Wintershall platform K13-A, 2016–2024

Offshore wind resources at the North Sea

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RvA is participant in the ILAC MRA.

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 K13-A platform where a ZX300M has been deployed, providing high quality data since 2016. The data are publicly available to be used for further purposes (offshorewind-measurements.tno.nl).

At the K13-A platform, the wind analysis for the 2016–2024 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 235.6° to 244.3° across the different sensor heights (63 m to 291 m). The average wind speed ranges from 9.38 m/s at the lowest measurement height of 63 m up to 10.73 m/s at 291 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 = 2.19 and c = 11.54 m/s at 141 m height).

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Abbreviations

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
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 K13-A platform, located about 101 km north-west from the coast of Den Helder.

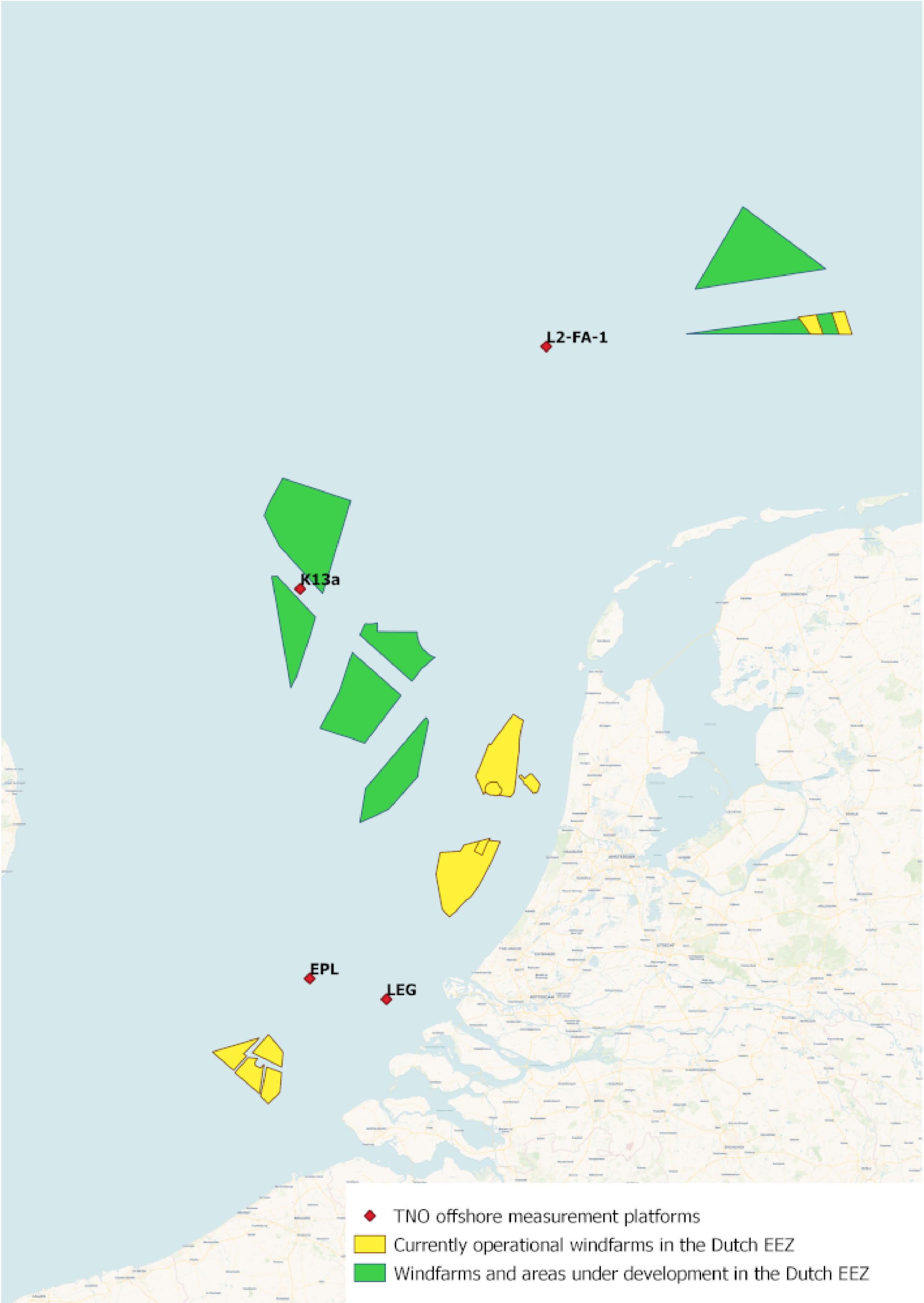

Figure 1.1: TNO's long-term offshore wind measurement campaign locations at Lichteiland Goeree (LEG), Europlatform (EPL), Wintershall platform K13-A (K13a) and L2-FA-1, along with wind farm development zones in the Dutch North Sea.

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 K13-A location, see table 2.1. These reports are available at offshorewind-measurements.tno.nl. This report includes the specific wind conditions for the period 2016–2024 at the K13-A 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 K13-A

Period	Report
2016–2019	TNO 2020 R10551 [6]
2016–2020	TNO 2021 R10919 [7]
2016–2021	TNO 2022 R10909 [8]
2016–2022	TNO 2023 R10578 [9]
2016–2023	TNO 2024 R11676 [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       = {K13-A lidar measurement campaign},
subtitle    = {Instrumentation Report 2024},
number      = {TNO 2025 R10298},
date        = {2025-03-17},
url         = {https://publications.tno.nl/publication/34644009/E1Vu6L55/TNO-2025-R10298.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    = {Wintershall platform K13-A, 2016\textendash2024},
number      = {TNO 2025 R11112},
date        = {2025-05-27},
```

The publication date at 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 K13-A measurement campaign please adhere to the following information:

- https://offshorewind-measurements.tno.nl/en/measurement-locations/k13a/
- For monthly files use: `K13A-yyyy-mm.csv`.
- After a quarter of a year is completed the monthly files will be replaced by `K13A-yyyy-Qx.csv`.
- After a year is completed the quarterly files will be replaced by a yearly file `K13A-yyyy.csv`.

3 Measurement campaign at K13-A

3.1 Location, lidar installation and operation

The Wintershall platform K13-A is located about 101 km north-west from the coast of Den Helder, see figure 1.1. The platform is part of the North Sea Monitoring Network consisting of several permanent monitoring locations over the North Sea.

The K13-A platform serves as a production platform for natural gas and since November 2016 also for wind measurements using a platform-mounted (35 m above MSL) ZX300M wind lidar. The aim is to collect up-to-date meteorological information (including the air pressure, wind speed and direction, air temperature, relative humidity and visibility) as well as oceanographic data (water level, temperature and height). These activities are coordinated by the weather meteorological agency (KNMI) and Rijkswaterstaat, the Dutch Ministry of Infrastructure and the Environment.

The current instrumentation at K13-A is a ZX300M lidar. The instrument measures wind profiles at up to ten different heights by conically emitting a laser beam into the air, even if an object blocks the laser beam at some positions (see [11] for the lidar specifications). Before the lidar was installed at the K13-A platform, it was calibrated, see latest calibration report [12]. It is installed next to the helipad of the platform. The lidar provides both wind speed and direction measurements at ten different heights between 63 m and 291 m above MSL. To ensure good quality measurements it is crucial to select the right location for the lidar on the platform. More detailed information about the positioning and installation of the lidar on the K13-A platform is available in the instrumentation report [13].

The lidar measurement height and data acquisition configuration is chosen to be the same as at other measurement locations, i.e. the LEG, EPL and L2-FA-1 platforms. The lidar manufacturer guarantees adequate data quality up to 300 m.

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. Personnel from Wintershall, the oil and gas company operating the K13-A platform, supports monitoring and control of the lidar.

Table 3.1: Replacements of lidars at the K13-A platform

Lidar ID	Operational period	Reason for replacement
ZX563	01-11-2016 to 11-11-2022	First installation
ZX1524	11-11-2022 to 11-10-2024	Periodic replacement
ZX2126	11-10-2024 to now	

Figure 3.1: Wintershall platform K13-A

Figure 3.2: Lidar unit at K13-A

Table 3.2: Down-time periods and actions taken at K13-A platform during the year 2024

Date	Reason
11-10-2024	Replacement of lidar ZX1524 with lidar ZX2126

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 K13-A

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

An overview of the measured and recorded quantities by the lidar at K13-A 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 in 2016. 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 K13-A 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 191 m is at least 90.3 %, while farther up to 241 m it decreases to 89.1 %, and finally to 87.3 % at the highest altitude of 291 m. For the year 2024, the data availability for heights up to 191 m is at least 93.6 %, while farther up to 241 m it decreases to 90.3 %, and finally to 85.6 % at the highest altitude of 291 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.

For a more detailed overview of the lidar availability, the monthly availability is plotted in figure 3.3. 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.

Table 3.3: List of variables measured by the lidar. HXXX are the different measurement heights w.r.t. MSL: 63 m, 91 m, 116 m, 141 m, 166 m, 191 m, 216 m, 241 m, 266 m and 291 m

Acronym	Signal name	Units
K13A_batvoltage	battery voltage	V
K13A_tempcpu	CPU temperature inside the lidar	°C
K13A_humpod	relative humidity inside the lidar	%
K13A_bearing	lidar bearing	°
K13A_tilt	lidar tilt angle	°
K13A_pair	air pressure at lidar position	hPa
K13A_wsmet	wind speed measured by lidar meteo station	m/s
K13A_wdmet	wind direction measured by lidar meteo station	°
K13A_HXXX_npts	measuring points	-
K13A_HXXX_missed	missed points	-
K13A_HXXX_npackets	packets in fit	-
K13A_HXXX_Wd	wind direction	°
K13A_HXXX_Wshor_avg	horizontal wind speed average	m/s
K13A_HXXX_Wshor_std	horizontal wind speed standard deviation	m/s
K13A_HXXX_Wshor_min	horizontal wind speed minimum	m/s
K13A_HXXX_Wshor_max	horizontal wind speed maximum	m/s
K13A_HXXX_WsVer_avg	vertical wind speed average	m/s
K13A_HXXX_cs	CS	-
K13A_HXXX_BackScatter	back scatter	-

There are complementary reports with data verification comparing with other measurements. In particular, [14] examines the wind speed and direction measurement campaigns at eight offshore measurement locations distributed throughout the North Sea, including the K13-A 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.

	63 m	91 m	116 m	141 m	166 m	191 m	216 m	241 m	266 m	291 m
2016	93.3	93.4	94.1	93.8	93.1	92.3	92.0	91.6	90.7	89.5
2017	96.6	96.9	97.2	96.9	96.6	96.3	96.2	96.0	95.5	94.9
2018	90.0	89.5	89.5	89.2	88.9	88.7	88.5	88.5	88.2	87.6
2019	90.4	90.6	90.7	90.5	90.2	90.0	89.8	89.6	89.3	89.0
2020	89.4	89.4	89.5	89.4	89.1	88.9	88.7	88.5	88.1	87.6
2021	85.1	85.0	84.7	84.4	84.1	83.9	83.7	83.5	83.2	82.8
2022	88.0	87.7	87.5	87.0	86.5	86.1	85.6	85.0	84.2	83.3
2023	99.7	98.7	98.1	97.3	95.6	94.6	93.3	91.2	89.4	87.2
2024	99.3	98.8	97.8	97.0	94.7	93.6	92.4	90.3	88.5	85.6
Overall	92.3	92.1	91.9	91.5	90.8	90.3	89.8	89.1	88.4	87.3

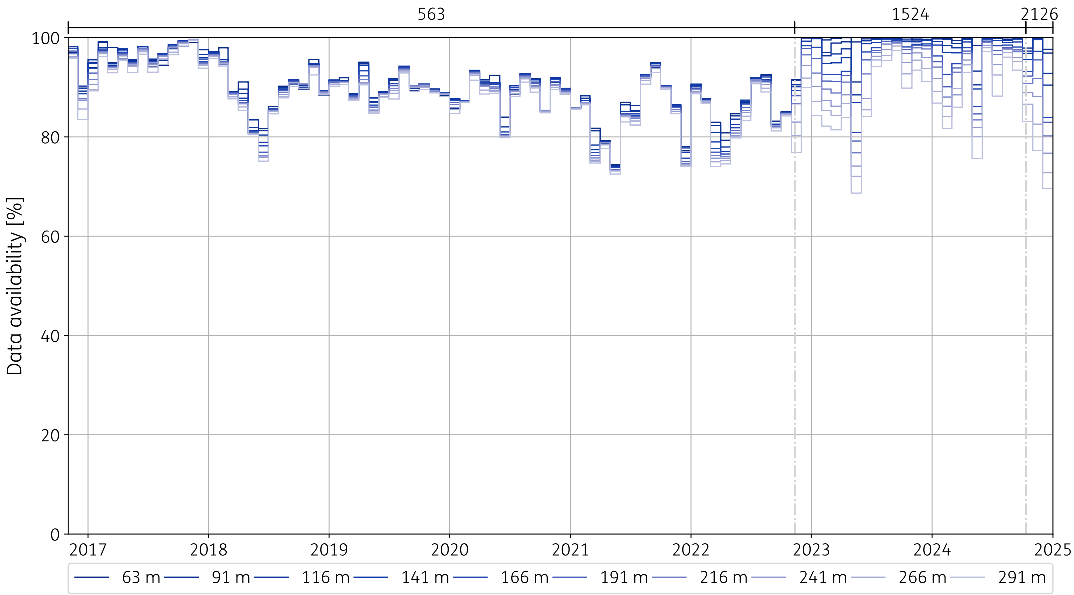

Figure 3.3: Monthly lidar data availability showing the lidar IDs and their operational periods.

4 Wind conditions at K13-A

This section presents the results following an assessment of the weather conditions during the entire measurement campaign at K13-A. 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[1] (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[2]. A Weibull probability density function (pdf) is fitted to the wind speed frequency distribution[3]. 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[4].

For the wind direction distribution the MoMM is computed too. The mean direction is computed as the average direction of the wind velocity[5].

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.

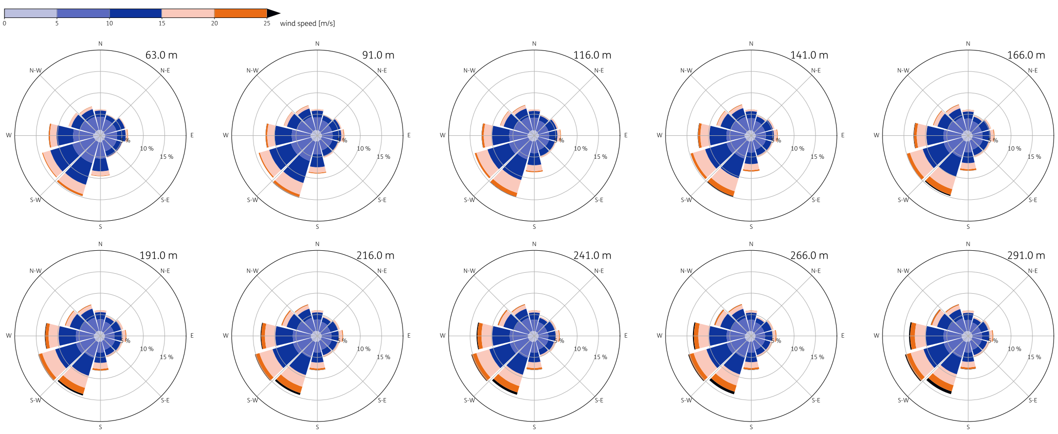

Figure 4.1: Wind roses for the complete measurement campaign

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

[2]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.

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

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

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

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

Height	Wind speed						Wind direction
	N	Q_1	median	Q_3	maximum	MoMM	MoMM
m	#	m/s	m/s	m/s	m/s	m/s	°
63	396 534	6.24	9.05	12.21	32.41	9.38	235.6
91	395 520	6.42	9.43	12.81	34.02	9.77	236.7
116	394 716	6.49	9.62	13.20	34.88	10.02	237.4
141	392 990	6.53	9.74	13.47	35.77	10.20	238.4
166	389 818	6.55	9.83	13.67	36.43	10.35	239.4
191	387 801	6.57	9.88	13.82	36.84	10.45	240.5
216	385 632	6.59	9.93	13.93	37.27	10.54	241.6
241	382 675	6.60	9.96	14.01	37.67	10.61	242.8
266	379 433	6.61	9.98	14.08	38.00	10.67	243.5
291	374 861	6.62	10.02	14.15	38.59	10.73	244.3

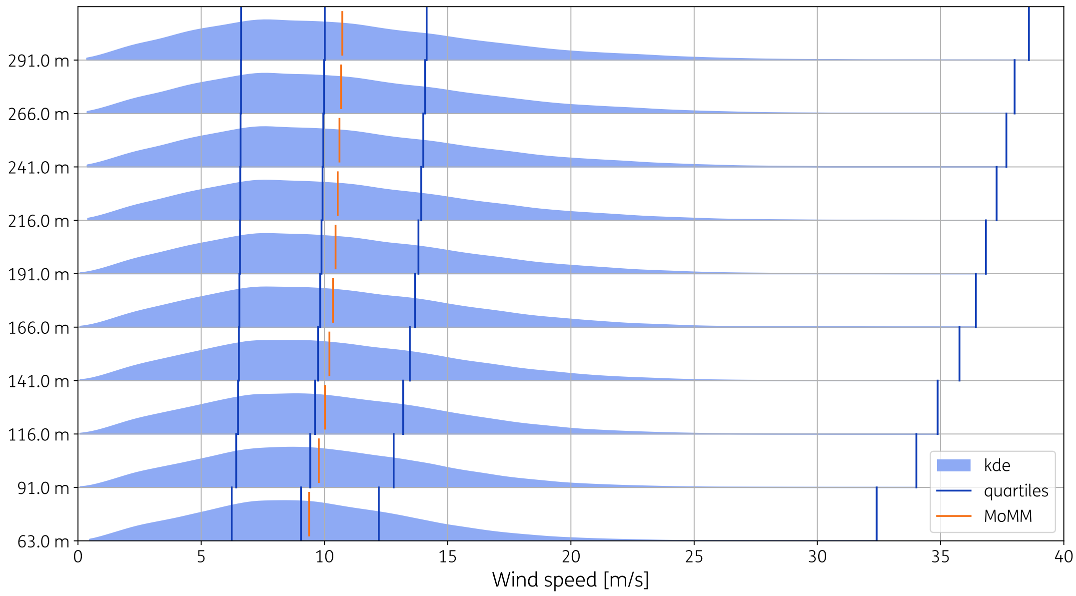

Figure 4.2: Wind speed distributions. The kde is shown with blue markers for the quartiles (Q_1, median, Q_3 and maximum) and an orange marker for the MoMM, as listed in table 4.1.

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

Height	Shape (k)	Scale (c)
m	–	m/s
63	2.304	10.61
91	2.276	11.06
116	2.234	11.34
141	2.194	11.55
166	2.159	11.71
191	2.128	11.83
216	2.102	11.93
241	2.081	12.01
266	2.063	12.07
291	2.047	12.13

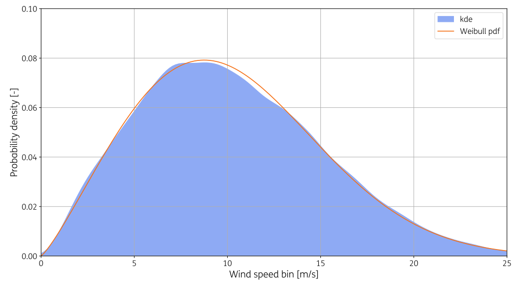

Figure 4.3: Weibull pdf of wind speed distribution at 141 m

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

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[6]. The lidar provides an internally computed 10-minute average value for the turbulence intensity.

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.

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

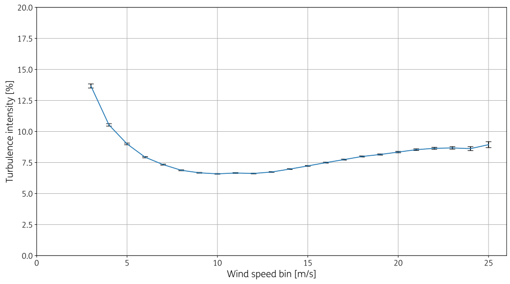

Figure 4.4: Turbulence intensity at 63 m

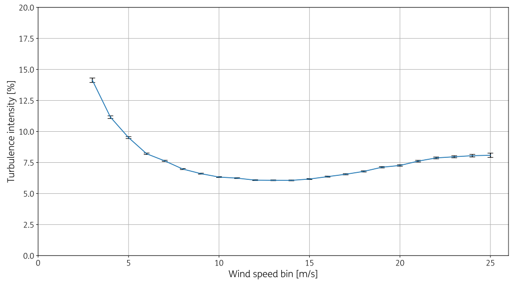

Figure 4.5: Turbulence intensity at 91 m

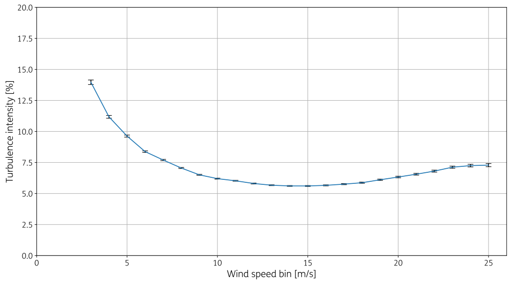

Figure 4.6: Turbulence intensity at 116 m

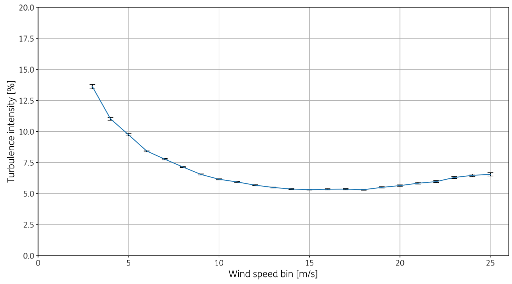

Figure 4.7: Turbulence intensity at 141 m

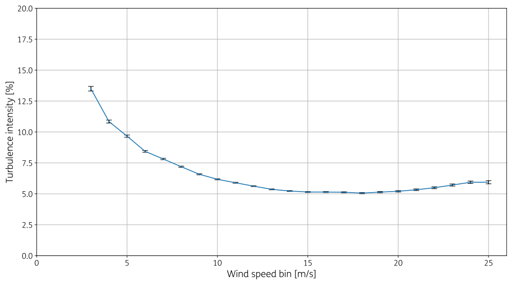

Figure 4.8: Turbulence intensity at 166 m

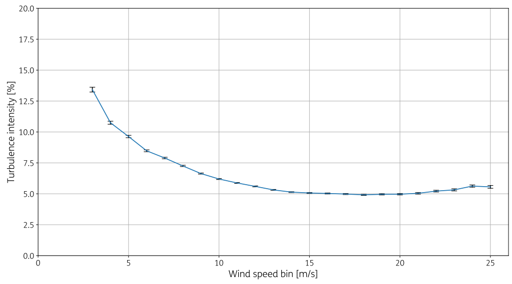

Figure 4.9: Turbulence intensity at 191 m

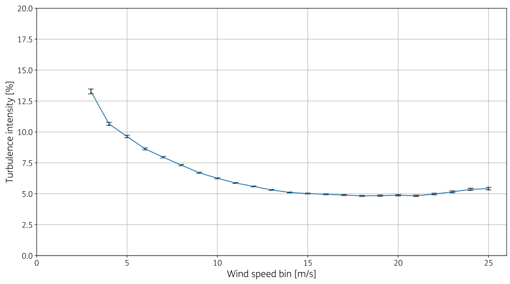

Figure 4.10: Turbulence intensity at 216 m

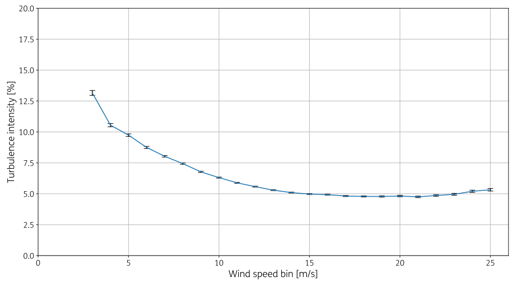

Figure 4.11: Turbulence intensity at 241 m

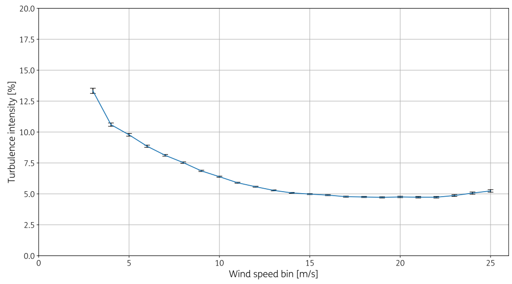

Figure 4.12: Turbulence intensity at 266 m

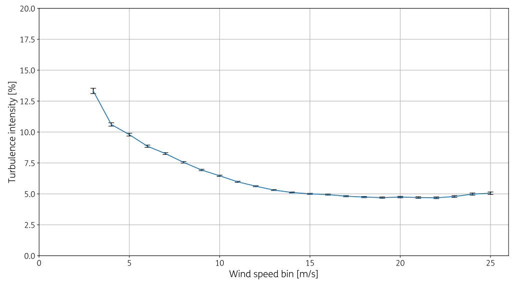

Figure 4.13: Turbulence intensity at 291 m

4.3 Wind shear and veer

When 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[7].
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[8].

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 (4.2). 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.

$$v_z = v_H \left(\frac{z}{H}\right)^\alpha \tag{4.2}$$

[7]This threshold is based on the MEASNET procedure [15, clause 9.4].

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

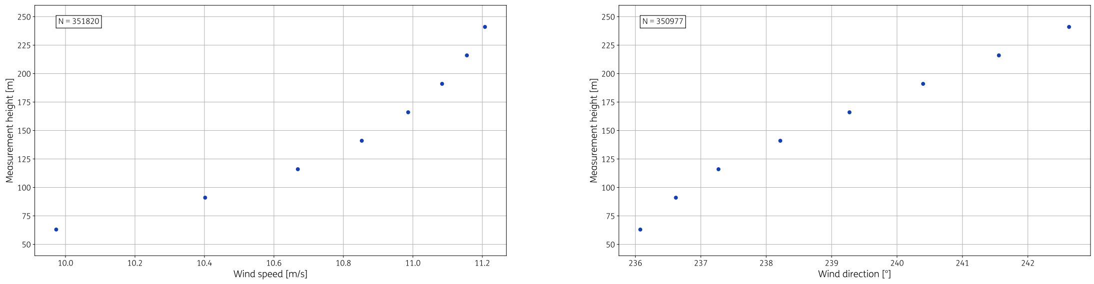

Figure 4.14: Average wind speed and wind direction (MoMM) of the dataset per height. ‘N’ is the number of 10-minute average samples remaining after filtering used to compute the MoMM values.

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[9], 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.

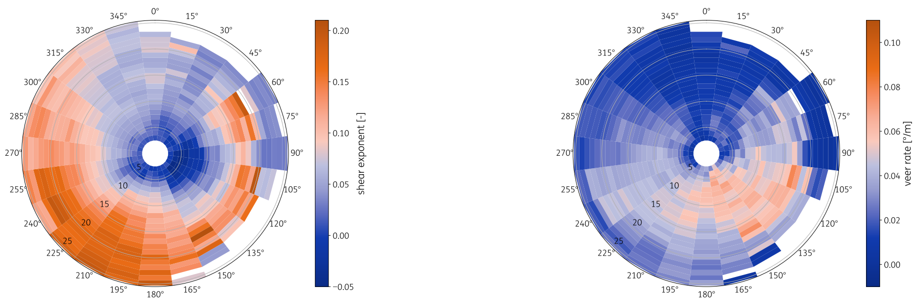

Figure 4.15: Wind shear and veer as function of wind speed and direction. The azimuth indicates the wind direction bin, the radius labels indicate the wind speed bin and the colour represents the mean value for the shear exponent (left) and veer rate (right).

[9]This follows the MEASNET procedure [15, clause 9.4].

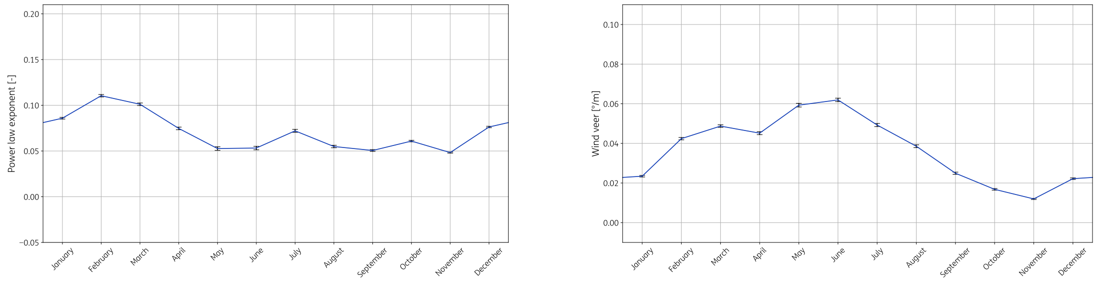

Figure 4.16: Wind shear and veer as function of the month-of-year

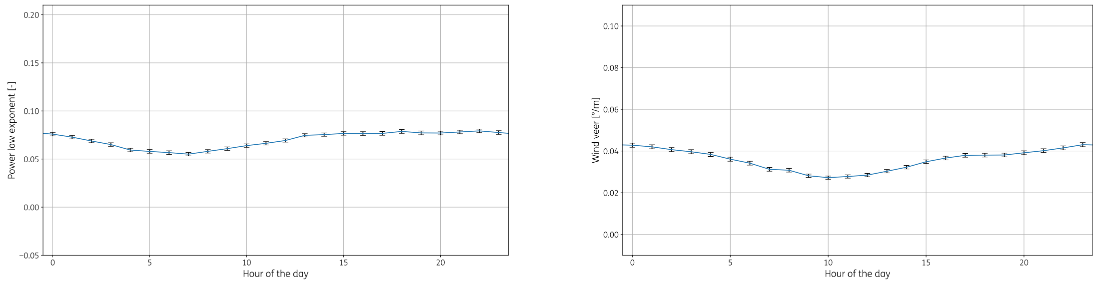

Figure 4.17: Wind shear and veer as function the hour-of-day

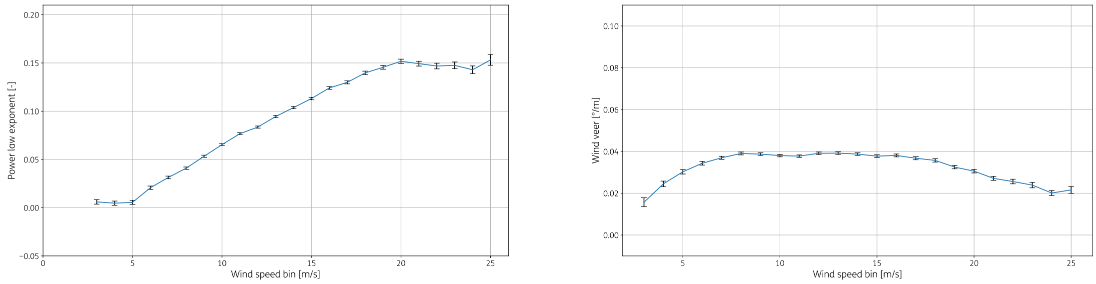

Figure 4.18: Wind shear and veer as function of wind speed

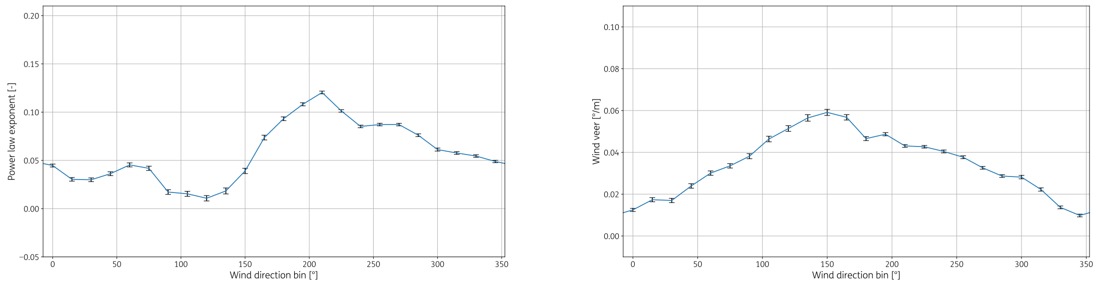

Figure 4.19: Wind shear and veer as function of wind direction

5 Conclusions and recommendations

This report refers to the measurement campaign at the K13-A platform where a ZX300M lidar has been deployed, providing high quality data since 2016. 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 191 m is at least 93.6 %, while farther up to 241 m it decreases to 90.3 %, and finally to 85.6 % at the highest altitude of 291 m.

At the K13-A platform, the wind analysis for the 2016–2024 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 235.6° to 244.3° across the different sensor heights (63 m to 291 m). The average wind speed ranges from 9.38 m/s at the lowest measurement height of 63 m up to 10.73 m/s at 291 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 = 2.19 and c = 11.54 m/s at 141 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 K13-A 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 [16]. 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 K13-A 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 K13-A

A.1 Wind rose

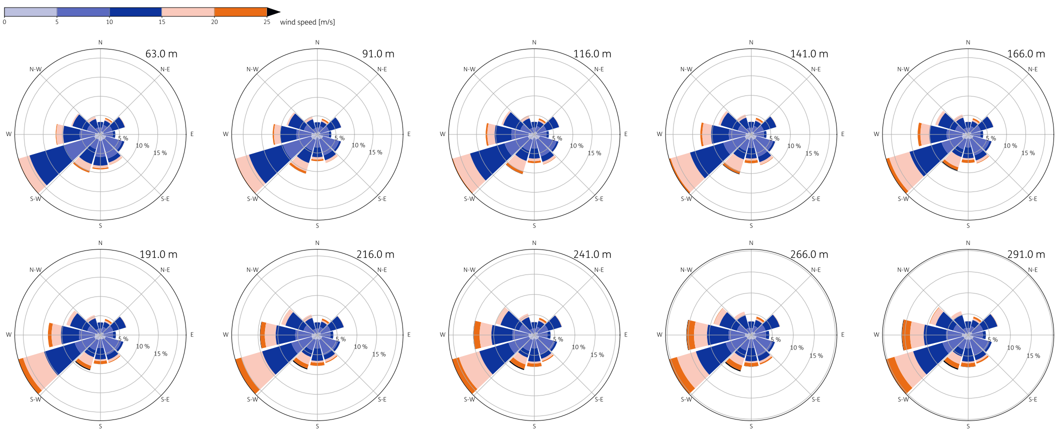

Figure A.1: Wind roses for 2016

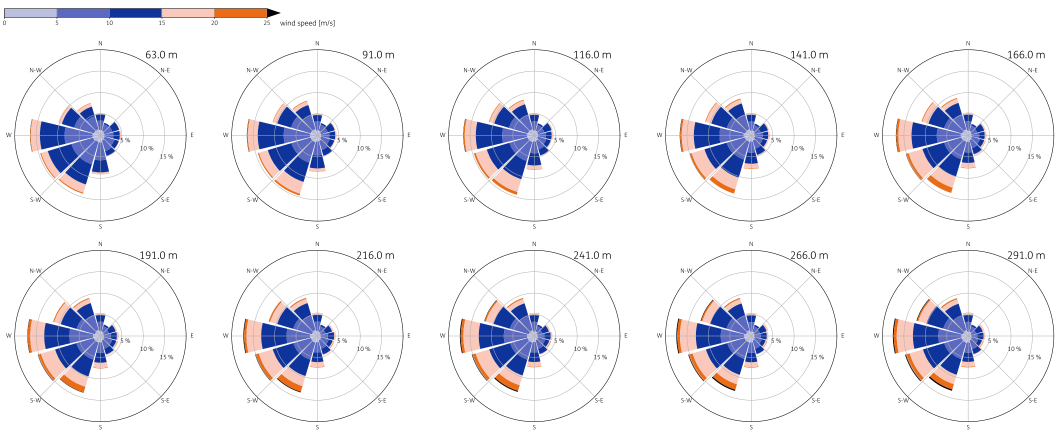

Figure A.2: Wind roses for 2017

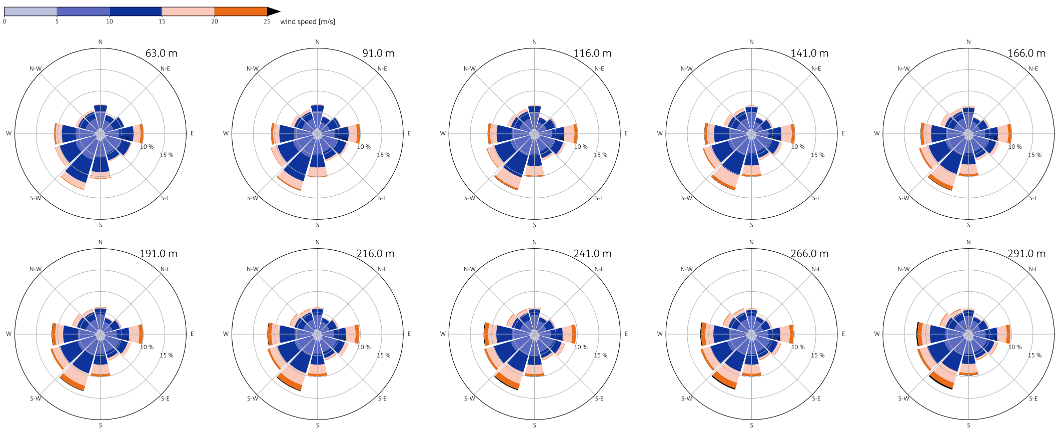

Figure A.3: Wind roses for 2018

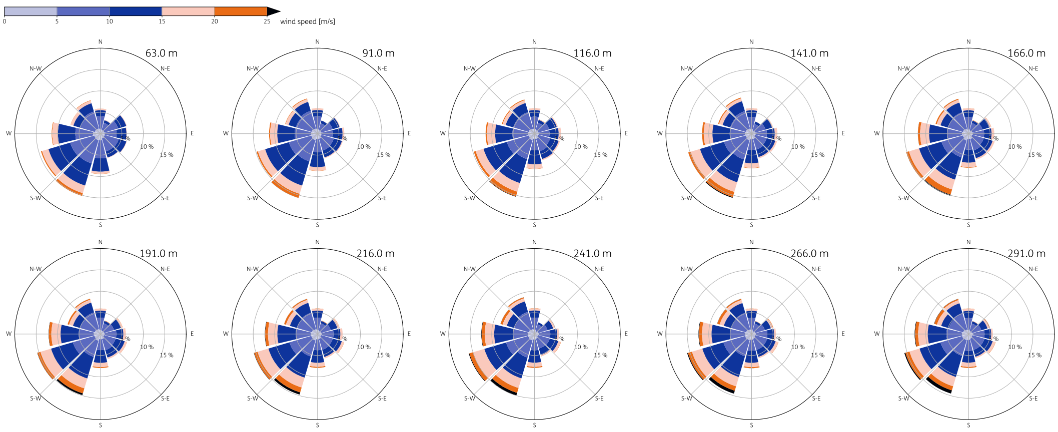

Figure A.4: Wind roses for 2019

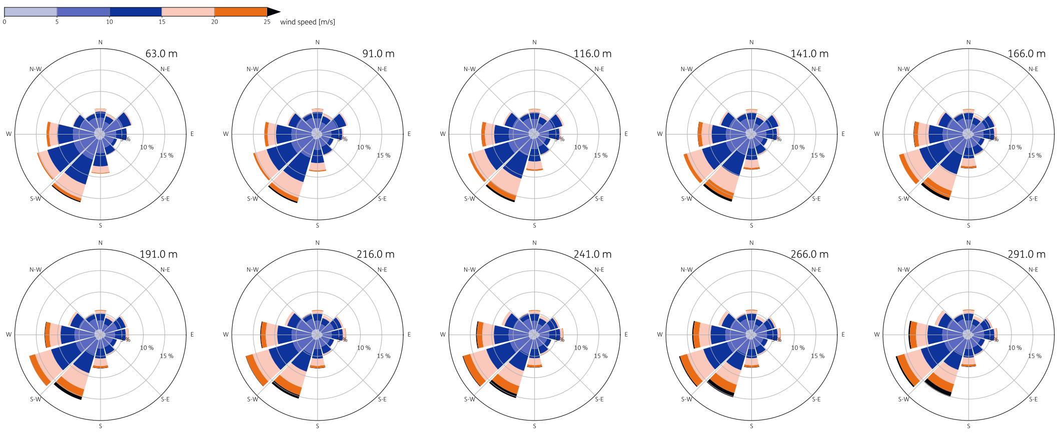

Figure A.5: Wind roses for 2020

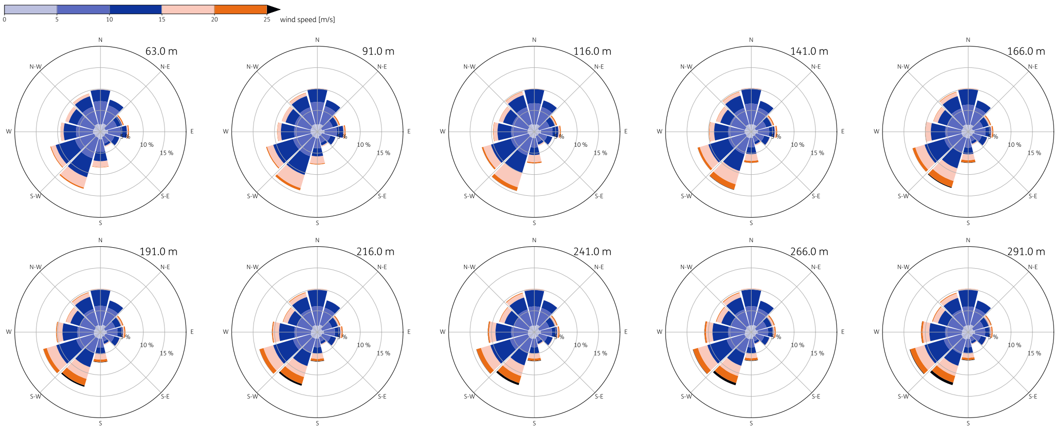

Figure A.6: Wind roses for 2021

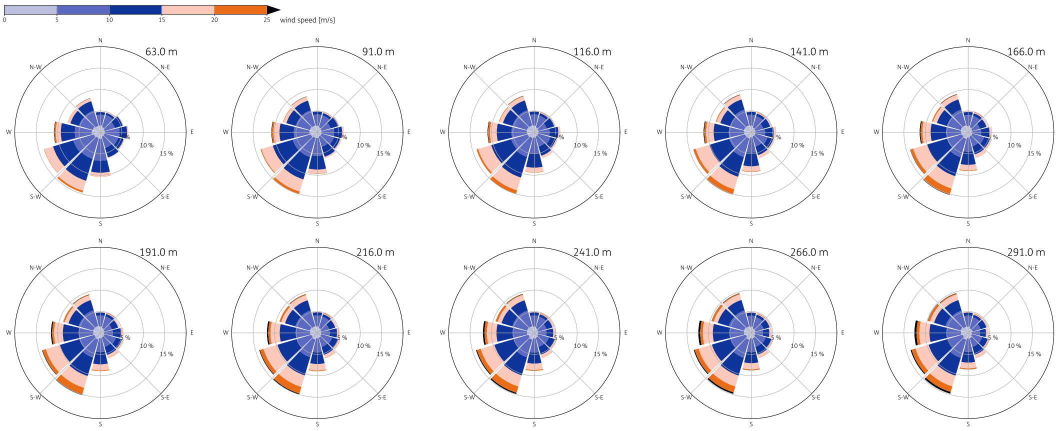

Figure A.7: Wind roses for 2022

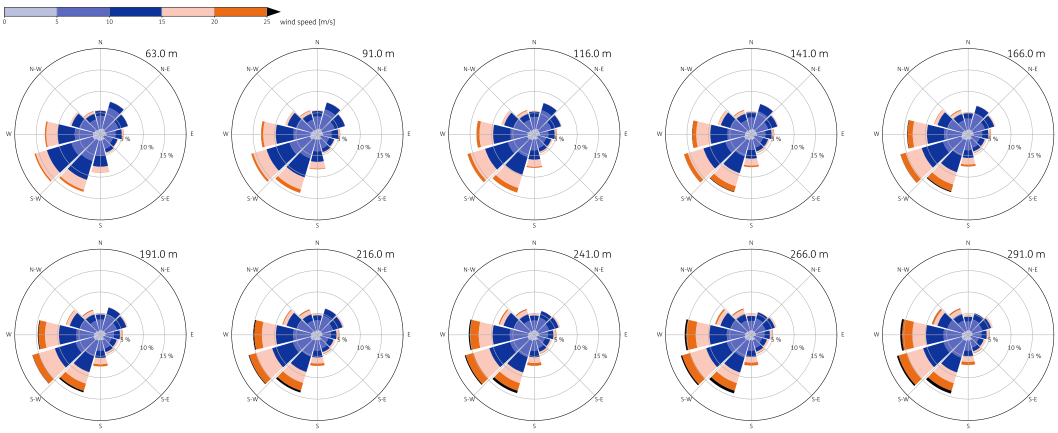

Figure A.8: Wind roses for 2023

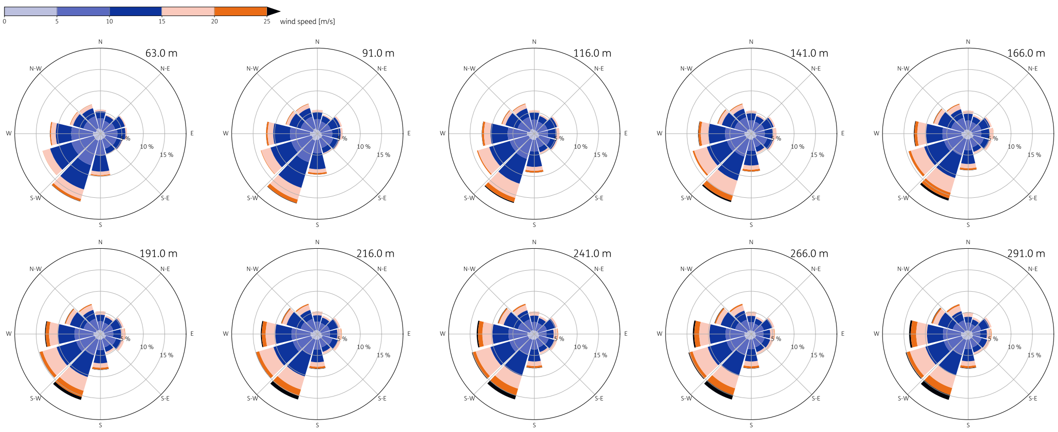

Figure A.9: Wind roses for 2024

A.2 Wind speed and direction statistics

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

Height	Wind speed						Wind direction
	N	Q_1	median	Q_3	maximum	MoMM	MoMM
m	#	m/s	m/s	m/s	m/s	m/s	°
63	8063	6.67	9.58	12.53	24.43	9.78	237.6
91	8067	6.81	9.86	12.95	25.12	10.09	240.0
116	8129	6.82	10.01	13.21	25.97	10.25	240.2
141	8106	6.82	10.17	13.43	26.75	10.42	240.7
166	8044	6.87	10.32	13.63	27.00	10.57	242.1
191	7978	6.93	10.41	13.80	27.31	10.71	243.7
216	7953	6.95	10.46	13.90	27.78	10.81	245.2
241	7915	7.02	10.52	13.97	29.26	10.91	246.7
266	7834	7.08	10.57	14.05	30.38	10.99	247.3
291	7732	7.10	10.63	14.13	30.98	11.07	248.7

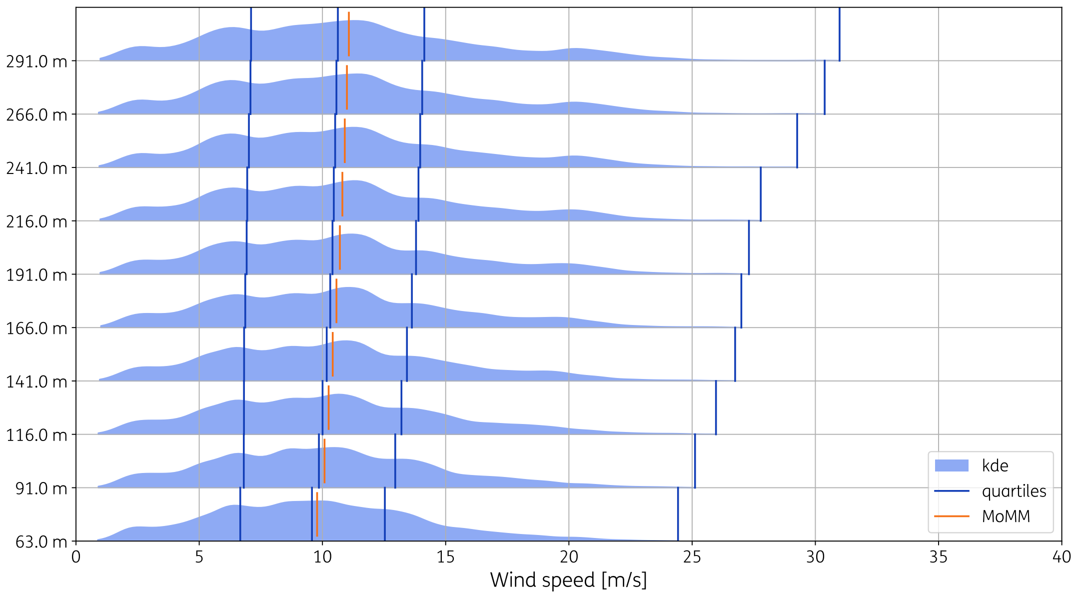

Figure A.10: Wind speed distributions for 2016

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

Height	Wind speed						Wind direction
	N	Q_1	median	Q_3	maximum	MoMM	MoMM
m	#	m/s	m/s	m/s	m/s	m/s	°
63	50 783	6.27	9.09	12.11	29.40	9.31	248.0
91	50 944	6.44	9.50	12.73	30.22	9.71	248.7
116	51 068	6.52	9.72	13.16	30.98	9.97	249.6
141	50 940	6.58	9.86	13.47	31.73	10.17	250.4
166	50 762	6.63	9.95	13.68	31.97	10.31	251.3
191	50 634	6.66	10.01	13.82	32.40	10.41	252.3
216	50 538	6.70	10.05	13.91	32.56	10.49	253.4
241	50 433	6.72	10.09	13.97	32.79	10.55	254.6
266	50 198	6.75	10.14	14.03	32.84	10.60	255.2
291	49 877	6.79	10.18	14.06	32.97	10.64	255.8

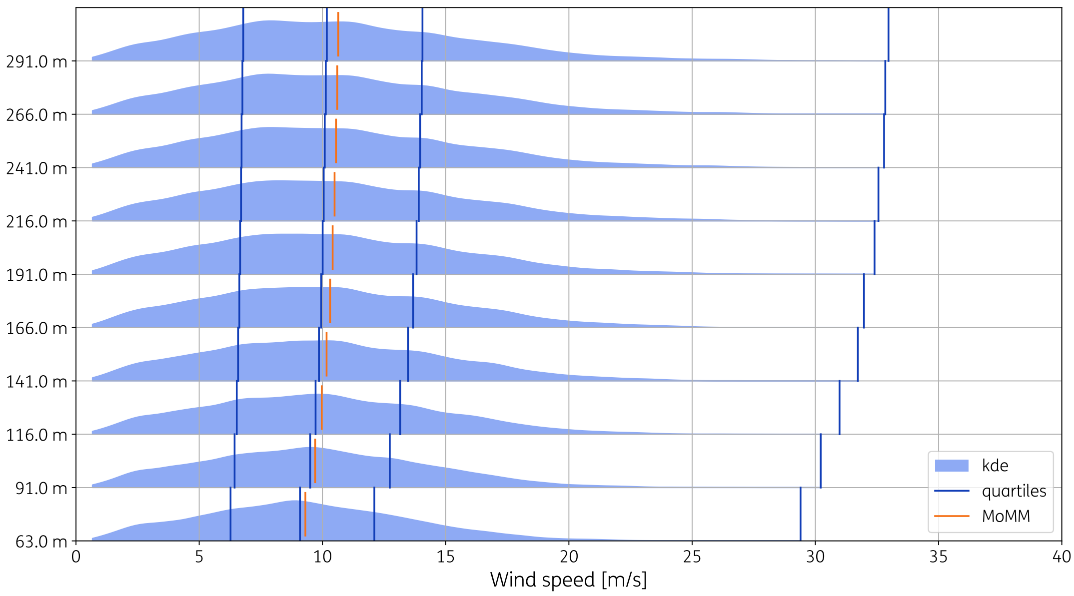

Figure A.11: Wind speed distributions for 2017

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

Height	Wind speed						Wind direction
	N	Q_1	median	Q_3	maximum	MoMM	MoMM
m	#	m/s	m/s	m/s	m/s	m/s	°
63	47 291	6.32	9.17	12.23	29.51	9.44	205.2
91	47 052	6.50	9.52	12.98	30.70	9.85	207.2
116	47 027	6.54	9.66	13.37	31.65	10.07	209.0
141	46 882	6.56	9.76	13.63	32.35	10.22	211.2
166	46 751	6.57	9.82	13.78	32.65	10.32	213.2
191	46 613	6.57	9.84	13.88	33.35	10.39	215.1
216	46 541	6.57	9.86	13.94	34.61	10.43	216.9
241	46 492	6.58	9.85	13.98	35.40	10.46	218.6
266	46 360	6.56	9.85	14.01	35.78	10.49	220.2
291	46 059	6.56	9.85	14.04	35.99	10.51	221.5

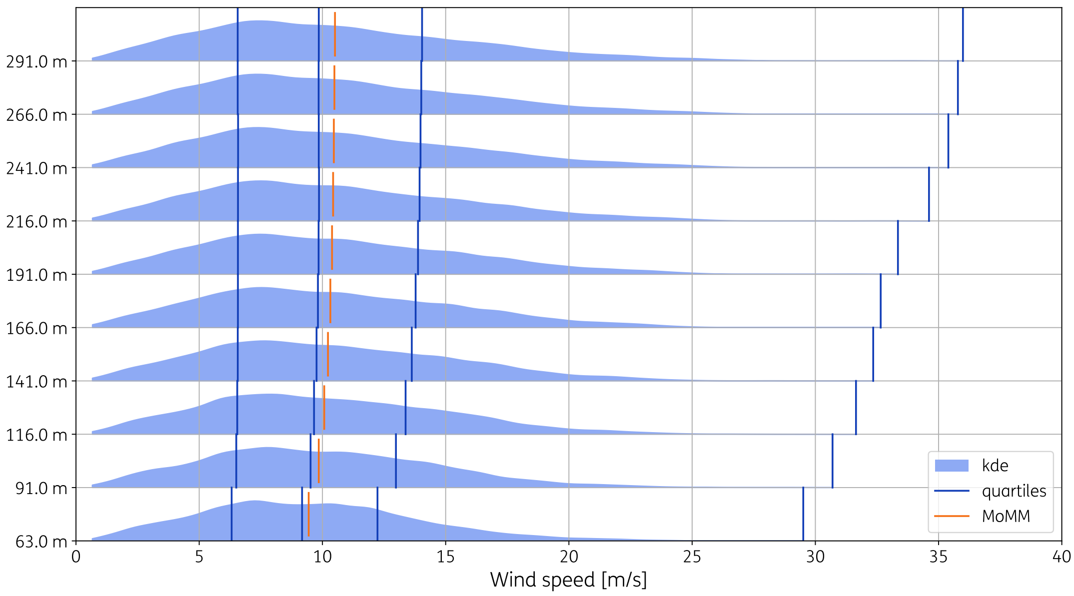

Figure A.12: Wind speed distributions for 2018

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

Height	Wind speed						Wind direction
	N	Q_1	median	Q_3	maximum	MoMM	MoMM
m	#	m/s	m/s	m/s	m/s	m/s	°
63	47 509	6.46	8.98	11.82	26.74	9.28	232.7
91	47 618	6.67	9.36	12.42	27.06	9.67	234.2
116	47 675	6.70	9.54	12.81	27.96	9.90	234.1
141	47 589	6.71	9.64	13.06	28.68	10.05	235.8
166	47 431	6.73	9.69	13.24	29.18	10.17	236.0
191	47 318	6.74	9.71	13.34	29.49	10.26	237.0
216	47 191	6.75	9.73	13.41	30.99	10.32	238.1
241	47 093	6.75	9.74	13.45	32.98	10.37	239.7
266	46 959	6.75	9.75	13.48	33.81	10.41	239.5
291	46 758	6.76	9.76	13.52	34.55	10.44	240.3

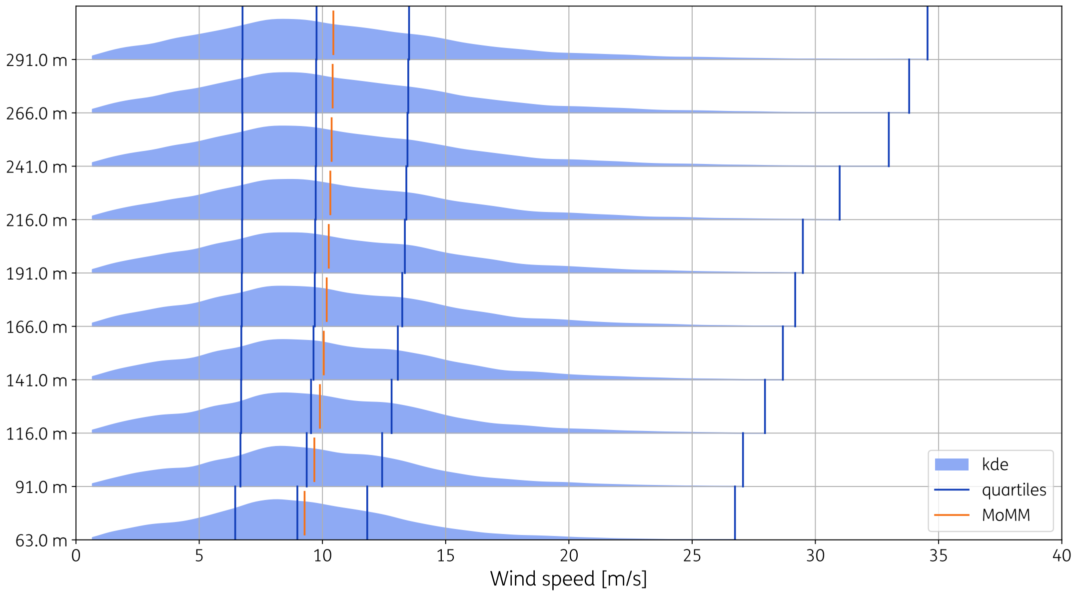

Figure A.13: Wind speed distributions for 2019

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

Height	Wind speed						Wind direction
	N	Q_1	median	Q_3	maximum	MoMM	MoMM
m	#	m/s	m/s	m/s	m/s	m/s	°
63	47 093	6.44	9.41	12.91	32.41	9.88	229.8
91	47 134	6.58	9.78	13.40	34.02	10.23	230.1
116	47 192	6.63	9.96	13.71	34.88	10.46	230.4
141	47 096	6.68	10.07	13.95	35.77	10.64	231.1
166	46 984	6.70	10.16	14.16	36.43	10.78	232.0
191	46 829	6.73	10.22	14.31	36.84	10.89	232.9
216	46 730	6.73	10.25	14.44	37.27	10.98	234.0
241	46 621	6.74	10.26	14.53	37.67	11.06	235.0
266	46 449	6.74	10.27	14.61	38.00	11.13	235.5
291	46 193	6.75	10.28	14.68	38.09	11.18	236.4

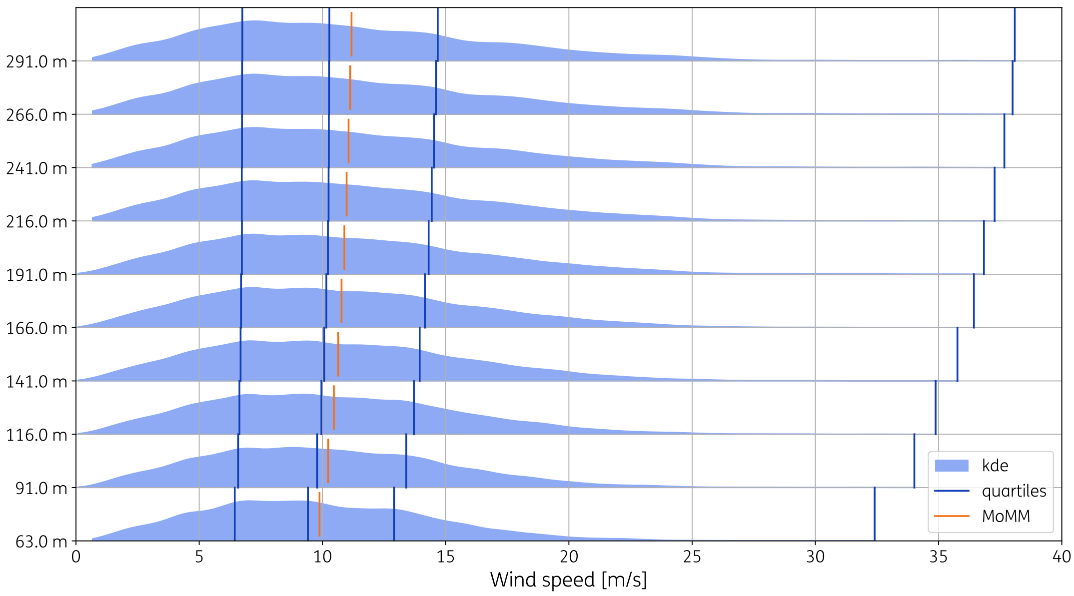

Figure A.14: Wind speed distributions for 2020

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

Height	Wind speed						Wind direction
	N	Q_1	median	Q_3	maximum	MoMM	MoMM
m	#	m/s	m/s	m/s	m/s	m/s	°
63	44 746	5.78	8.57	11.58	25.97	8.95	255.4
91	44 677	5.94	8.89	12.07	26.71	9.30	256.2
116	44 539	6.00	9.06	12.37	27.37	9.53	256.5
141	44 375	6.03	9.16	12.58	27.65	9.69	257.0
166	44 214	6.04	9.22	12.73	28.64	9.80	257.7
191	44 091	6.04	9.25	12.82	29.90	9.88	258.6
216	43 985	6.04	9.28	12.88	30.32	9.94	259.7
241	43 910	6.04	9.30	12.93	30.72	9.98	260.9
266	43 752	6.03	9.31	12.96	31.24	10.01	261.7
291	43 517	6.02	9.32	12.99	32.71	10.03	262.4

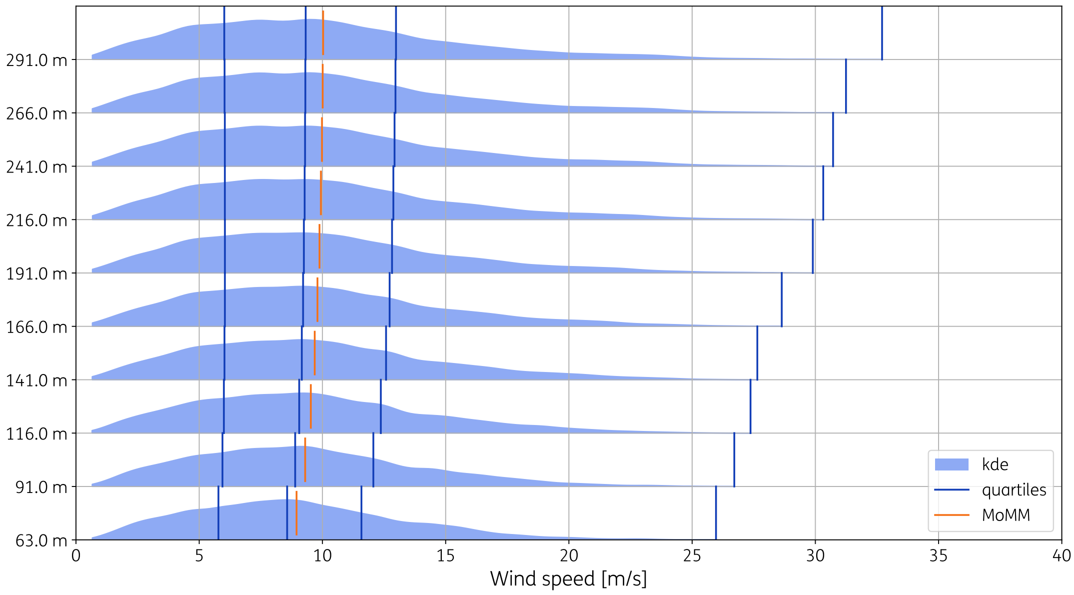

Figure A.15: Wind speed distributions for 2021

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

Height	Wind speed						Wind direction
	N	Q_1	median	Q_3	maximum	MoMM	MoMM
m	#	m/s	m/s	m/s	m/s	m/s	°
63	46 279	6.05	8.79	12.04	30.51	9.26	230.0
91	46 091	6.25	9.20	12.66	31.96	9.67	231.4
116	45 990	6.32	9.39	13.05	33.06	9.93	232.6
141	45 747	6.35	9.53	13.33	33.88	10.11	233.9
166	45 488	6.35	9.63	13.54	34.17	10.24	235.2
191	45 253	6.36	9.69	13.68	34.10	10.34	236.5
216	44 992	6.36	9.72	13.77	34.29	10.41	237.8
241	44 651	6.36	9.73	13.82	34.65	10.47	239.2
266	44 233	6.36	9.74	13.87	35.16	10.51	240.7
291	43 769	6.38	9.77	13.91	35.82	10.55	241.7

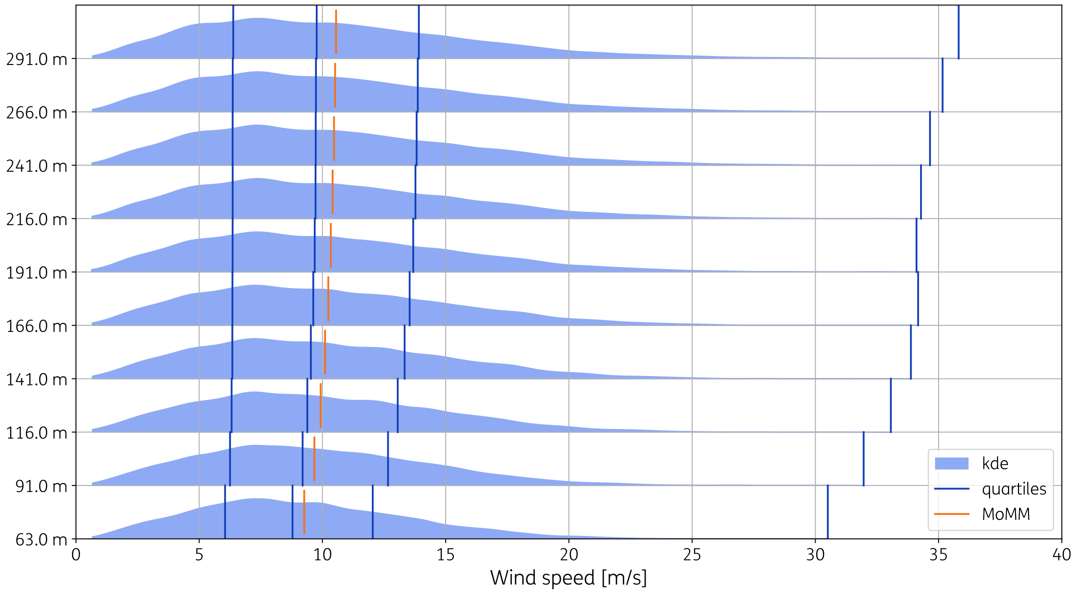

Figure A.16: Wind speed distributions for 2022

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

Height	Wind speed						Wind direction
	N	Q_1	median	Q_3	maximum	MoMM	MoMM
m	#	m/s	m/s	m/s	m/s	m/s	°
63	52 427	6.13	8.98	12.45	26.31	9.47	241.7
91	51 875	6.31	9.36	13.10	27.72	9.88	243.0
116	51 540	6.39	9.54	13.52	28.52	10.13	243.5
141	51 136	6.44	9.67	13.84	29.33	10.34	244.1
166	50 242	6.49	9.81	14.12	29.87	10.53	244.6
191	49 730	6.52	9.91	14.33	30.63	10.68	245.6
216	49 020	6.54	10.01	14.55	30.81	10.83	246.3
241	47 953	6.56	10.13	14.74	30.66	10.96	246.7
266	47 007	6.59	10.20	14.90	30.91	11.08	247.2
291	45 819	6.61	10.26	15.06	31.30	11.19	247.7

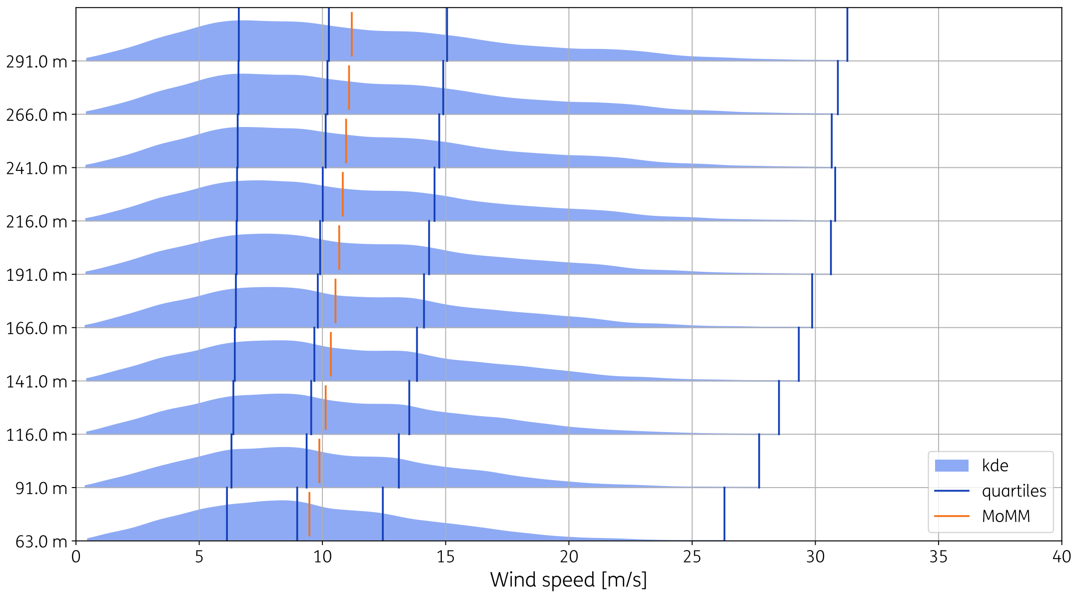

Figure A.17: Wind speed distributions for 2023

Table A.9: 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	°
63	52 343	6.40	9.29	12.34	28.18	9.52	234.7
91	52 062	6.60	9.70	12.98	29.31	9.93	235.2
116	51 556	6.72	9.96	13.44	30.64	10.25	236.1
141	51 119	6.77	10.11	13.74	31.59	10.47	237.0
166	49 902	6.81	10.25	14.00	32.61	10.68	238.6
191	49 355	6.86	10.34	14.23	33.78	10.83	239.7
216	48 682	6.91	10.43	14.41	34.58	10.97	240.9
241	47 607	6.94	10.50	14.54	35.52	11.10	242.1
266	46 641	7.00	10.60	14.69	37.45	11.24	242.7
291	45 137	7.01	10.73	14.86	38.59	11.37	242.7

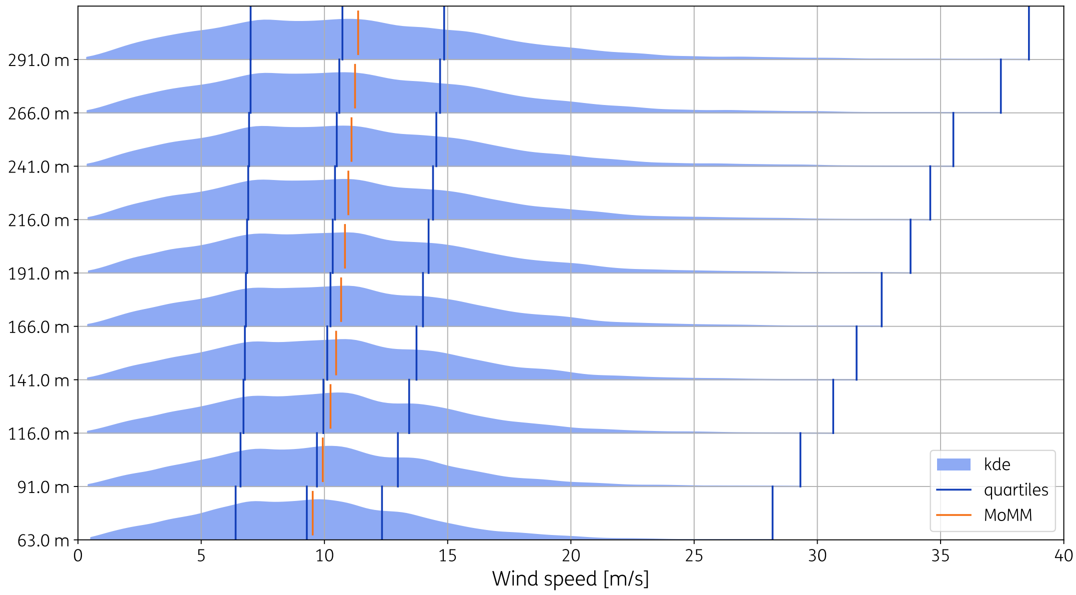

Figure A.18: Wind speed distributions for 2024

A.3 Wind speed distribution

Table A.10: Weibull parameters for 2016

Height	Shape (k)	Scale (c)
m	–	m/s
63	2.490	11.03
91	2.464	11.38
116	2.415	11.57
141	2.377	11.76
166	2.350	11.94
191	2.324	12.10
216	2.301	12.21
241	2.289	12.32
266	2.271	12.42
291	2.262	12.50

Table A.11: Weibull parameters for 2017

Height	Shape (k)	Scale (c)
m	–	m/s
63	2.358	10.50
91	2.329	10.96
116	2.287	11.25
141	2.250	11.47
166	2.222	11.63
191	2.198	11.75
216	2.179	11.84
241	2.165	11.91
266	2.155	11.97
291	2.150	12.02

Table A.12: Weibull parameters for 2018

Height	Shape (k)	Scale (c)
m	–	m/s
63	2.332	10.71
91	2.312	11.18
116	2.270	11.44
141	2.231	11.62
166	2.194	11.73
191	2.164	11.82
216	2.139	11.87
241	2.121	11.91
266	2.103	11.94
291	2.088	11.97

Table A.13: Weibull parameters for 2019

Height	Shape (k)	Scale (c)
m	–	m/s
63	2.388	10.46
91	2.354	10.90
116	2.302	11.16
141	2.259	11.34
166	2.223	11.48
191	2.188	11.58
216	2.158	11.66
241	2.134	11.72
266	2.114	11.77
291	2.100	11.81

Table A.14: Weibull parameters for 2020

Height	Shape (k)	Scale (c)
m	–	m/s
63	2.281	11.11
91	2.242	11.52
116	2.199	11.78
141	2.163	11.98
166	2.128	12.13
191	2.097	12.26
216	2.067	12.37
241	2.041	12.46
266	2.017	12.53
291	1.999	12.60

Table A.15: Weibull parameters for 2021

Height	Shape (k)	Scale (c)
m	–	m/s
63	2.238	10.10
91	2.210	10.50
116	2.168	10.75
141	2.125	10.92
166	2.085	11.04
191	2.054	11.13
216	2.029	11.19
241	2.010	11.24
266	1.991	11.27
291	1.974	11.30

Table A.16: Weibull parameters for 2022

Height	Shape (k)	Scale (c)
m	–	m/s
63	2.270	10.45
91	2.246	10.91
116	2.203	11.19
141	2.166	11.39
166	2.133	11.55
191	2.103	11.66
216	2.078	11.75
241	2.058	11.80
266	2.040	11.85
291	2.029	11.89

Table A.17: Weibull parameters for 2023

Height	Shape (k)	Scale (c)
m	–	m/s
63	2.245	10.71
91	2.219	11.18
116	2.174	11.48
141	2.137	11.72
166	2.102	11.95
191	2.074	12.12
216	2.053	12.29
241	2.036	12.44
266	2.023	12.57
291	2.006	12.68

Table A.18: Weibull parameters for 2024

Height	Shape (k)	Scale (c)
m	–	m/s
63	2.339	10.73
91	2.313	11.21
116	2.278	11.55
141	2.236	11.80
166	2.195	12.01
191	2.161	12.18
216	2.132	12.32
241	2.107	12.44
266	2.089	12.58
291	2.069	12.71

A.4 Wind shear and veer

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

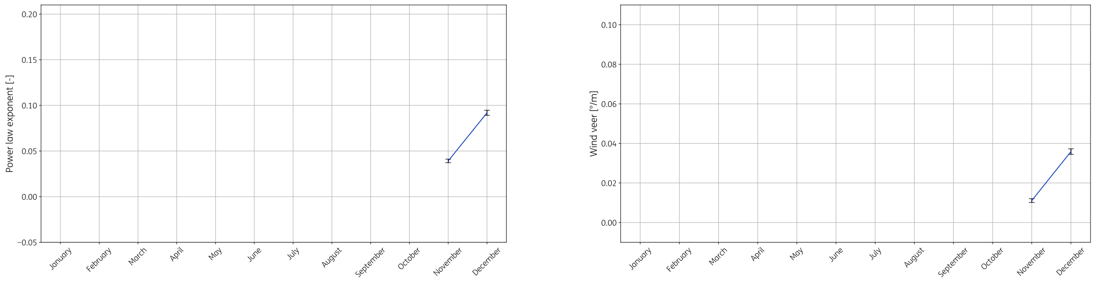

Figure A.19: Wind shear and veer as function of the month-of-year for 2016

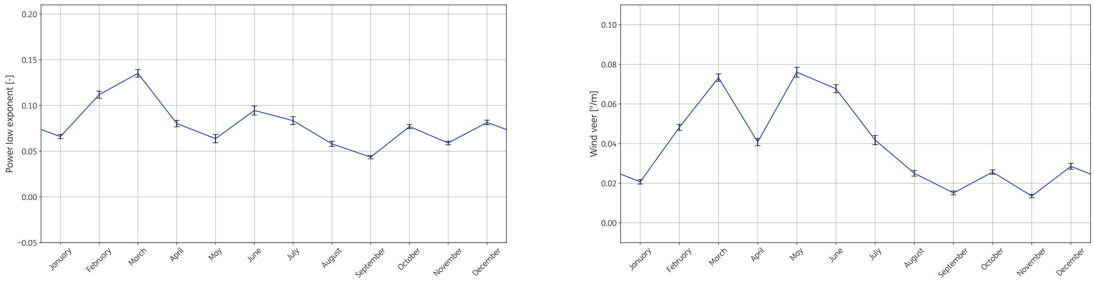

Figure A.20: Wind shear and veer as function of the month-of-year for 2017

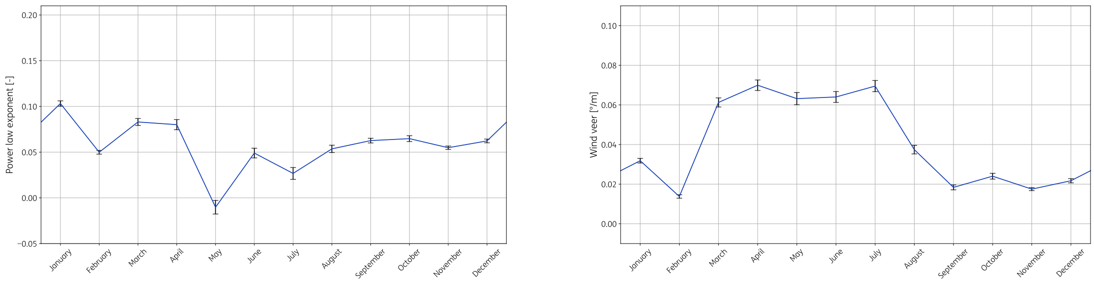

Figure A.21: Wind shear and veer as function of the month-of-year for 2018

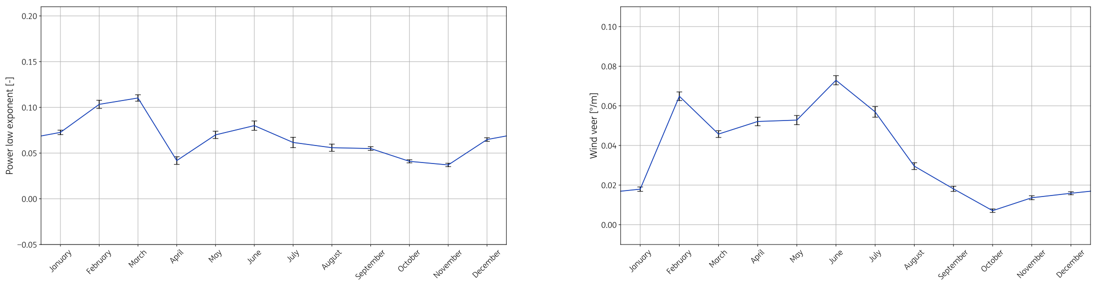

Figure A.22: Wind shear and veer as function of the month-of-year for 2019

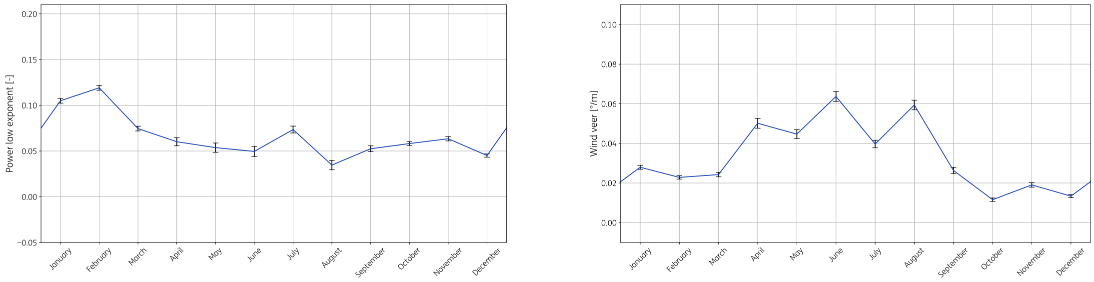

Figure A.23: Wind shear and veer as function of the month-of-year for 2020

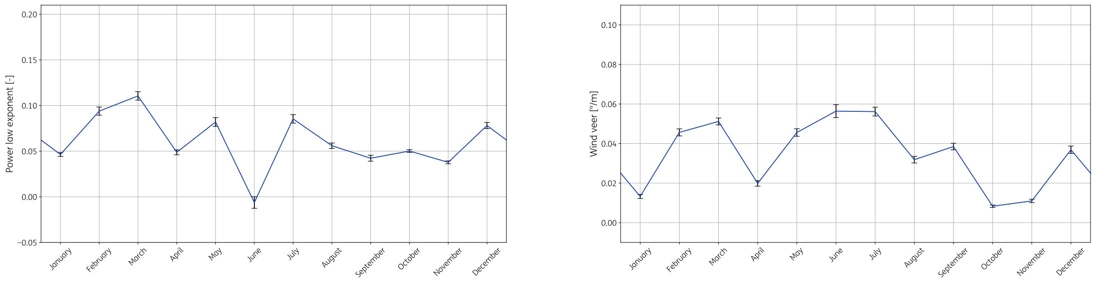

Figure A.24: Wind shear and veer as function of the month-of-year for 2021

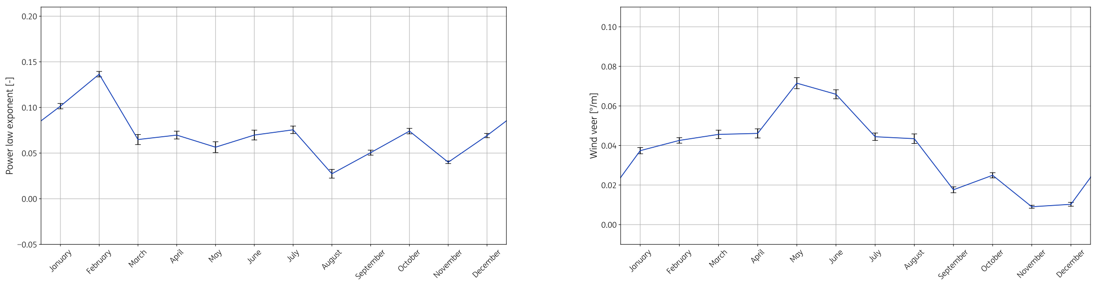

Figure A.25: Wind shear and veer as function of the month-of-year for 2022

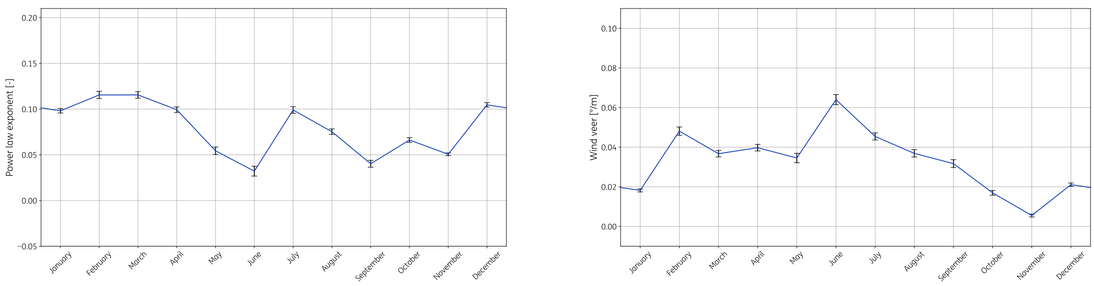

Figure A.26: Wind shear and veer as function of the month-of-year for 2023

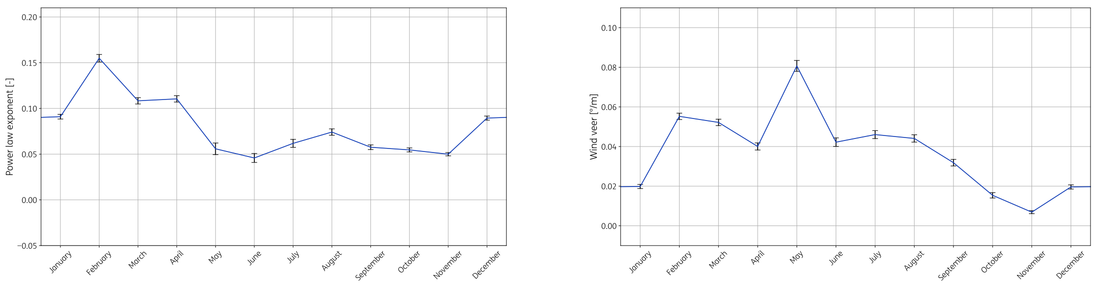

Figure A.27: Wind shear and veer as function of the month-of-year for 2024

A.4.2 Wind shear and veer as function of hour

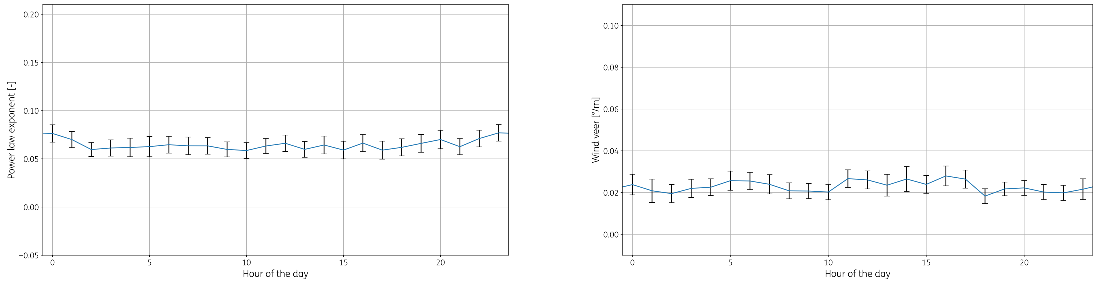

Figure A.28: Wind shear and veer as function the hour-of-day for 2016

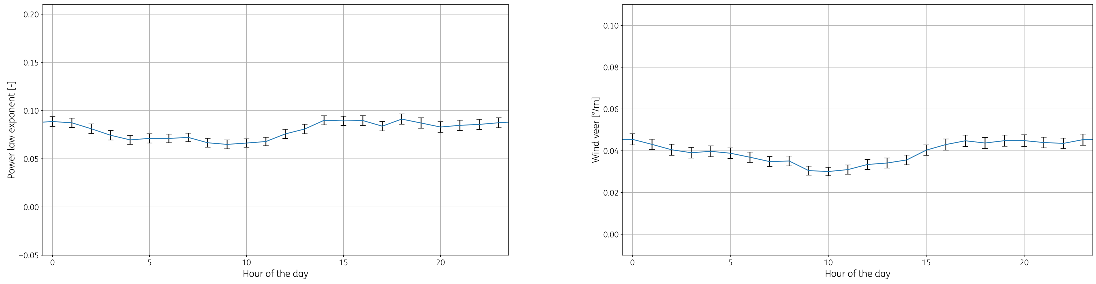

Figure A.29: Wind shear and veer as function the hour-of-day for 2017

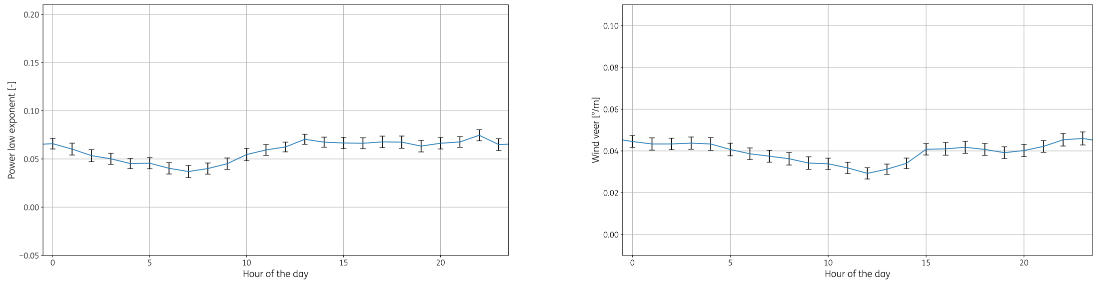

Figure A.30: Wind shear and veer as function the hour-of-day for 2018

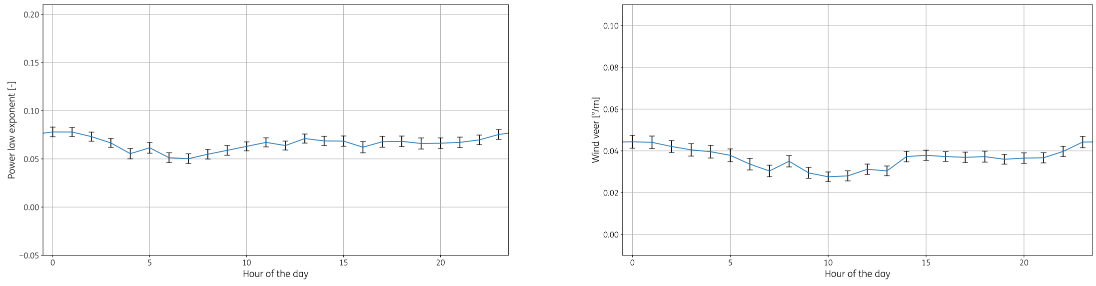

Figure A.31: Wind shear and veer as function the hour-of-day for 2019

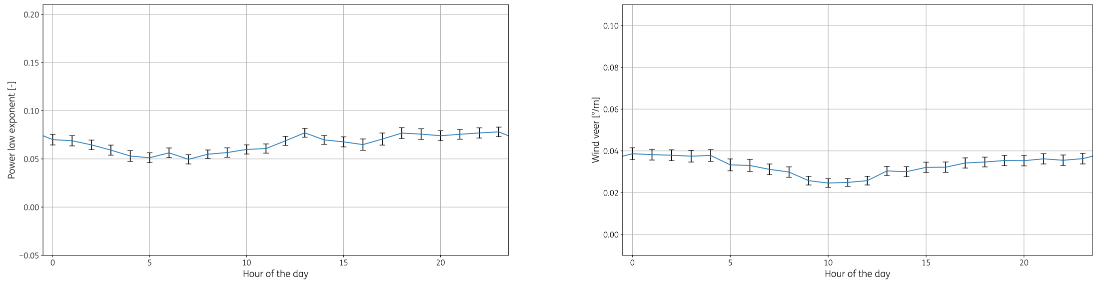

Figure A.32: Wind shear and veer as function the hour-of-day for 2020

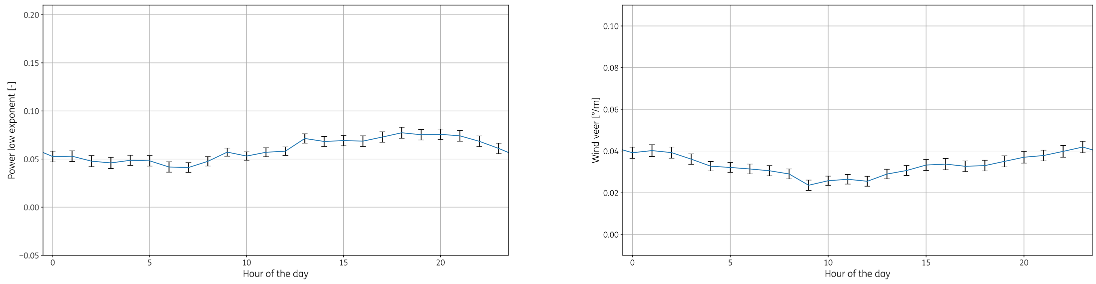

Figure A.33: Wind shear and veer as function the hour-of-day for 2021

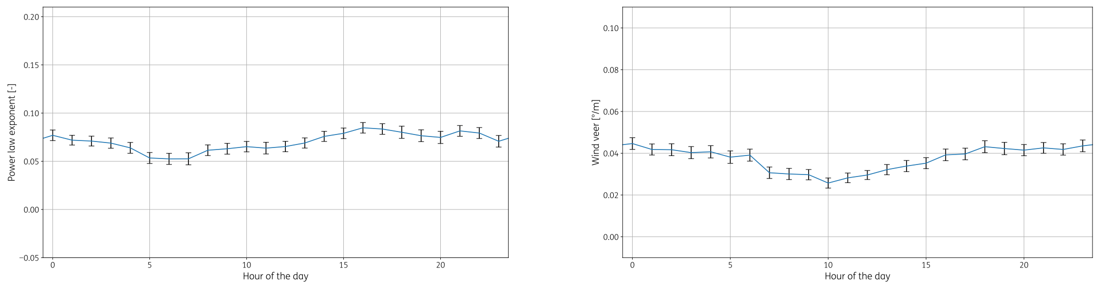

Figure A.34: Wind shear and veer as function the hour-of-day for 2022

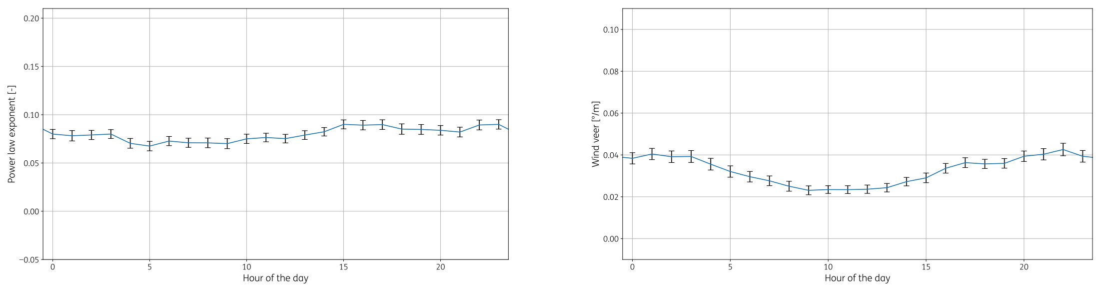

Figure A.35: Wind shear and veer as function the hour-of-day for 2023

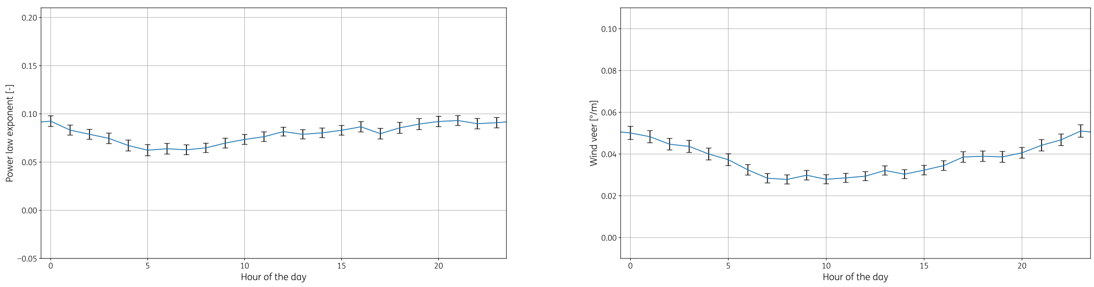

Figure A.36: Wind shear and veer as function the hour-of-day for 2024

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

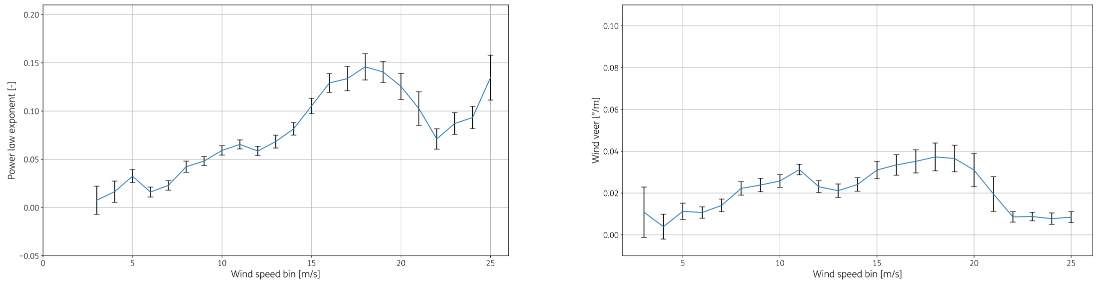

Figure A.37: Wind shear and veer as function of wind speed for 2016

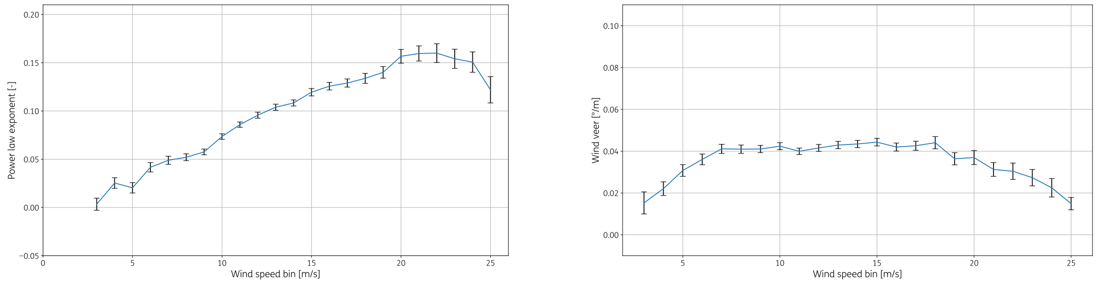

Figure A.38: Wind shear and veer as function of wind speed for 2017

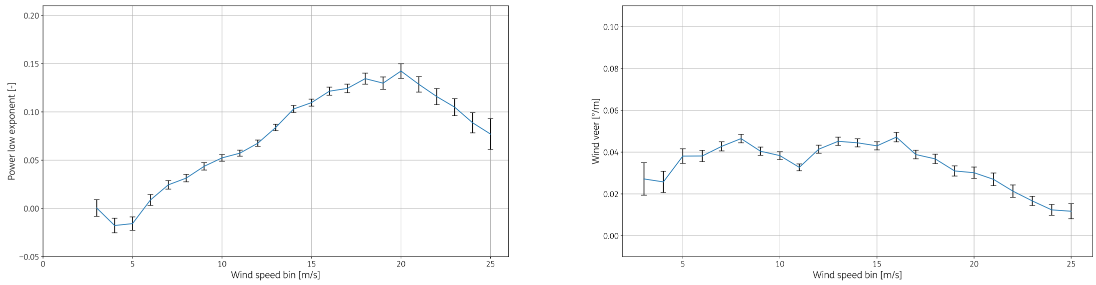

Figure A.39: Wind shear and veer as function of wind speed for 2018

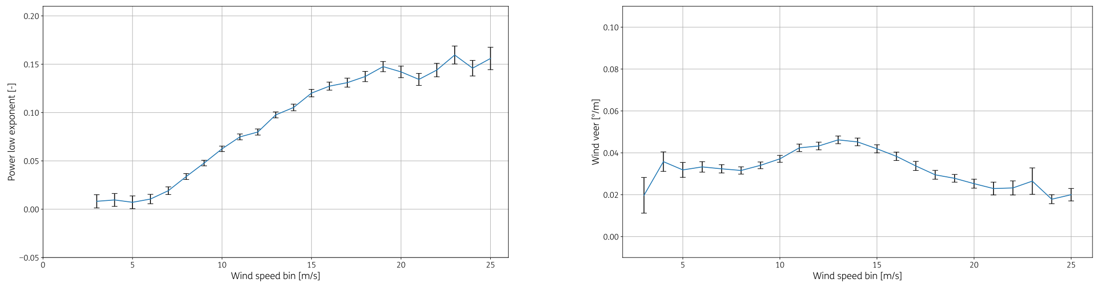

Figure A.40: Wind shear and veer as function of wind speed for 2019

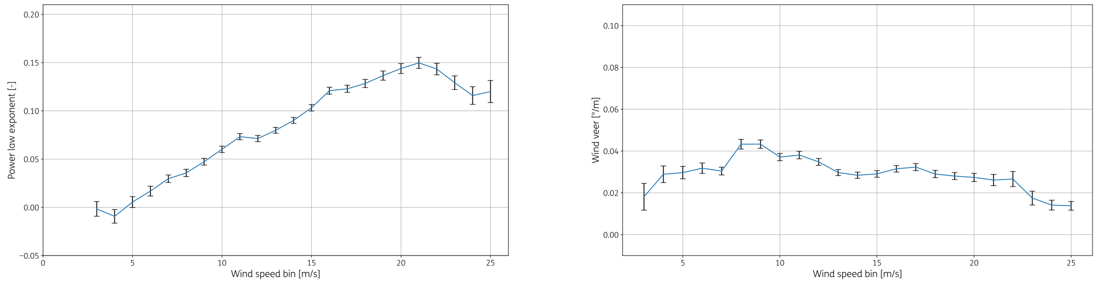

Figure A.41: Wind shear and veer as function of wind speed for 2020

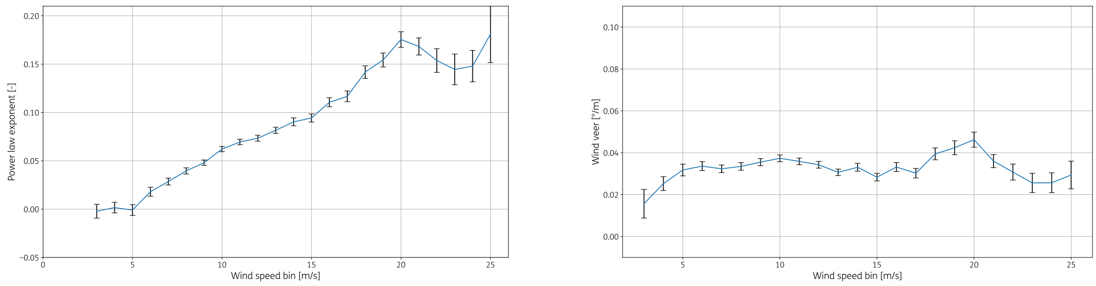

Figure A.42: Wind shear and veer as function of wind speed for 2021

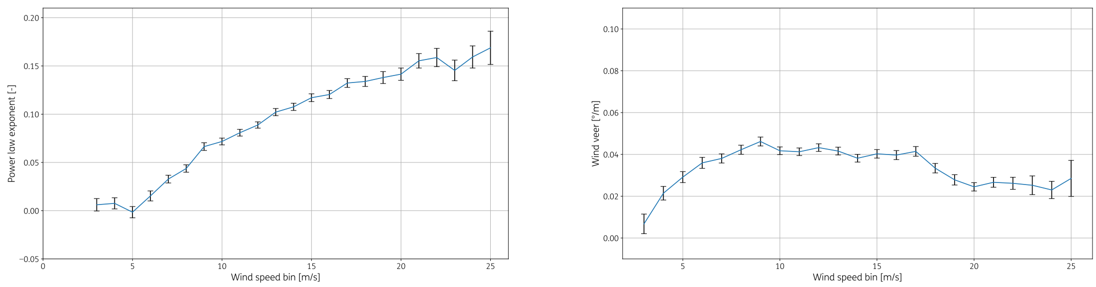

Figure A.43: Wind shear and veer as function of wind speed for 2022

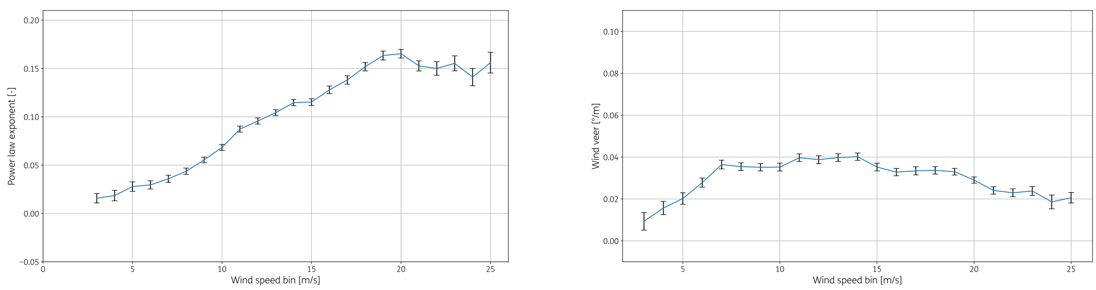

Figure A.44: Wind shear and veer as function of wind speed for 2023

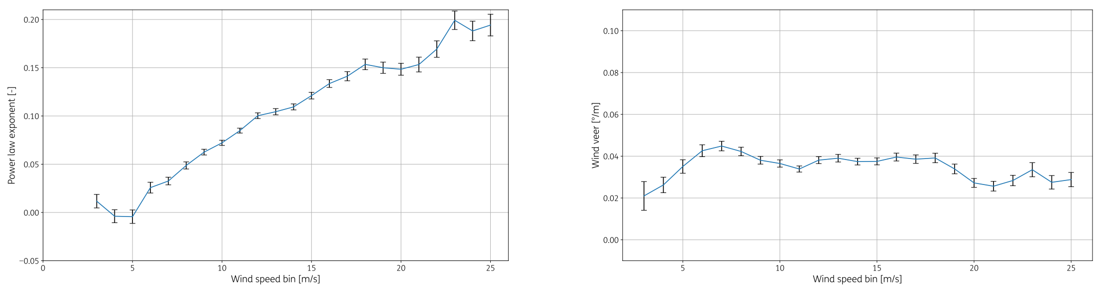

Figure A.45: Wind shear and veer as function of wind speed for 2024

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

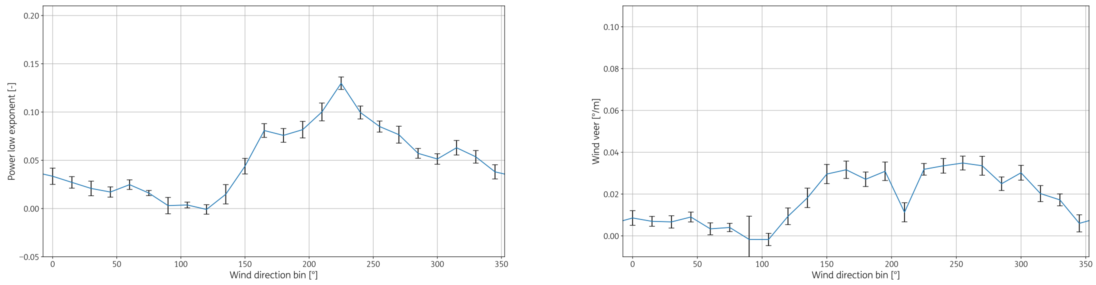

Figure A.46: Wind shear and veer as function of wind direction for 2016

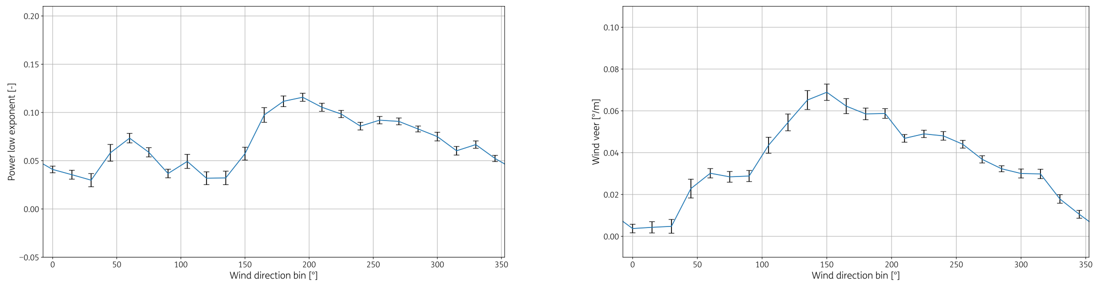

Figure A.47: Wind shear and veer as function of wind direction for 2017

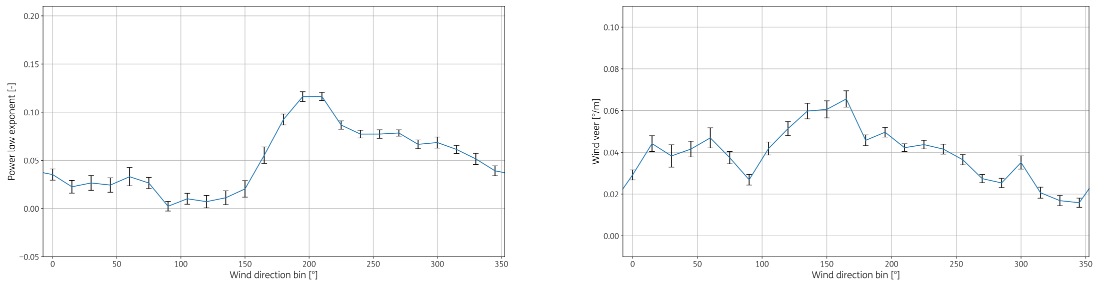

Figure A.48: Wind shear and veer as function of wind direction for 2018

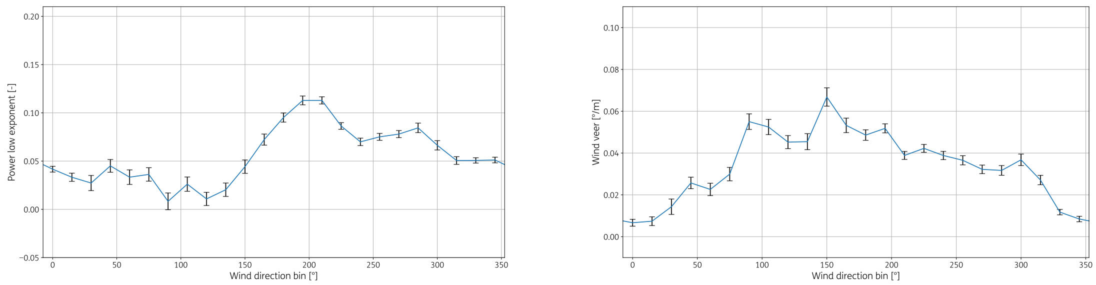

Figure A.49: Wind shear and veer as function of wind direction for 2019

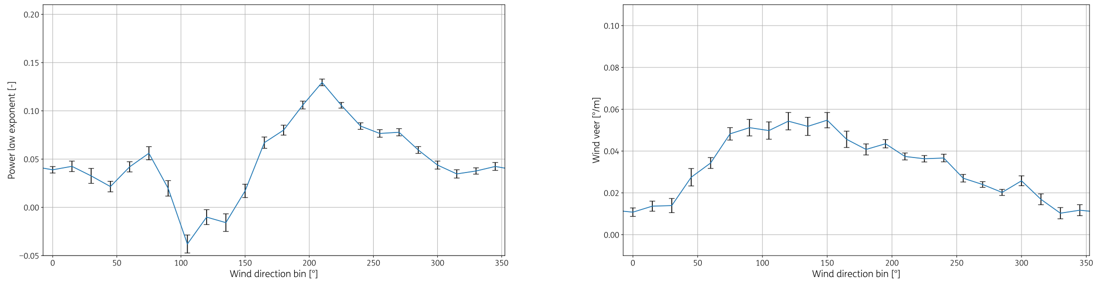

Figure A.50: Wind shear and veer as function of wind direction for 2020

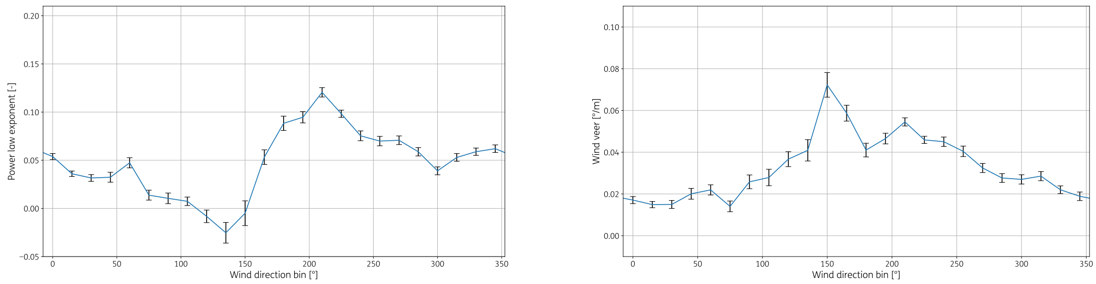

Figure A.51: Wind shear and veer as function of wind direction for 2021

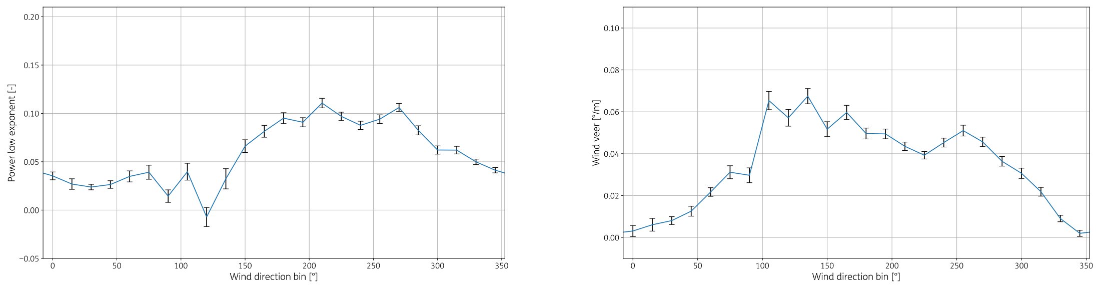

Figure A.52: Wind shear and veer as function of wind direction for 2022

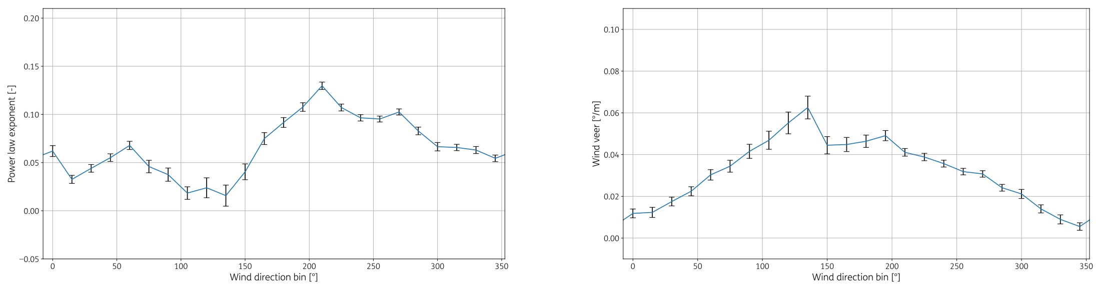

Figure A.53: Wind shear and veer as function of wind direction for 2023

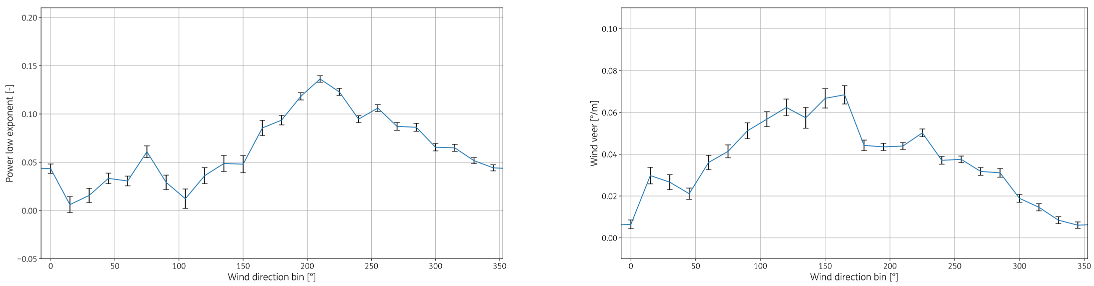

Figure A.54: Wind shear and veer as function of wind direction for 2024

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

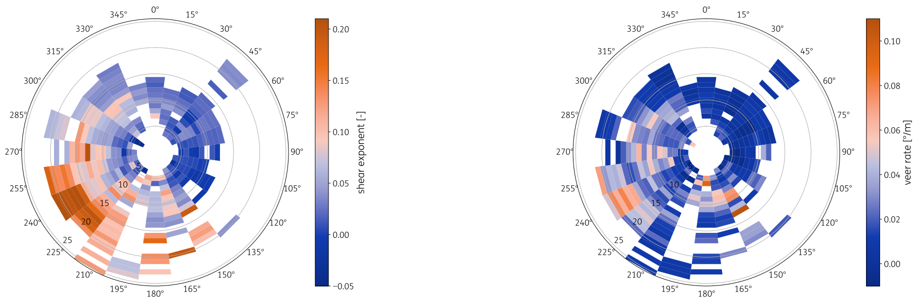

Figure A.55: Wind shear and veer as function of wind speed and direction for 2016

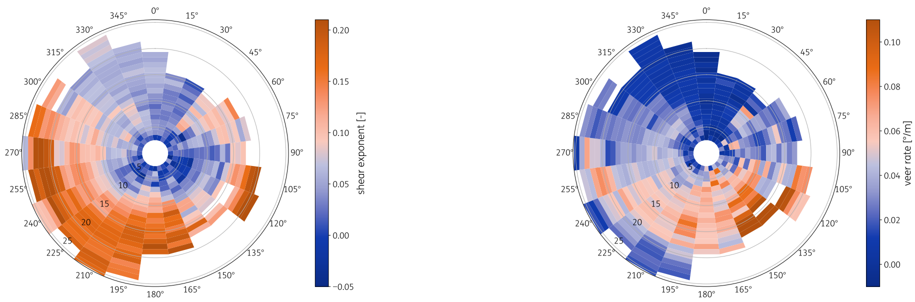

Figure A.56: Wind shear and veer as function of wind speed and direction for 2017

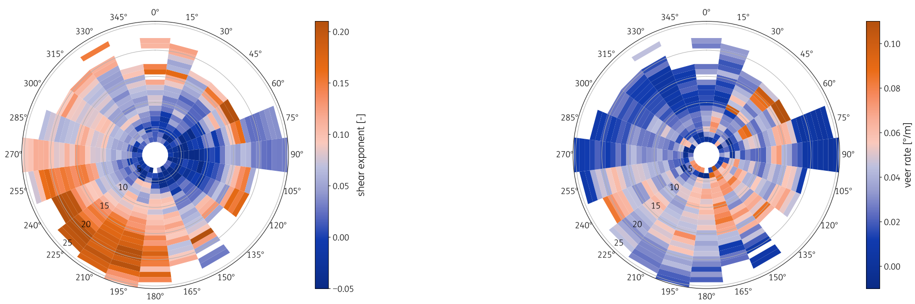

Figure A.57: Wind shear and veer as function of wind speed and direction for 2018

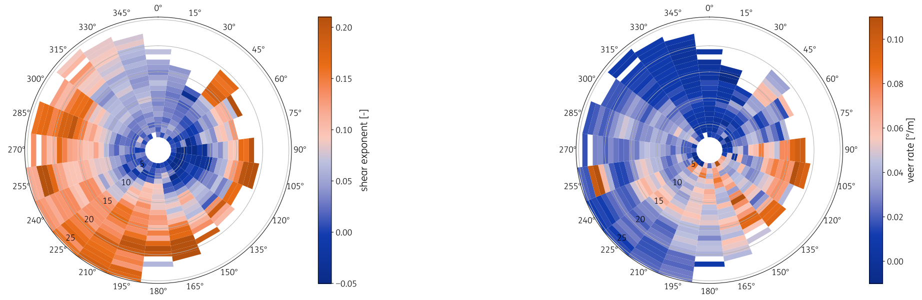

Figure A.58: Wind shear and veer as function of wind speed and direction for 2019

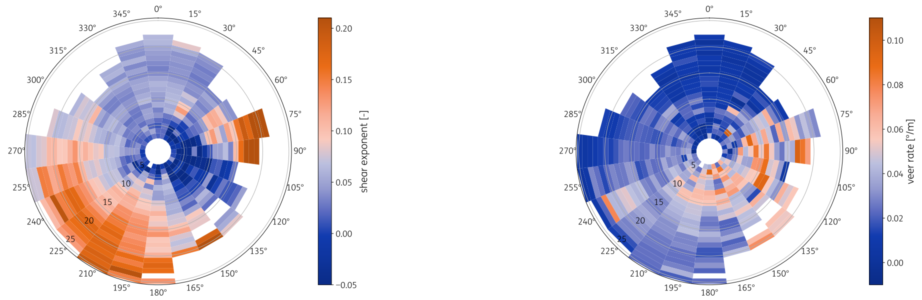

Figure A.59: Wind shear and veer as function of wind speed and direction for 2020

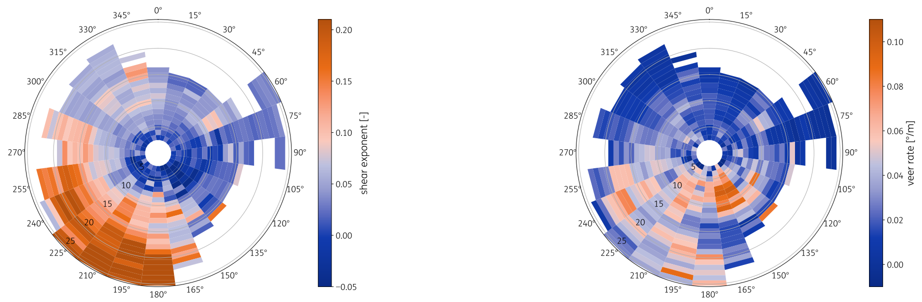

Figure A.60: Wind shear and veer as function of wind speed and direction for 2021

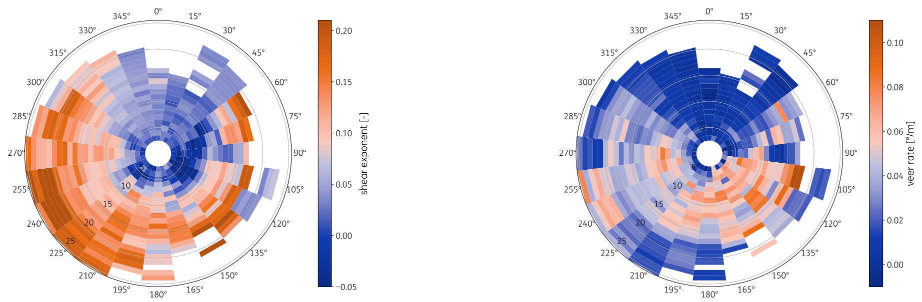

Figure A.61: Wind shear and veer as function of wind speed and direction for 2022

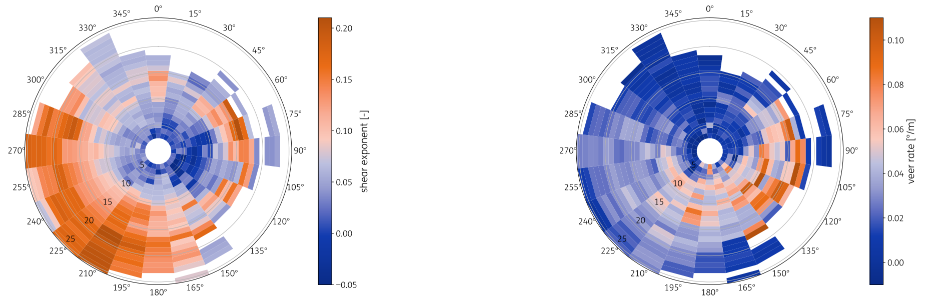

Figure A.62: Wind shear and veer as function of wind speed and direction for 2023

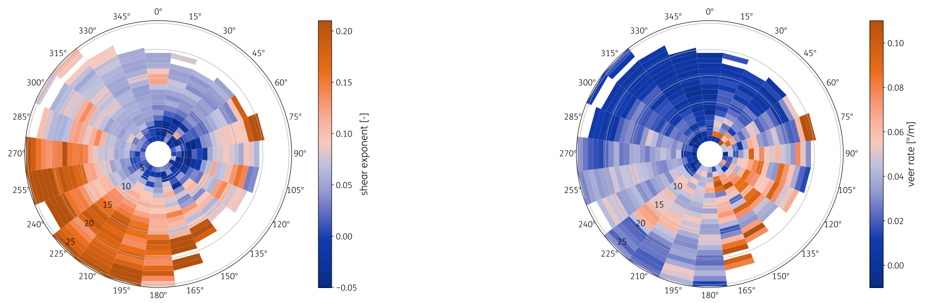

Figure A.63: Wind shear and veer as function of wind speed and direction for 2024

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