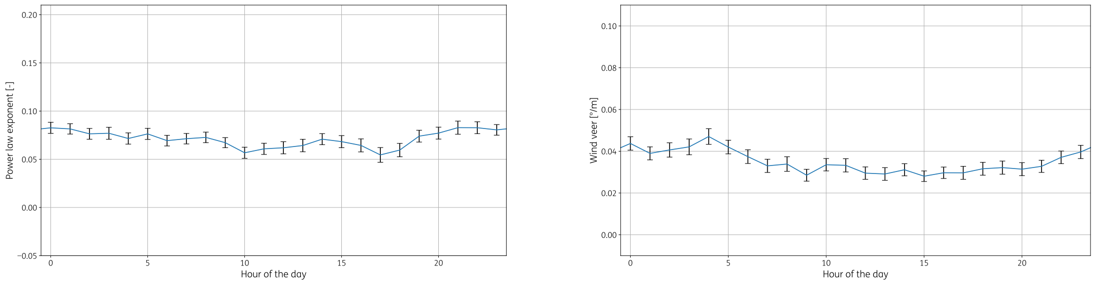

Figure A.40: Wind shear and veer as function the hour-of-day for 2020

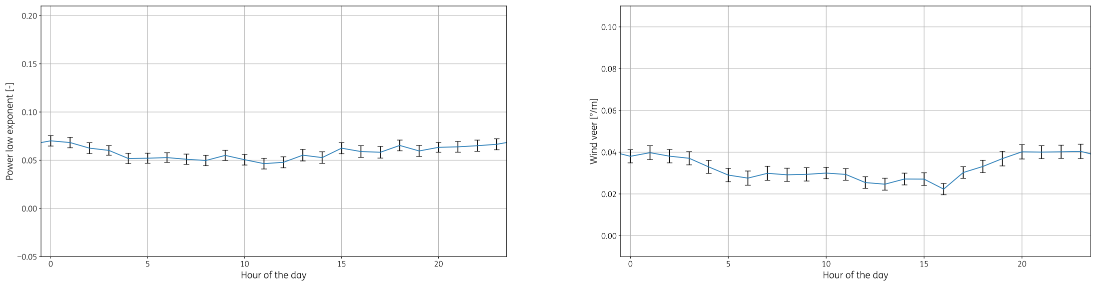

Figure A.41: Wind shear and veer as function the hour-of-day for 2021

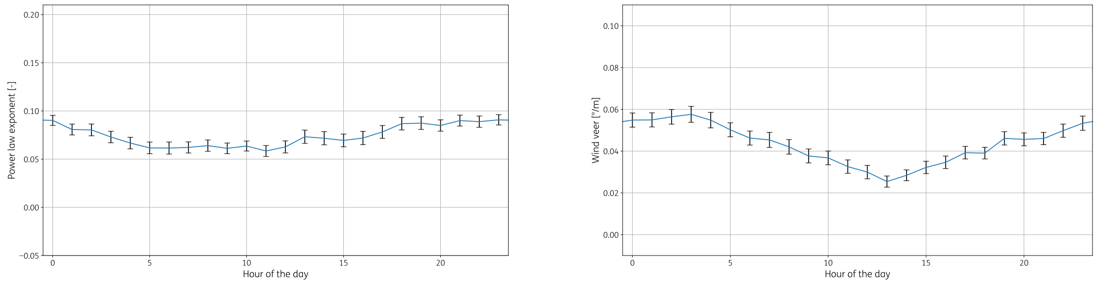

Figure A.42: Wind shear and veer as function the hour-of-day for 2022

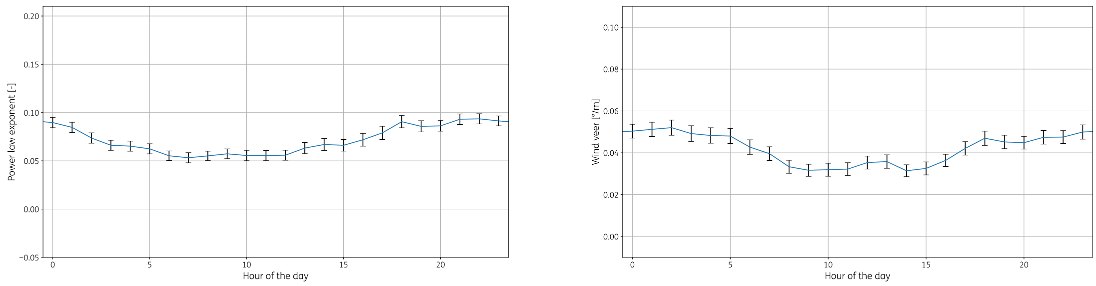

Figure A.43: Wind shear and veer as function the hour-of-day for 2023

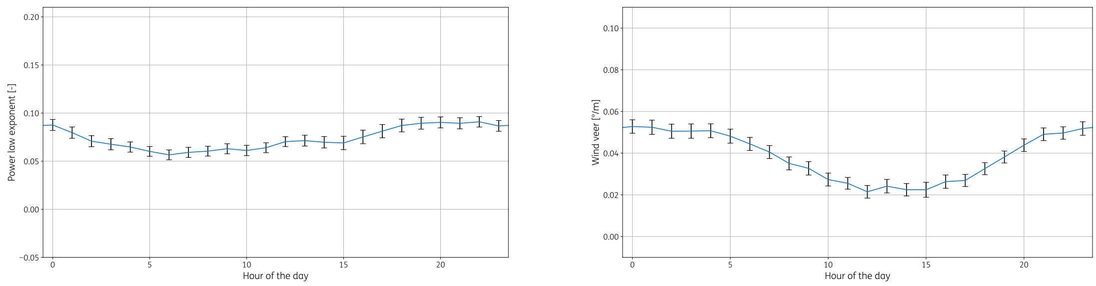

Figure A.44: Wind shear and veer as function the hour-of-day for 2024

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

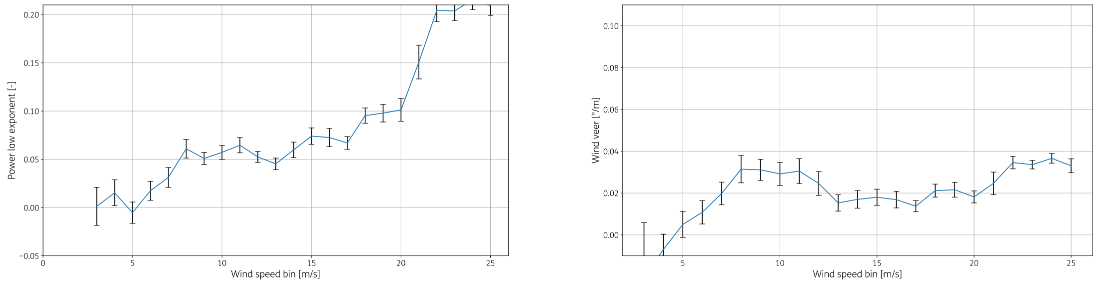

Figure A.45: Wind shear and veer as function of wind speed for 2014

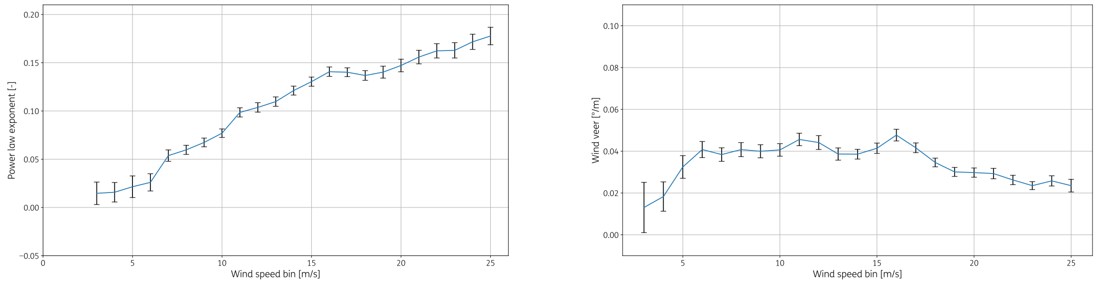

Figure A.46: Wind shear and veer as function of wind speed for 2015

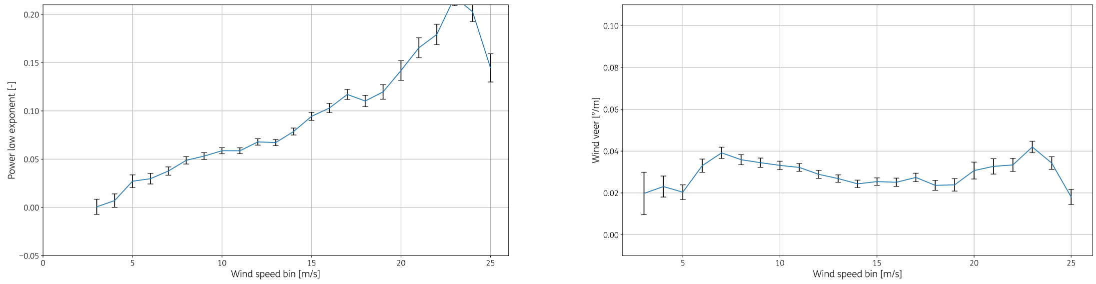

Figure A.47: Wind shear and veer as function of wind speed for 2016

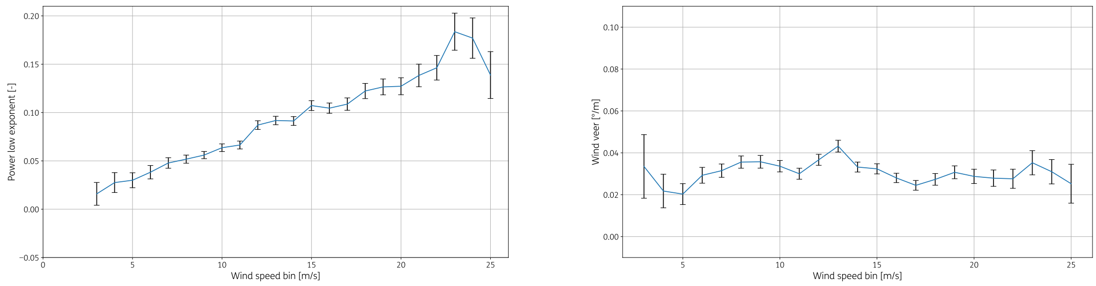

Figure A.48: Wind shear and veer as function of wind speed for 2017

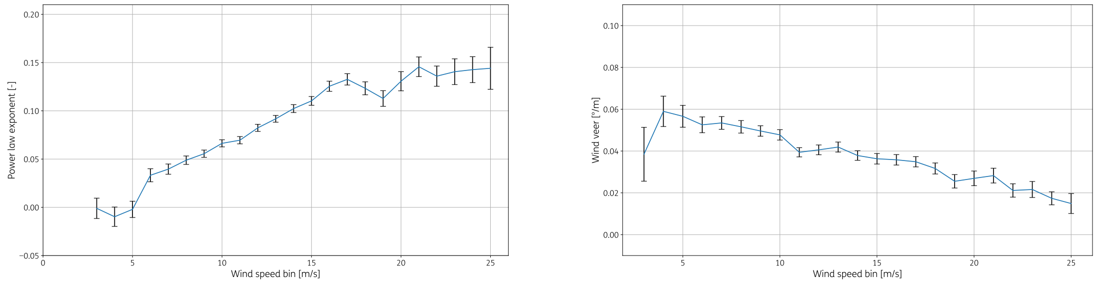

Figure A.49: Wind shear and veer as function of wind speed for 2018

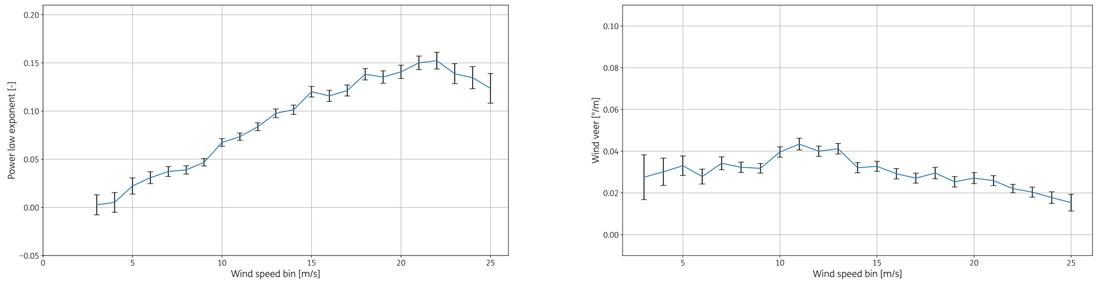

Figure A.50: Wind shear and veer as function of wind speed for 2019

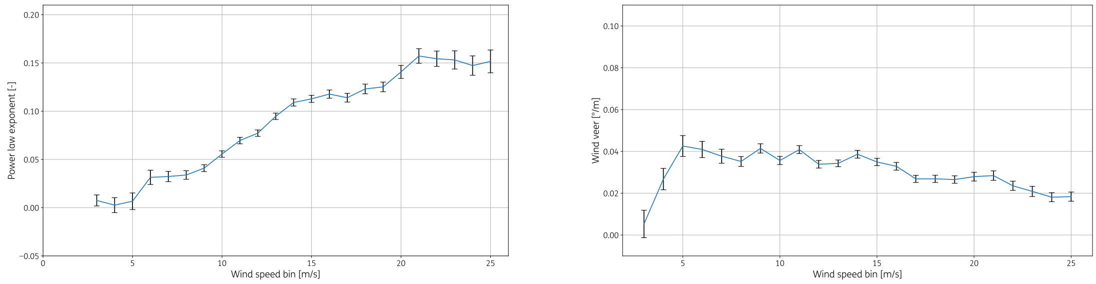

Figure A.51: Wind shear and veer as function of wind speed for 2020

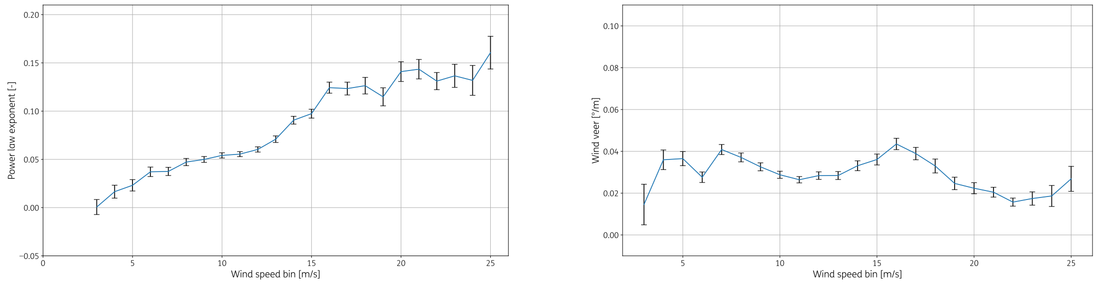

Figure A.52: Wind shear and veer as function of wind speed for 2021

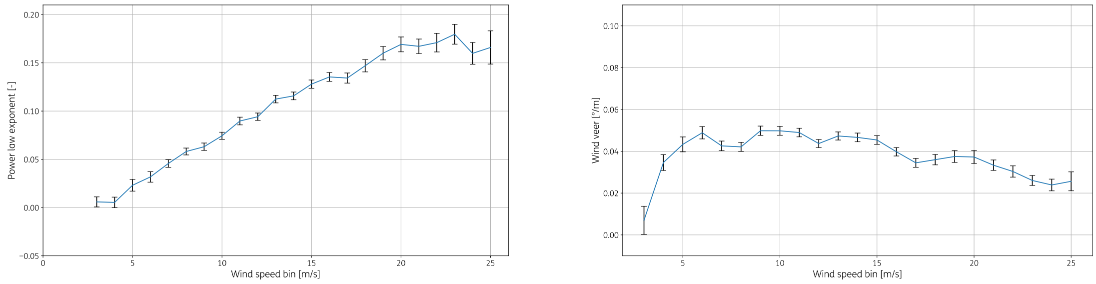

Figure A.53: Wind shear and veer as function of wind speed for 2022

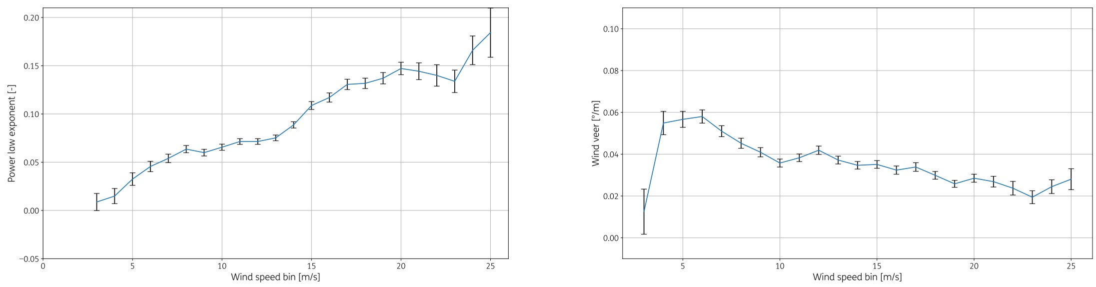

Figure A.54: Wind shear and veer as function of wind speed for 2023

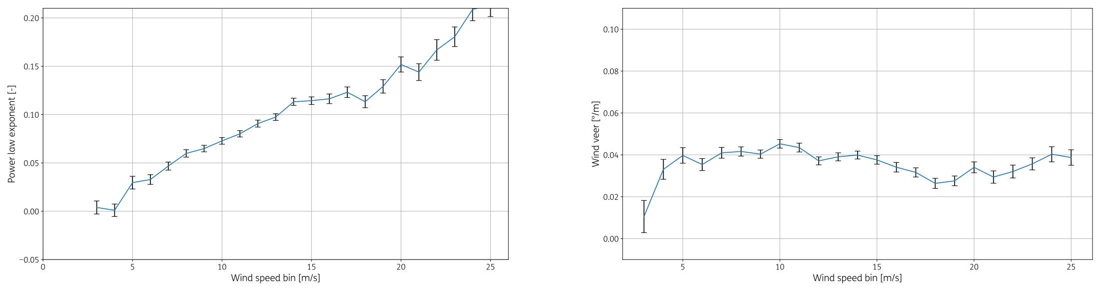

Figure A.55: Wind shear and veer as function of wind speed for 2024

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

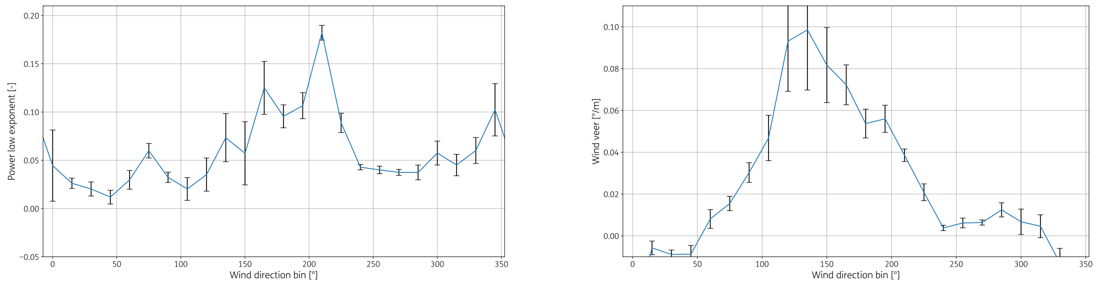

Figure A.56: Wind shear and veer as function of wind direction for 2014

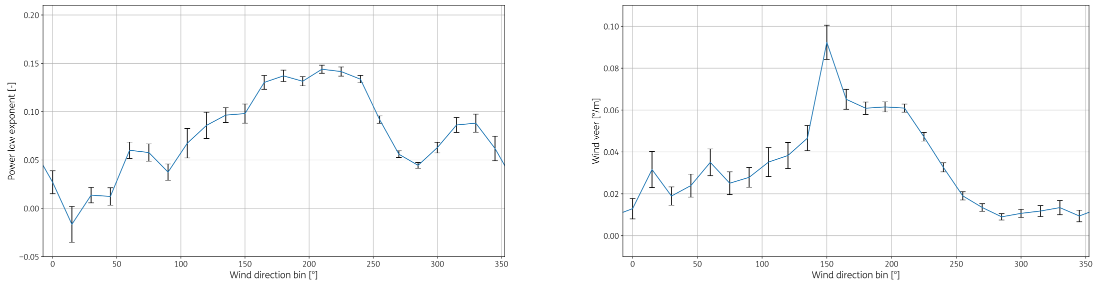

Figure A.57: Wind shear and veer as function of wind direction for 2015

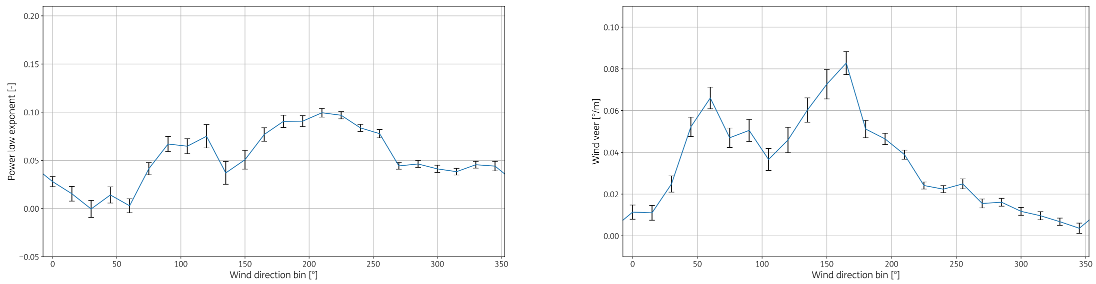

Figure A.58: Wind shear and veer as function of wind direction for 2016

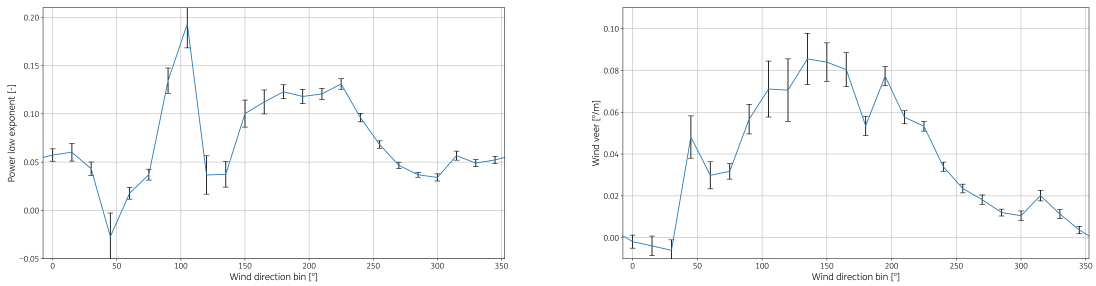

Figure A.59: Wind shear and veer as function of wind direction for 2017

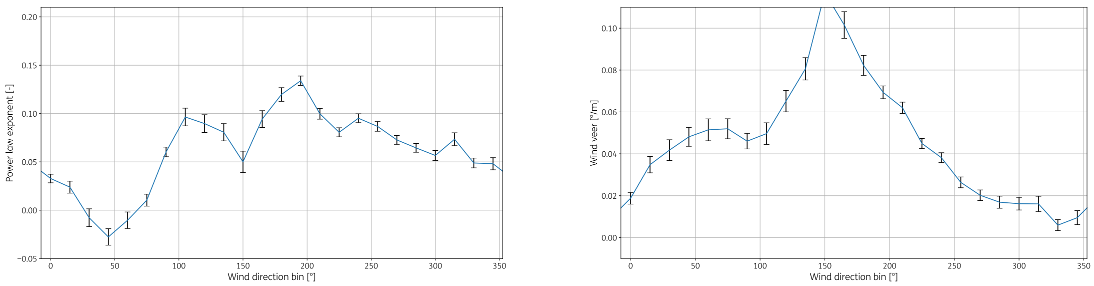

Figure A.60: Wind shear and veer as function of wind direction for 2018

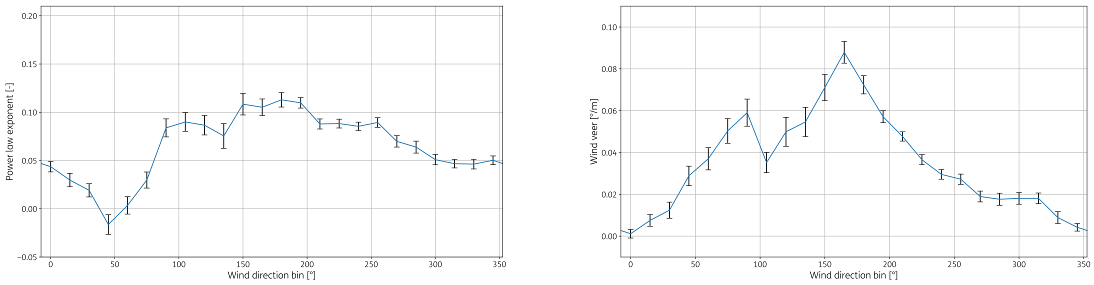

Figure A.61: Wind shear and veer as function of wind direction for 2019

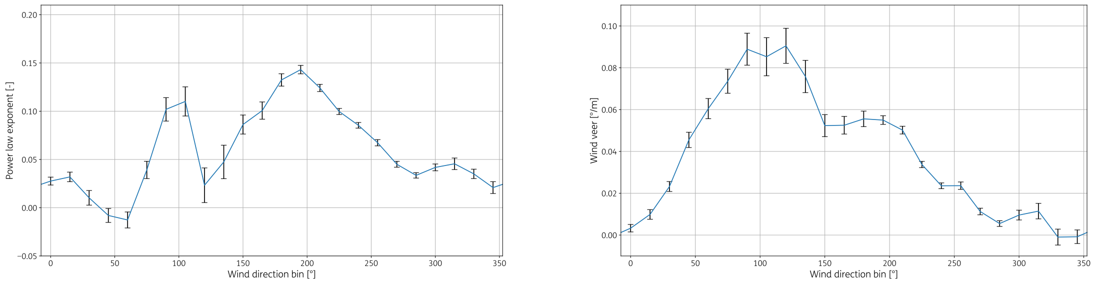

Figure A.62: Wind shear and veer as function of wind direction for 2020

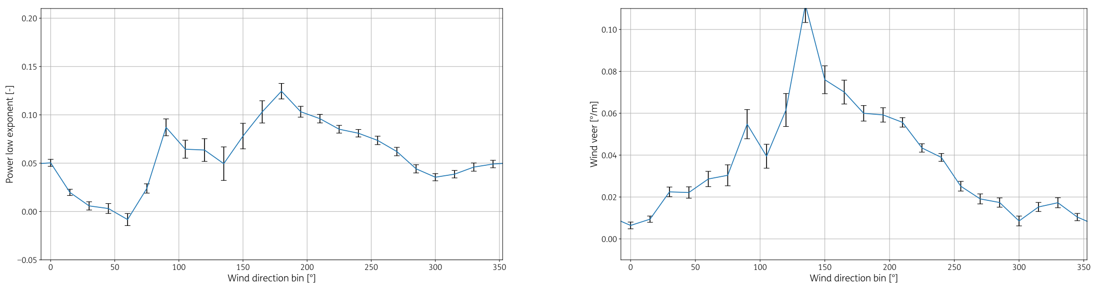

Figure A.63: Wind shear and veer as function of wind direction for 2021

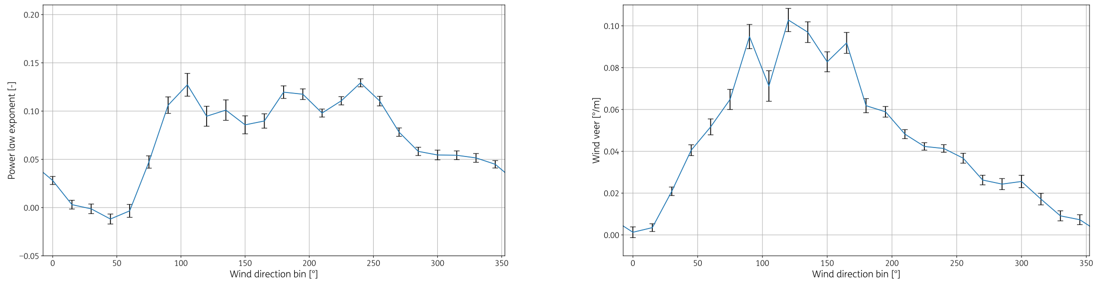

Figure A.64: Wind shear and veer as function of wind direction for 2022

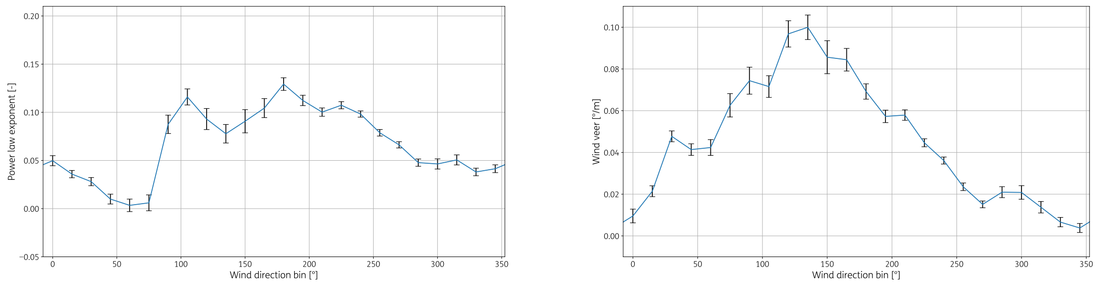

Figure A.65: Wind shear and veer as function of wind direction for 2023

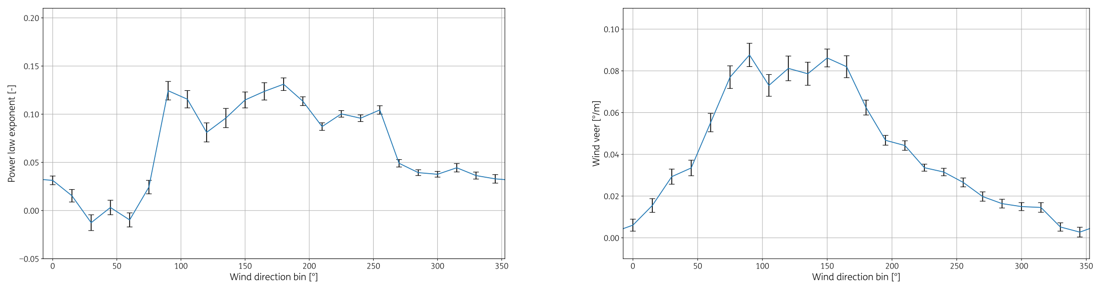

Figure A.66: Wind shear and veer as function of wind direction for 2024

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

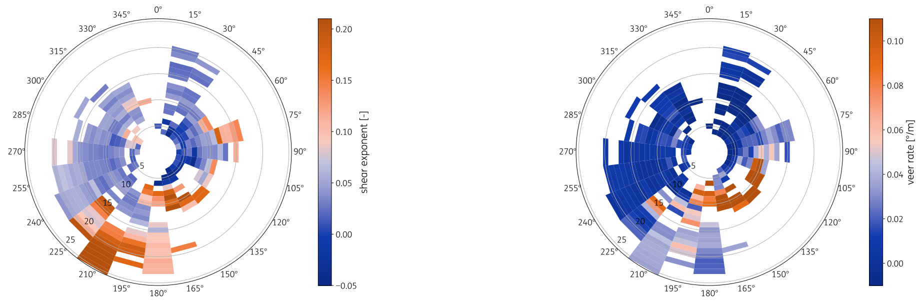

Figure A.67: Wind shear and veer as function of wind speed and direction for 2014

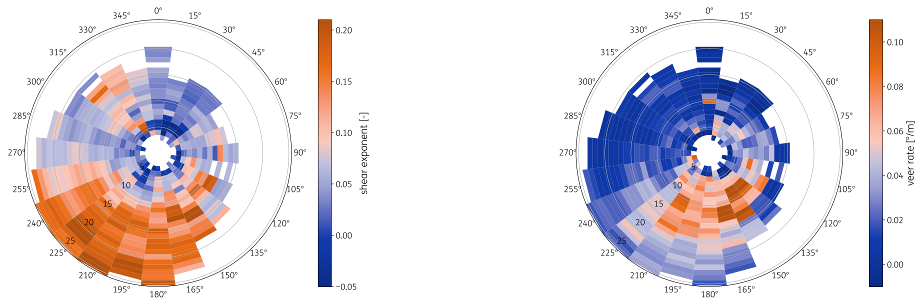

Figure A.68: Wind shear and veer as function of wind speed and direction for 2015

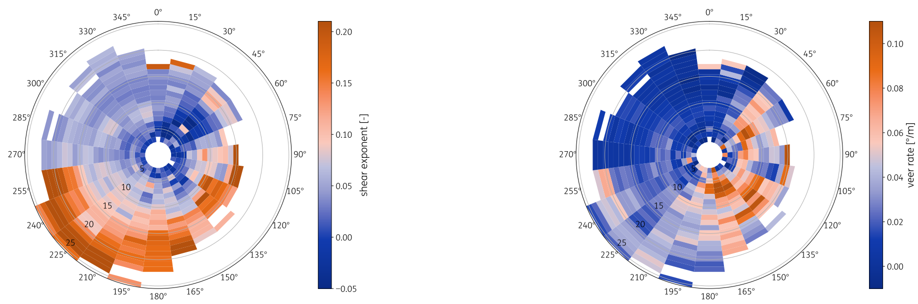

Figure A.69: Wind shear and veer as function of wind speed and direction for 2016

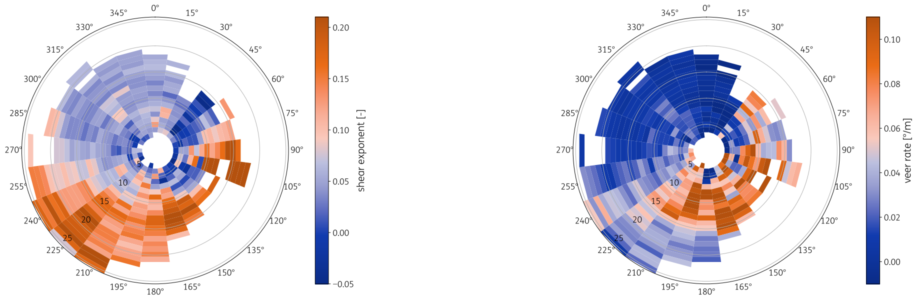

Figure A.70: Wind shear and veer as function of wind speed and direction for 2017

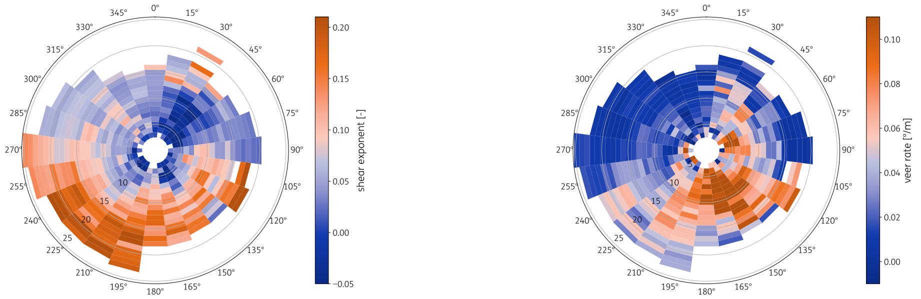

Figure A.71: Wind shear and veer as function of wind speed and direction for 2018

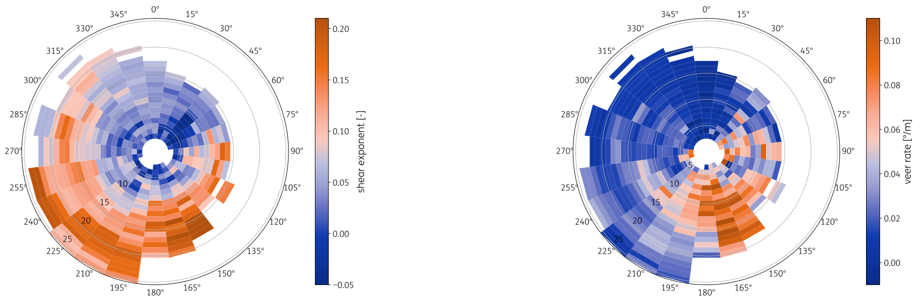

Figure A.72: Wind shear and veer as function of wind speed and direction for 2019

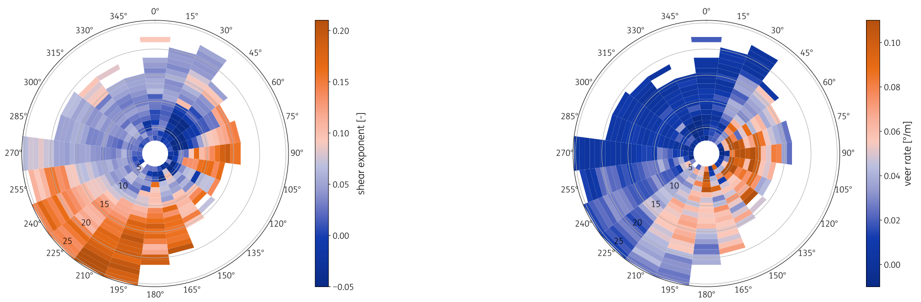

Figure A.73: Wind shear and veer as function of wind speed and direction for 2020

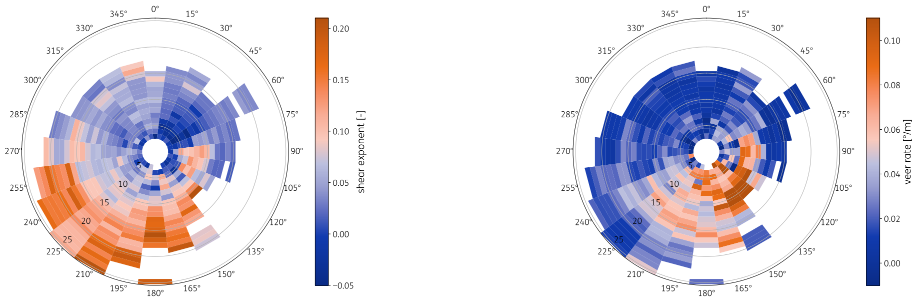

Figure A.74: Wind shear and veer as function of wind speed and direction for 2021

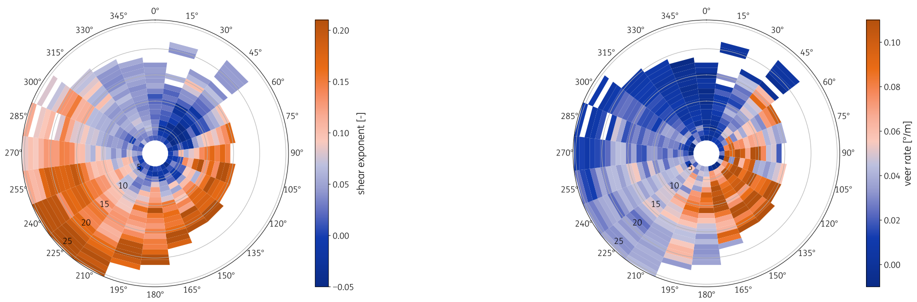

Figure A.75: Wind shear and veer as function of wind speed and direction for 2022

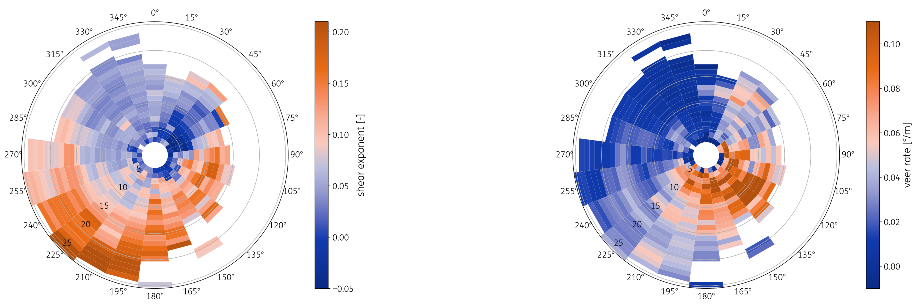

Figure A.76: Wind shear and veer as function of wind speed and direction for 2023

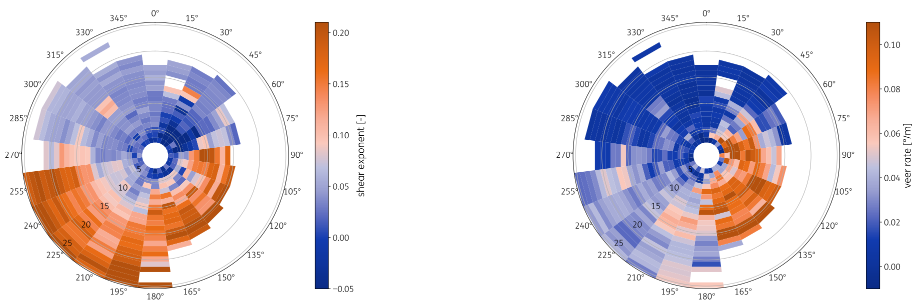

Figure A.77: Wind shear and veer as function of wind speed and direction for 2024

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