

Offshore wind resources at the North Sea

Tenaz Energy platform L2-FA-1, 2023–2025



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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 23 GW by 2033. 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 5.5 GW are currently under construction in the wind farm sites *Hollandse Kust West* and *IJmuiden Ver*.

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 m tall 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. These campaigns are part of the *Wind op Zee* project that is meant to support the implementation of the Dutch offshore wind roadmap. They consist of four long-standing locations: Lichteiland Goeree (LEG), Europlatform (EPL), K13-A and L2-FA-1. Recently TNO commissioned a lidar measurement on a fifth platform F2-A-Hanze, where measurements started in February 2026. TNO is accredited for performing the aforementioned meteorological measurements in accordance with IEC 61400-50-2.

This report refers to the measurement campaign at the L2-FA-1 platform where a ZX 300M has been deployed, providing high quality data since 2023. The data are publicly available to be used for further purposes (offshorewind-measurements.tno.nl).

At the L2-FA-1 platform, the wind analysis for the 2023–2025 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 233.1° to 240.1° across the different sensor heights (63 m to 291 m). The average wind speed ranges from 9.49 m/s at the lowest measurement height of 63 m up to 11.23 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 ($k = 2.18$ and $c = 11.52$ m/s at 141 m height).

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Abbreviations

BWFZ	Borssele Wind Farm Zone
CfD	Contract for Difference
ECMWF	European Centre for Medium-Range Weather Forecasts
EEZ	Exclusive economic zone
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 MBA	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)
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)
RVO	Rijksdienst voor Ondernemend Nederland (Netherlands Enterprise Agency)
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 23 GW by 2033 [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 5.5 GW are currently under construction in the wind farm sites *Hollandse Kust West* and *IJmuiden Ver* (see figure 1.1).

In recent years the development of offshore wind energy has stagnated due to higher material and installation costs in combination with a volatile electricity price. Last year's tender for the *Nederwiek I-A* wind farm site did not receive any bids [4]. In order to support the key role that offshore wind energy plays in the energy transition, the Dutch Ministry of Economic Affairs and Climate has defined an action plan to accelerate the expansion of wind at sea [5]. The plan acknowledges the difficult market situation and aims to stimulate both the supply and demand sites for electricity from wind energy. On the supply side, future tenders will include a *Contract for Difference* (CfD) subsidy scheme, which aims at guaranteeing a minimum price of electricity while capping profit whenever the energy price is high. On the demand side, measures will be taken to make it more attractive for industry parties with a high energy consumption to establish long-term agreements with energy providers.

To achieve the 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 valuable 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 that 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 provides information for 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 m tall 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. These campaigns are part of the *Wind op Zee* project that is meant to support the implementation of the Dutch offshore wind roadmap. They consist of four long-standing locations: Lichteiland Goeree (LEG), Europlatform (EPL), K13-A and L2-FA-1 (see figure 1.2). Recently TNO commissioned a lidar measurement on a fifth platform F2-A-Hanze, where measurements started in February 2026. TNO is accredited for performing the aforementioned wind measurements in accordance with IEC 61400-50-2 [6].

This report will focus on the wind conditions characterisation of the L2-FA-1 platform, located about 80 km north from the Frysian Islands.

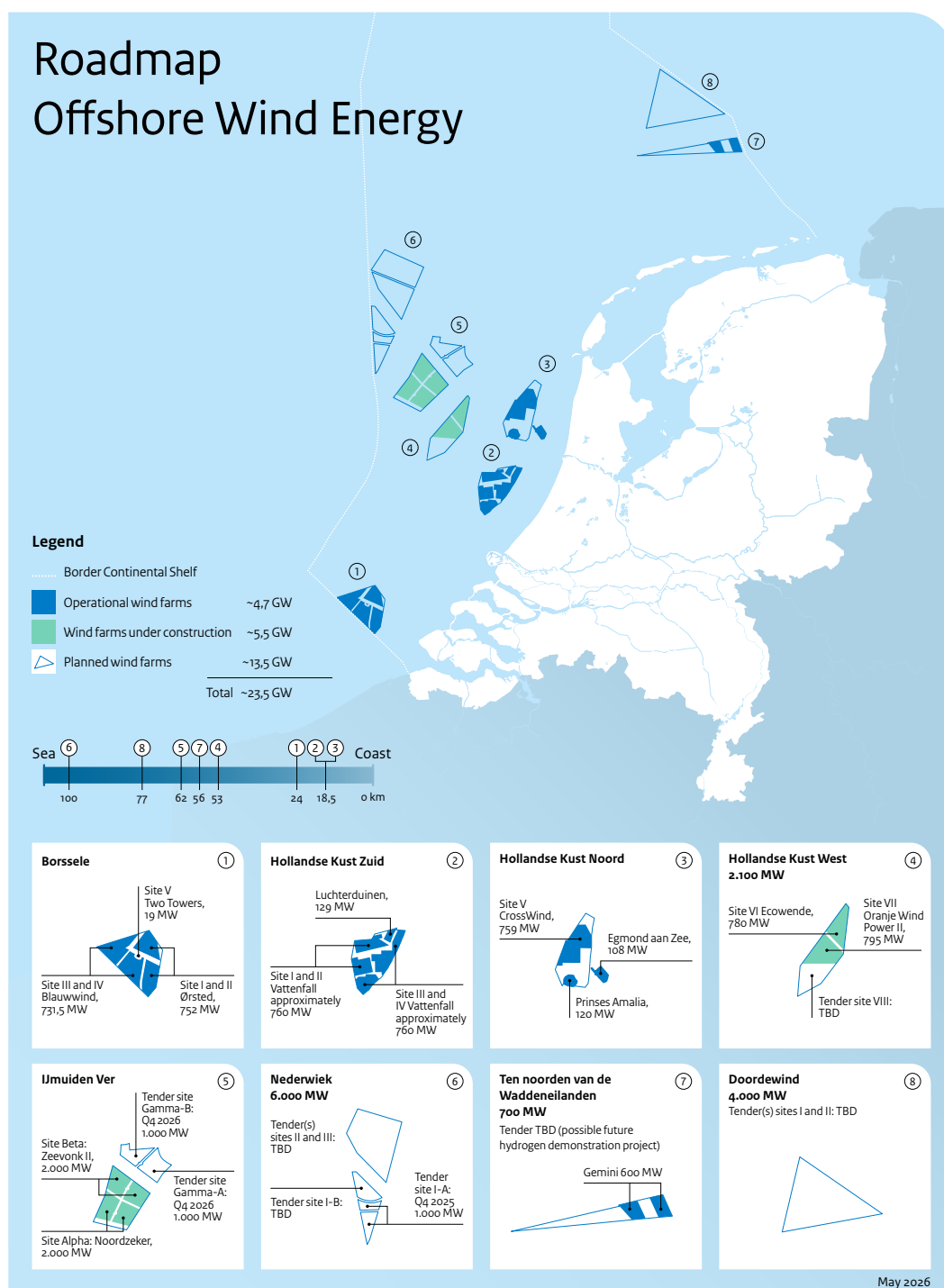


Figure 1.1: Roadmap Offshore Wind Energy providing an overview of wind farms in the Dutch North Sea (in operation, under construction and planned) [2].

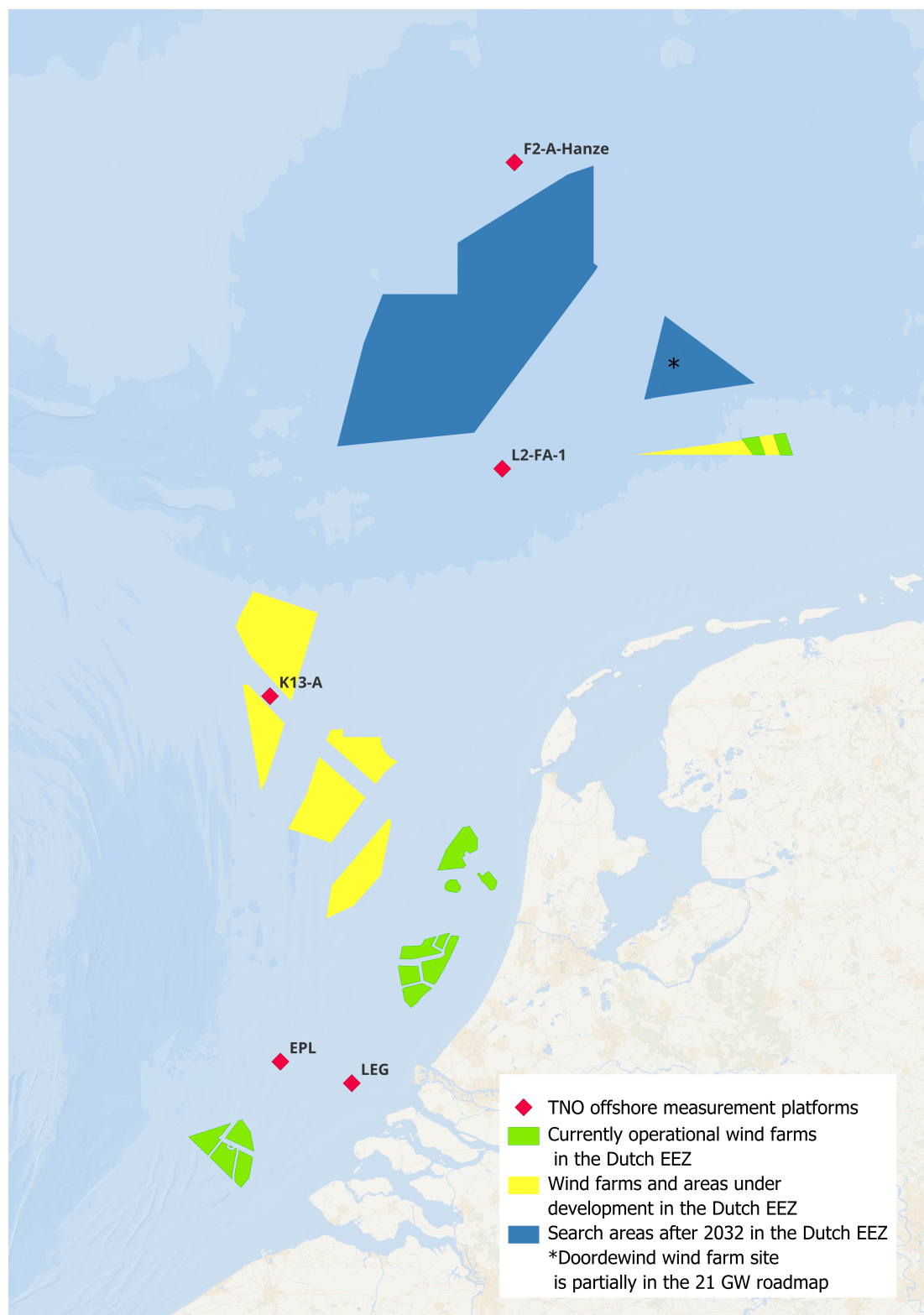


Figure 1.2: Map of TNO's long-term offshore wind measurement campaign locations at Lichteiland Goeree (LEG), Europlatform (EPL), K13-A, L2-FA-1 and F2-A-Hanze along with wind farm development zones in the Dutch North Sea.

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 2024 TNO has published annual reports on the wind conditions for the L2-FA-1 location, see table 2.1. These reports are available at offshorewind-measurements.tno.nl. This report includes the specific wind conditions for the period 2023–2025 at the L2-FA-1 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 L2-FA-1

Period	Report
2023	TNO 2024 R11677 [7]
2023–2024	TNO 2025 R11114 [8]

The data measured in the *Wind op Zee* project are retrieved and post-processed before making the information publicly accessible through the web-service offshorewind-measurements.tno.nl. 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 latest instrumentation report *with the type of data used, location and date*:

```
author = {Bergman, G. and van Dooren, M. F.},  
institution = {TNO},  
title = {L2-FA-1 lidar measurement campaign},  
subtitle = {Instrumentation Report 2026},  
number = {TNO 2026 R10603},  
date = {2026-04-14},
```

2. citation to this report:

```
author = {van Dooren, M. F. and Wouters, D. A. J. and Bergman, G.},  
institution = {TNO},  
title = {Offshore wind resources at the North Sea},  
subtitle = {NAM platform L2-FA-1, 2023-2025},  
number = {TNO-2026-17438},  
date = {2026-09-11},
```

The publication date at which the data have last been accessed must be indicated along the citations, e.g. “Last accessed July 2026”.

The data is shared in .csv format. In the case of the L2-FA-1 measurement campaign please adhere to the following information:

- › offshorewind-measurements.tno.nl/en/measurement-locations/l2-fa-1-platform/
- › For monthly files use: L2FA-yyyy-mm.CSV.
- › After a quarter of a year is completed the monthly files will be replaced by L2FA-yyyy-Qx.CSV.
- › After a year is completed the quarterly files will be replaced by a yearly file L2FA-yyyy.CSV.

3 Measurement campaign at L2-FA-1

3.1 Location, lidar installation and operation

The L2-FA-1 offshore platform is owned by NAM B.V. and located about 80 km north of the Frysian Islands, see figure 1.2. It includes both a helicopter pad and an accommodation deck. The platform is part of the North Sea Monitoring Network consisting of several permanent monitoring locations over the North Sea.

The L2-FA-1 platform serves as a production platform for natural gas and since the beginning of 2023 also for wind measurements using a platform-mounted ZX 300M 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 Dutch national weather service (KNMI) and Rijkswaterstaat (both part of the Dutch Ministry of Infrastructure and Water Management).

The current instrumentation at L2-FA-1 is a ZX 300M 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 [9] for the lidar specifications). Before the lidar was installed at the L2-FA-1 platform, it was calibrated, see latest calibration report [10]. 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 L2-FA-1 platform is available in the instrumentation report [11].

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 K13-A 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 2025 are summarised in table 3.2. Personnel from NAM B.V., the oil and gas company operating the L2-FA-1 platform, supports monitoring and control of the lidar.

Table 3.1: Replacements of lidars at the L2-FA-1 platform

Lidar ID	Operational period	Reason for replacement
ZX1525	22-03-2023 to 30-06-2025	First installation
ZX2128	30-06-2025 to present	Periodic replacement



Figure 3.1: Tenaz Energy platform L2-FA-1



Figure 3.2: Lidar unit at L2-FA-1

Table 3.2: Down-time periods and actions taken at L2-FA-1 platform during the year 2025

Date ID	Reason
30-06-2025	Replacement of lidar ZX1525 with ZX2128 including fluid pump
01-07-2025	Compass calibration of lidar orientation, indicating no significant offset
23-08-2025	Discovery of worn-out jerrycan containing wiper fluid by platform operator Tenaz Energy, replaced in September

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 L2-FA-1

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 L2-FA-1 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 2023. This report considers the measurement period until 31 December 2025 at 23:50 UTC. The campaign is still ongoing, with future yearly assessments envisioned.

The annual lidar data availability at L2-FA-1 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 90.9 %, while farther up to 241 m it decreases to 89.5 %, and finally to 87.3 % at the highest altitude of 291 m. For the year 2025, the data availability for heights up to 191 m is at least 95.9 %, while farther up to 241 m it decreases to 92.4 %, and finally to 87.3 % 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,

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
L2FA_batvoltage	battery voltage	V
L2FA_tempcpu	CPU temperature inside the lidar	°C
L2FA_humpod	relative humidity inside the lidar	%
L2FA_bearing	lidar bearing	°
L2FA_tilt	lidar tilt angle	°
L2FA_pair	air pressure at lidar position	hPa
L2FA_wsmet	wind speed measured by lidar meteo station	m/s
L2FA_wdmet	wind direction measured by lidar meteo station	°
L2FA_HXXX_npts	measuring points	-
L2FA_HXXX_missed	missed points	-
L2FA_HXXX_npackets	packets in fit	-
L2FA_HXXX_Wd	wind direction	°
L2FA_HXXX_Wshor_avg	horizontal wind speed average	m/s
L2FA_HXXX_Wshor_std	horizontal wind speed standard deviation	m/s
L2FA_HXXX_Wshor_min	horizontal wind speed minimum	m/s
L2FA_HXXX_Wshor_max	horizontal wind speed maximum	m/s
L2FA_HXXX_WsVer_avg	vertical wind speed average	m/s
L2FA_HXXX_cs	CS	-
L2FA_HXXX_BackScatter	back scatter	-

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.

There are complementary reports with data verification comparing with other measurements. In particular, [12] examines the wind speed and direction measurement campaigns at eight offshore measurement locations distributed throughout the North Sea, including the L2-FA-1 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
2023	99.9	98.8	97.5	96.8	94.9	94.2	92.9	91.1	89.2	86.5
2024	99.9	99.0	97.7	96.7	94.6	93.3	91.7	89.7	87.8	84.7
2025	99.6	99.0	98.6	98.2	96.3	95.7	94.5	92.9	90.8	88.1
Overall	99.8	98.9	97.9	97.3	95.3	94.4	93.1	91.2	89.3	86.4

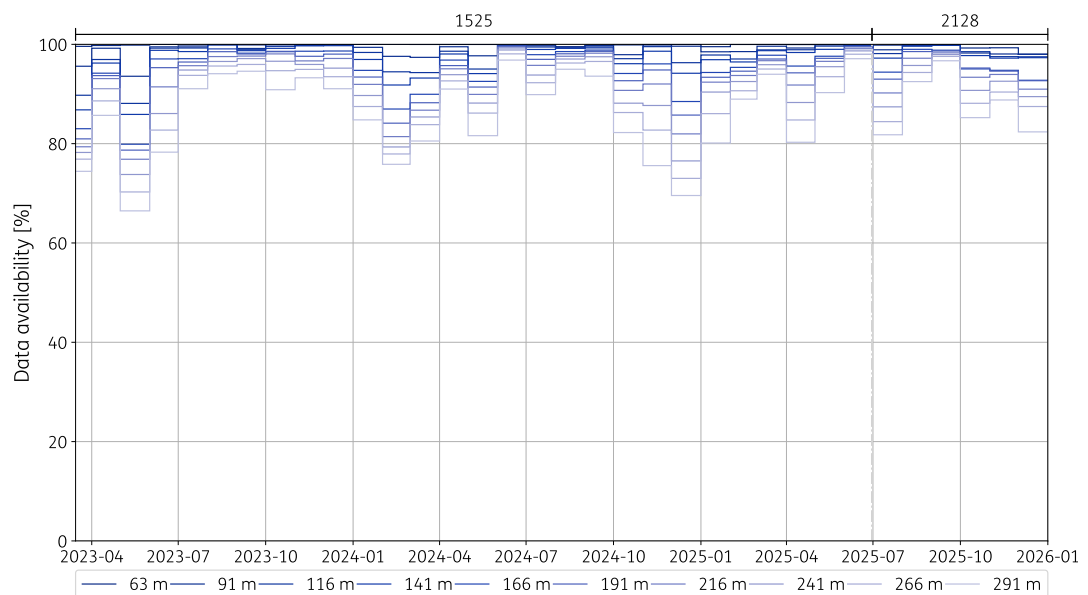


Figure 3.3: Monthly lidar data availability showing the lidar IDs and their operational periods.

4 Wind conditions at L2-FA-1

This section presents the results following an assessment of the weather conditions during the entire measurement campaign at L2-FA-1. 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 estimate¹ (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 computed². A Weibull probability density function (pdf) is fitted to the wind speed frequency distribution³. 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 height⁴.

For the wind direction distribution the MoMM is computed too. The mean direction is computed as the average direction of the wind velocity⁵.

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.

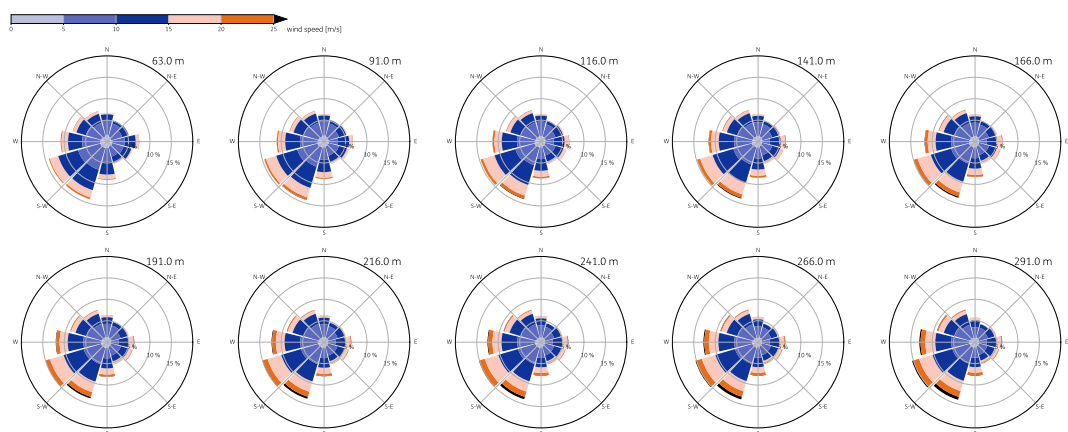


Figure 4.1: Wind roses for the complete measurement campaign

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

²First 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.

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

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

⁵The 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 m	N #	Wind speed					Wind direction
		Q ₁ m/s	median m/s	Q ₃ m/s	maximum m/s	MoMM m/s	MoMM °
63	147 021	6.20	9.04	12.17	29.31	9.49	233.1
91	145 754	6.36	9.40	12.75	42.90	9.88	233.1
116	144 292	6.45	9.58	13.12	41.73	10.14	233.7
141	143 273	6.52	9.70	13.37	31.42	10.33	234.7
166	140 362	6.60	9.83	13.60	44.71	10.53	236.2
191	139 070	6.64	9.91	13.78	33.97	10.67	237.2
216	137 104	6.69	10.00	13.96	35.87	10.82	238.1
241	134 405	6.74	10.08	14.12	37.31	10.95	238.8
266	131 524	6.80	10.18	14.26	60.80	11.09	239.5
291	127 341	6.83	10.30	14.44	38.92	11.23	240.1

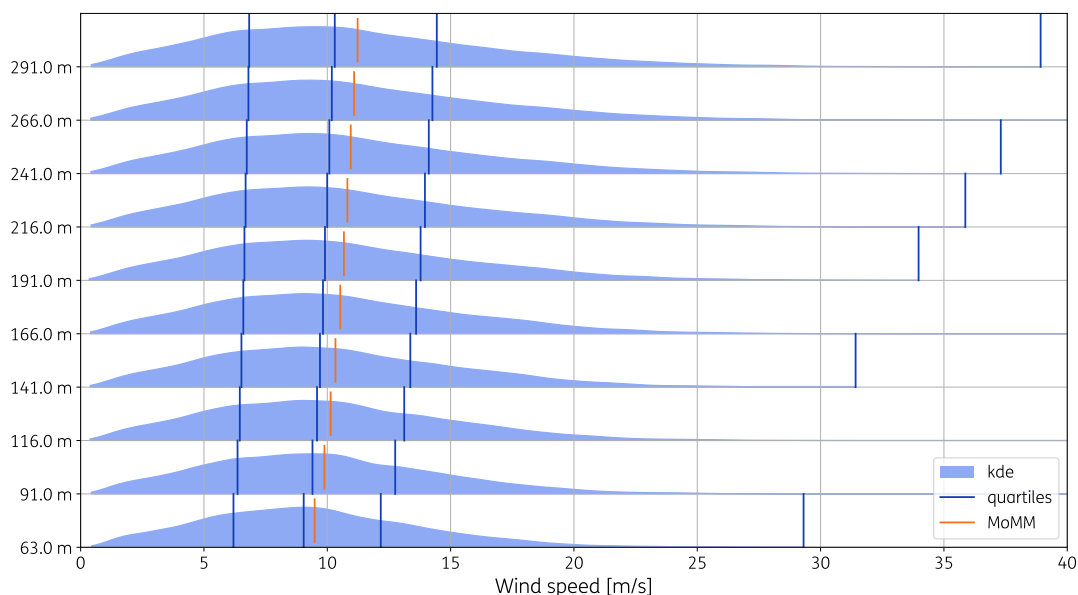
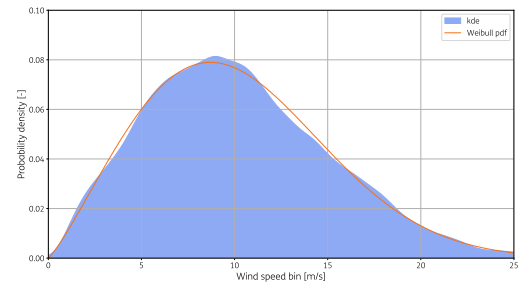


Figure 4.2: Wind speed distributions. The kde is shown with blue markers for the quartiles (Q₁, median, Q₃ and maximum) and an orange marker for the MoMM, as listed in table 4.1.

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

Height	Shape (k)	Scale (c)
m	–	m/s
63	2.273	10.61
91	2.242	11.04
116	2.213	11.31
141	2.180	11.52
166	2.151	11.73
191	2.122	11.89
216	2.101	12.04
241	2.085	12.18
266	2.075	12.32
291	2.060	12.46

**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 lidar⁶. 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.

⁶The 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.

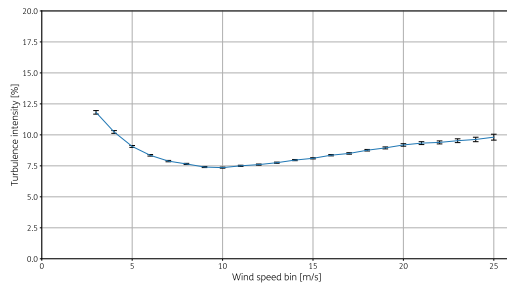


Figure 4.4: Turbulence intensity at 63 m

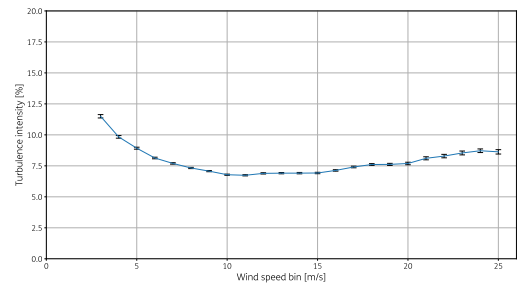


Figure 4.5: Turbulence intensity at 91 m

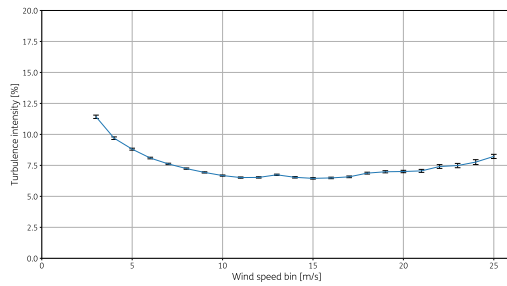


Figure 4.6: Turbulence intensity at 116 m

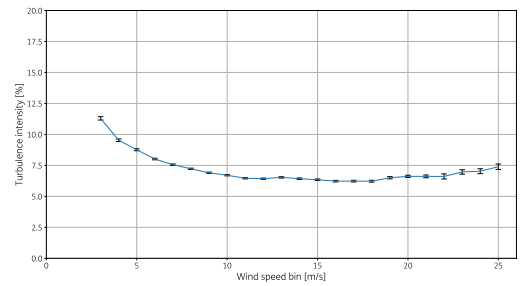


Figure 4.7: Turbulence intensity at 141 m

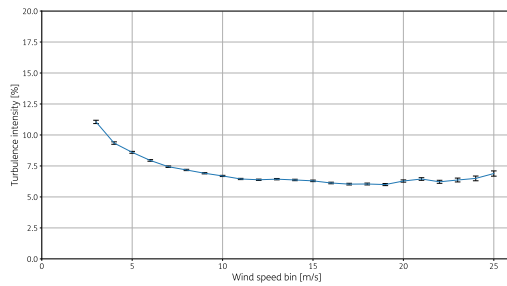


Figure 4.8: Turbulence intensity at 166 m

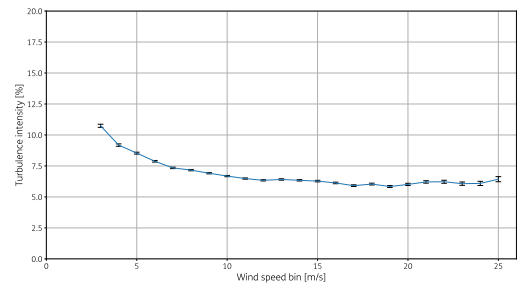


Figure 4.9: Turbulence intensity at 191 m

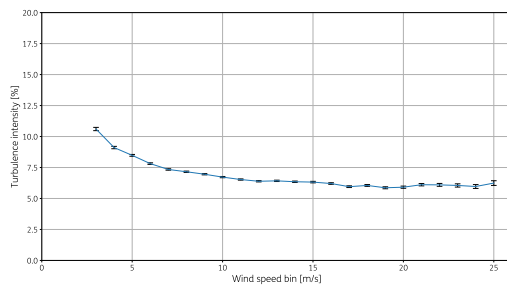


Figure 4.10: Turbulence intensity at 216 m

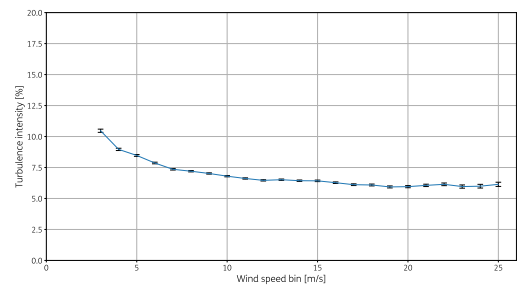


Figure 4.11: Turbulence intensity at 241 m

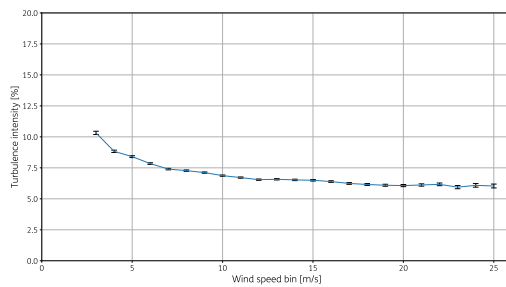


Figure 4.12: Turbulence intensity at 266 m

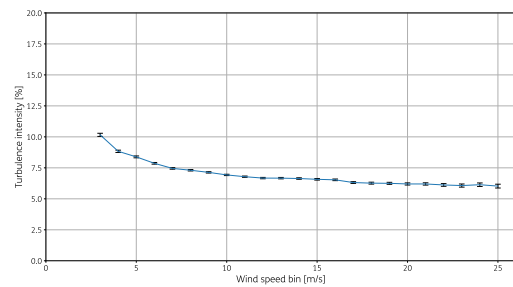


Figure 4.13: Turbulence intensity at 291 m

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 rejected⁷.
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 rejected⁸.

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.

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

⁷This threshold is based on the MEASNET procedure [13, clause 9.4].

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

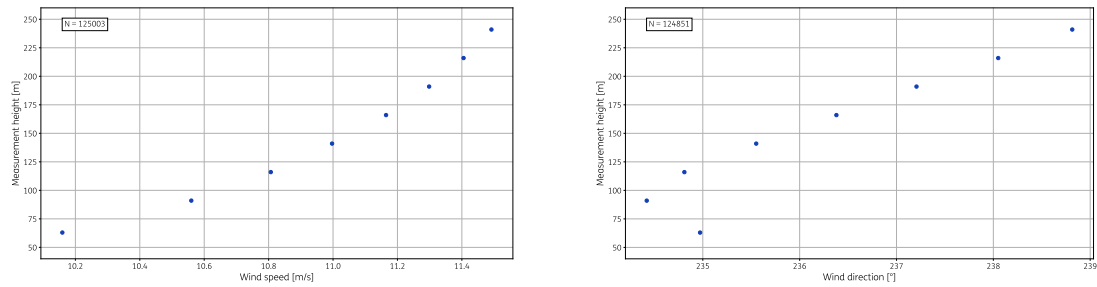


Figure 4.14: Average wind speed and wind direction (MoMM) of the dataset per height. ‘N’ is the number of 10-minute average samples remaining after filtering used to compute the MoMM values.

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 used⁹, 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.

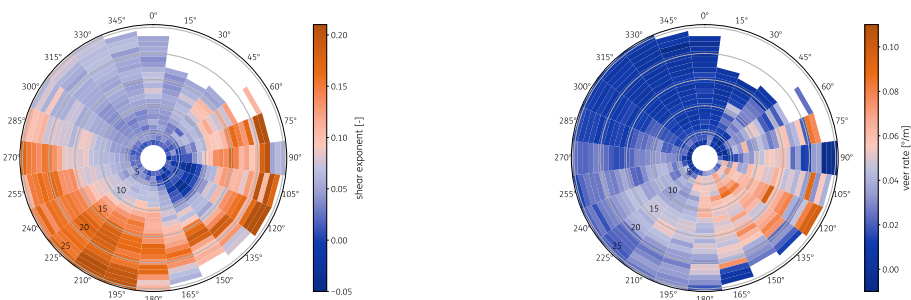


Figure 4.15: Wind shear and veer as function of wind speed and direction. The azimuth indicates the wind direction bin, the radius labels indicate the wind speed bin and the colour represents the mean value for the shear exponent (left) and veer rate (right).

⁹This follows the MEASNET procedure [13, clause 9.4].

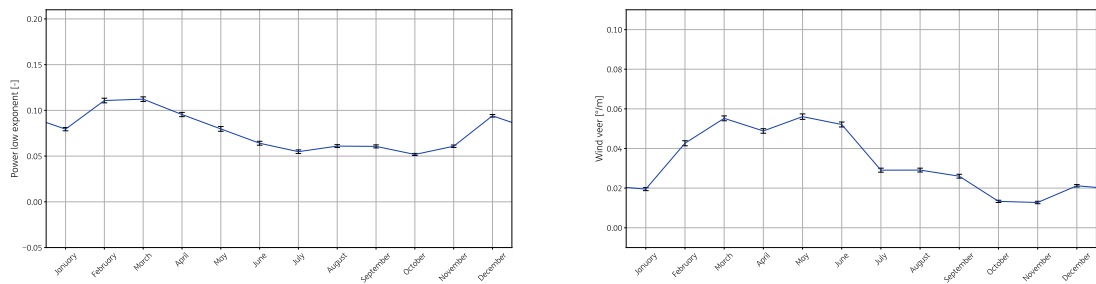


Figure 4.16: Wind shear and veer as function of the month-of-year

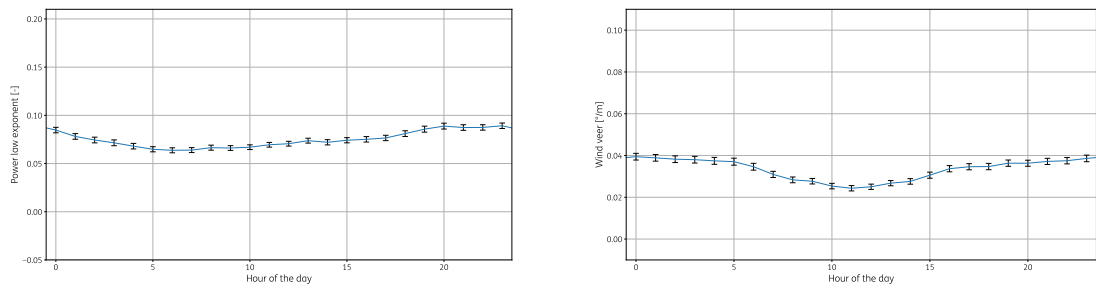


Figure 4.17: Wind shear and veer as function the hour-of-day

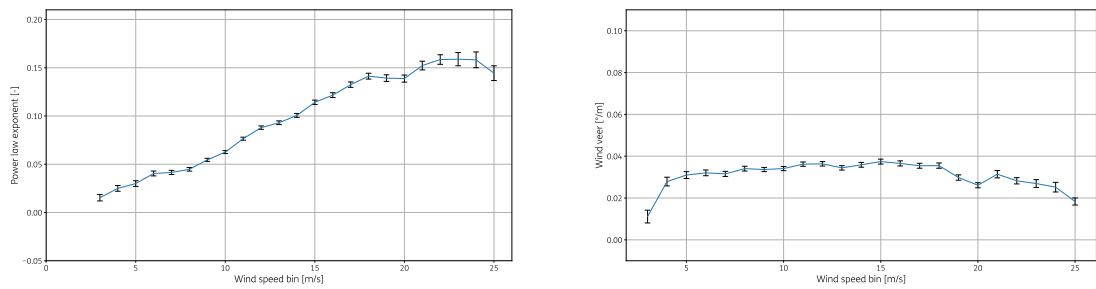


Figure 4.18: Wind shear and veer as function of wind speed

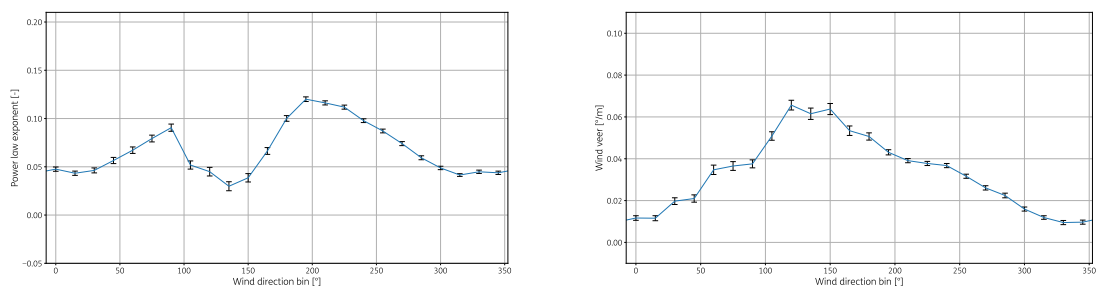


Figure 4.19: Wind shear and veer as function of wind direction

5 Conclusions and outlook

This report refers to the measurement campaign at the L2-FA-1 platform where a ZX 300M lidar has been deployed, providing high quality data since 2023. The data are publicly available to be used for further purposes (offshorewind-measurements.tno.nl).

For the year 2025, the data availability for heights up to 191 m is at least 95.9 %, while farther up to 241 m it decreases to 92.4 %, and finally to 87.3 % at the highest altitude of 291 m.

At the L2-FA-1 platform, the wind analysis for the 2023–2025 period shows that the long-term average 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 235.0° to 243.5° across the different sensor heights (63 m to 291 m). The average wind speed ranges from 9.37 m/s at the lowest measurement height of 63 m up to 10.72 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 ($k = 2.20$ and $c = 11.52$ 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 L2-FA-1 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 (2024) report [14]. 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 2025 version of this overarching report will be released later this year.

Acknowledgements

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Signatures

	Date: September 15, 2026		Report number: TNO-2026-17438
Title	Offshore wind resources at the North Sea Tenaz Energy platform L2-FA-1, 2023-2025		
Author(s)	M. F. van Dooren D. A. J. Wouters G. Bergman		
Principal(s)	Dutch Ministry of Economic Affairs and Climate Bezuidenhoutseweg 73, 2594 AC Den Haag		
Project number	060.63173		
Programme	Wind Energy		
Abstract	This report focuses on the wind conditions characterisation at the L2-FA-1 platform, located about 80 km north from the Frysian Islands.		
Keywords	Offshore, wind, energy, conditions, long-term, North Sea, L2-FA-1, 2025		
Task	Name	Role	Signature
First author	M.F. van Dooren	Project manager	 ValidSigned by Marijn van Dooren on 15-09-2026
Expert review	D.A.J. Wouters	Data analyst	 ValidSigned by Dennis Wouters on 15-09-2026
Generic review	G. Bergman	Lead engineer	 ValidSigned by Gerben Bergman on 15-09-2026
Approval	S. Mancini	Deputy research manager	 ValidSigned by Simone Mancini on 15-09-2026
Authorization	E.D. Nennie	Research manager	 ValidSigned by Erik Nennie on 17-09-2026

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- [1] *New offshore wind farms*. Netherlands Enterprise Agency (RVO). June 10, 2026.
- [2] *Roadmap Offshore Wind Energy*. Netherlands Enterprise Agency (RVO). May 2026.
- [3] *Windparken op zee: Nederland ruim op schema, begin 2024 start tenderronde voor verdubbeling*. Dutch Ministry of Economic Affairs and Climate (EZK). Dec. 20, 2023.
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- [7] D. A. J. Wouters et al. *Offshore wind resources at the North Sea. NAM platform L2-FA-1, 2023*. **TNO 2024 R11677**. TNO, Dec. 16, 2024.
- [8] D. A. J. Wouters et al. *Offshore wind resources at the North Sea. NAM platform L2-FA-1, 2023–2024*. **TNO 2025 R11114**. TNO, May 27, 2025.
- [9] *ZX300M Offshore Wind Lidar for Floating Devices*. ZX Lidars. 2025.
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- [13] *Evaluation of site-specific wind conditions*. Version 3. MEASNET, Sept. 2022.
- [14] M. F. van Dooren et al. *Offshore wind resources at the North Sea. Results of a long-term measurement campaign, 2024*. **TNO 2025 R12620**. TNO, Dec. 5, 2025.

Appendix A

Annual wind conditions during the campaign at L2-FA-1

A.1 Wind rose

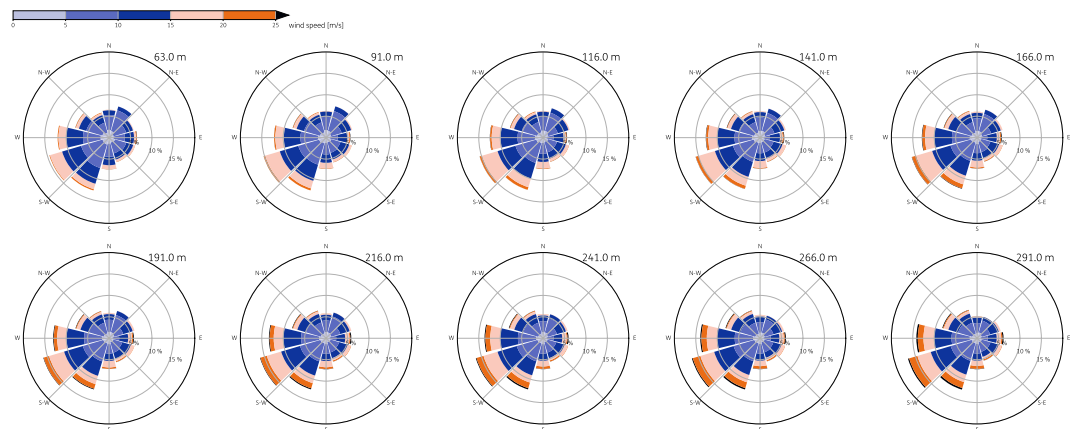


Figure A.1: Wind roses for 2023

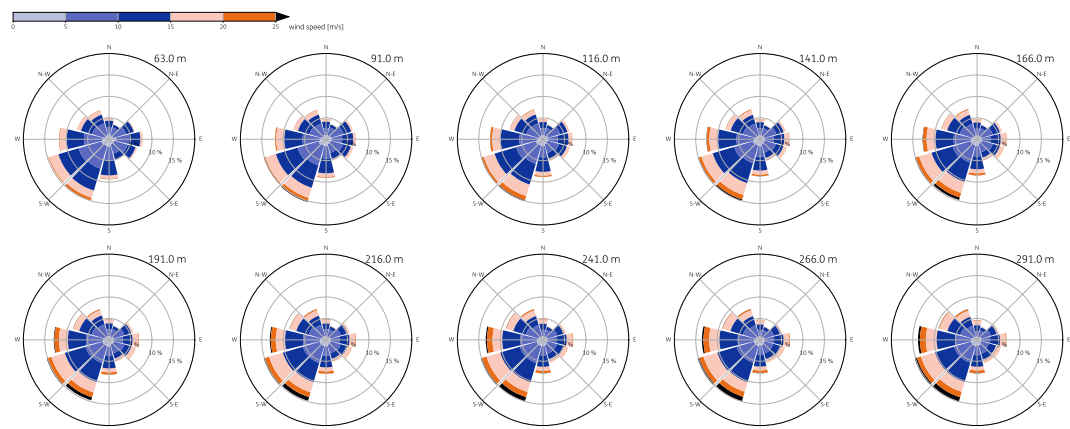


Figure A.2: Wind roses for 2024

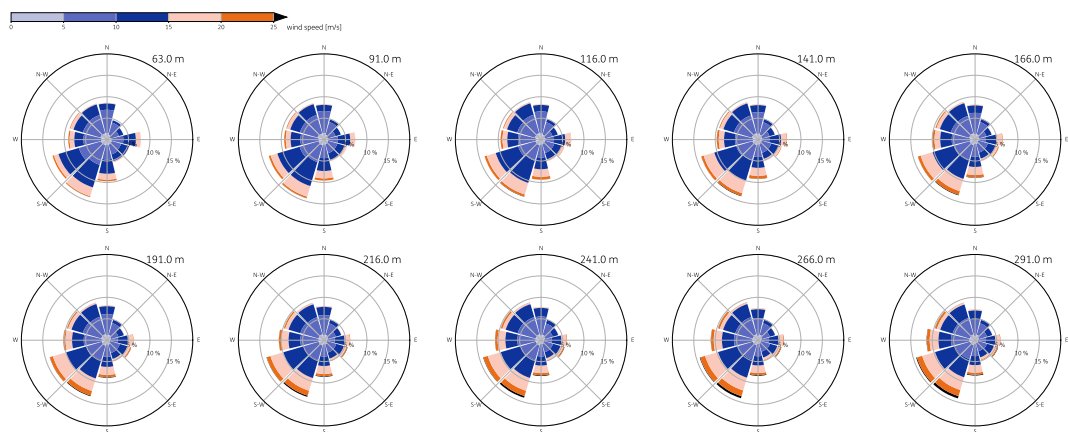


Figure A.3: Wind roses for 2025

A.2 Wind speed and direction statistics

Table A.1: Wind speed and wind direction statistics for 2023

Height m	Wind speed						Wind direction
	N #	Q ₁ m/s	median m/s	Q ₃ m/s	maximum m/s	MoMM m/s	MoMM °
63	42 002	5.97	8.80	12.02	29.01	9.30	235.6
91	41 531	6.13	9.17	12.61	30.62	9.71	235.0
116	40 985	6.22	9.34	12.99	30.95	9.97	235.0
141	40 697	6.29	9.46	13.23	31.12	10.17	235.7
166	39 923	6.37	9.60	13.46	31.49	10.37	236.5
191	39 592	6.41	9.67	13.62	31.59	10.51	237.5
216	39 081	6.45	9.75	13.79	31.89	10.63	238.4
241	38 307	6.48	9.83	13.95	31.93	10.75	238.9
266	37 522	6.54	9.92	14.09	32.08	10.87	239.4
291	36 374	6.55	10.03	14.28	32.31	10.99	239.7

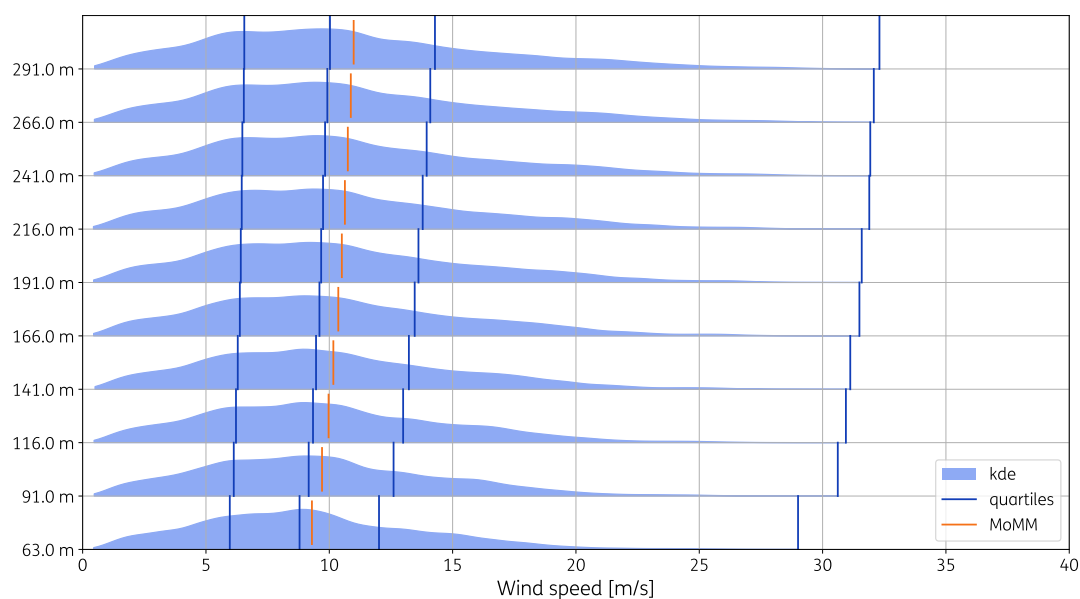


Figure A.4: Wind speed distributions for 2023

Table A.2: 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	52 659	6.38	9.38	12.44	29.31	9.60	233.0
91	52 165	6.57	9.76	13.09	29.89	10.03	232.8
116	51 469	6.67	9.97	13.52	30.68	10.31	233.6
141	50 970	6.74	10.12	13.85	31.42	10.54	234.8
166	49 843	6.81	10.25	14.11	32.51	10.76	236.5
191	49 169	6.85	10.35	14.32	33.97	10.94	237.8
216	48 345	6.90	10.45	14.50	35.87	11.11	239.0
241	47 262	6.97	10.54	14.68	37.31	11.28	240.1
266	46 256	7.05	10.64	14.83	38.28	11.43	241.1
291	44 640	7.09	10.80	15.03	38.92	11.60	241.8

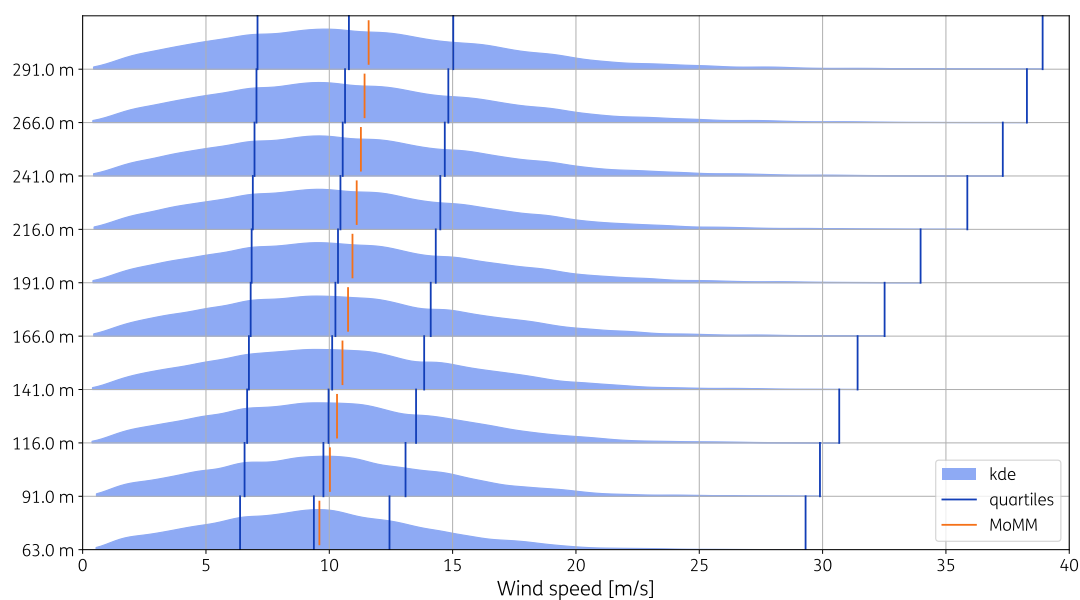


Figure A.5: Wind speed distributions for 2024

Table A.3: Wind speed and wind direction statistics for 2025

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	52 360	6.21	8.93	11.97	27.60	9.34	232.2
91	52 058	6.36	9.25	12.52	42.90	9.68	232.1
116	51 838	6.44	9.41	12.83	41.73	9.88	232.7
141	51 606	6.49	9.53	13.07	29.89	10.05	233.6
166	50 596	6.58	9.62	13.25	44.71	10.21	235.4
191	50 309	6.63	9.69	13.42	31.58	10.33	236.1
216	49 678	6.68	9.77	13.58	32.17	10.45	236.8
241	48 836	6.73	9.86	13.73	32.80	10.56	237.2
266	47 746	6.81	9.95	13.86	60.80	10.67	237.7
291	46 327	6.84	10.08	14.02	34.86	10.79	238.2

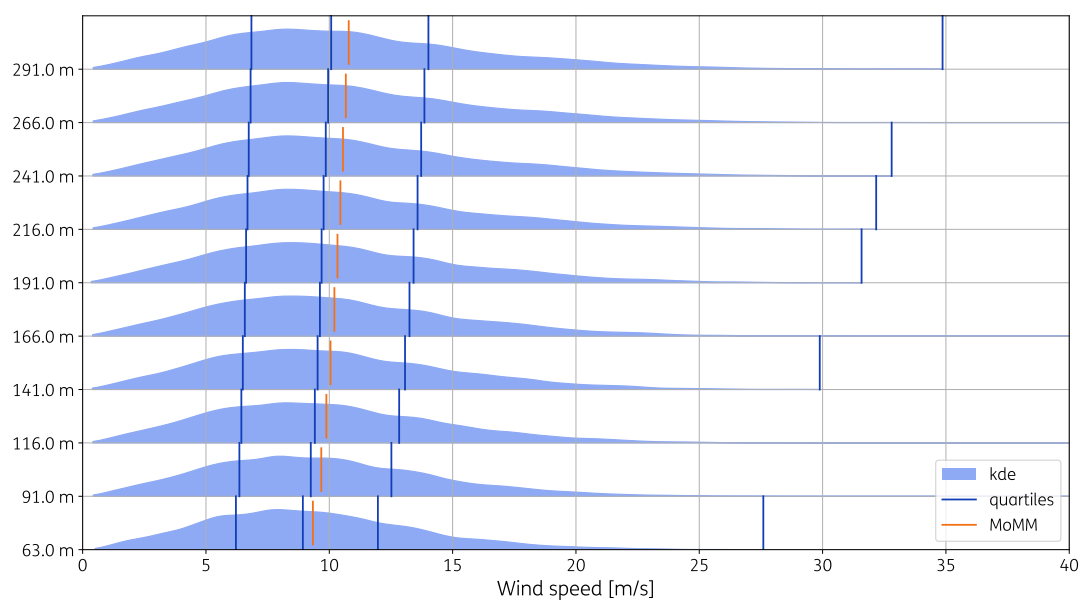


Figure A.6: Wind speed distributions for 2025

A.3 Wind speed distribution

Table A.4: Weibull parameters for 2023

Height	Shape (k)	Scale (c)
m	–	m/s
63	2.181	10.42
91	2.163	10.86
116	2.139	11.14
141	2.111	11.34
166	2.085	11.56
191	2.056	11.71
216	2.033	11.85
241	2.014	11.99
266	2.003	12.14
291	1.986	12.27

Table A.5: Weibull parameters for 2024

Height	Shape (k)	Scale (c)
m	–	m/s
63	2.288	10.83
91	2.258	11.31
116	2.226	11.62
141	2.186	11.85
166	2.151	12.08
191	2.120	12.26
216	2.098	12.43
241	2.084	12.59
266	2.074	12.74
291	2.059	12.90

Table A.6: Weibull parameters for 2025

Height	Shape (k)	Scale (c)
m	–	m/s
63	2.340	10.53
91	2.299	10.92
116	2.268	11.15
141	2.239	11.34
166	2.215	11.51
191	2.190	11.66
216	2.173	11.81
241	2.157	11.93
266	2.147	12.06
291	2.138	12.18

A.4 Wind shear and veer

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

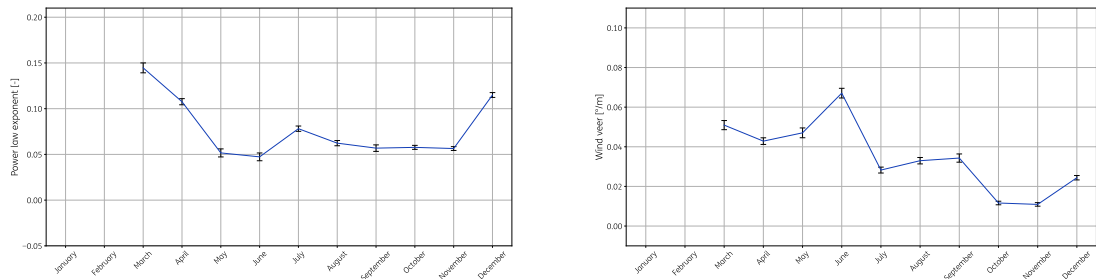


Figure A.7: Wind shear and veer as function of the month-of-year for 2023

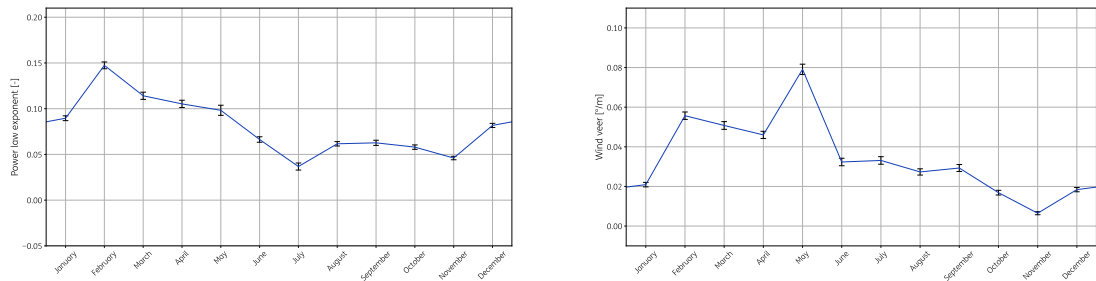


Figure A.8: Wind shear and veer as function of the month-of-year for 2024

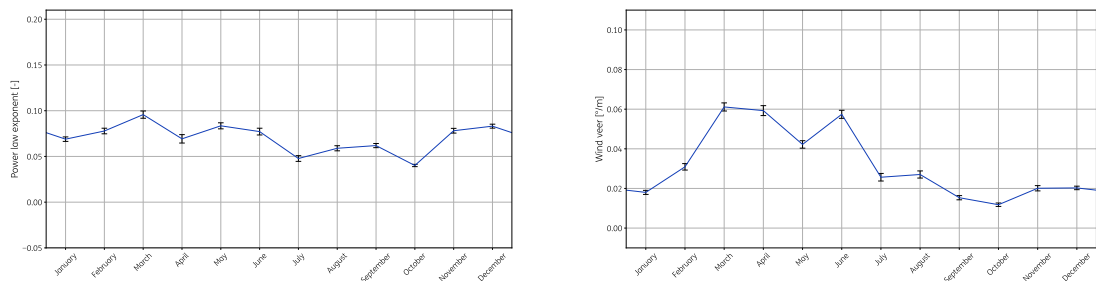


Figure A.9: Wind shear and veer as function of the month-of-year for 2025

A.4.2 Wind shear and veer as function of hour

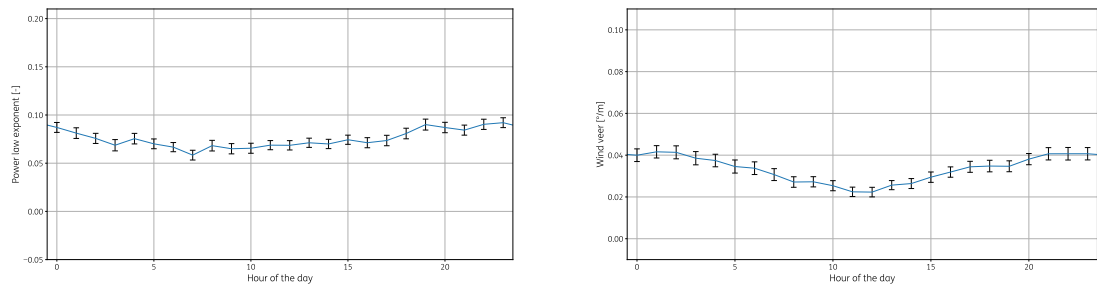


Figure A.10: Wind shear and veer as function the hour-of-day for 2023

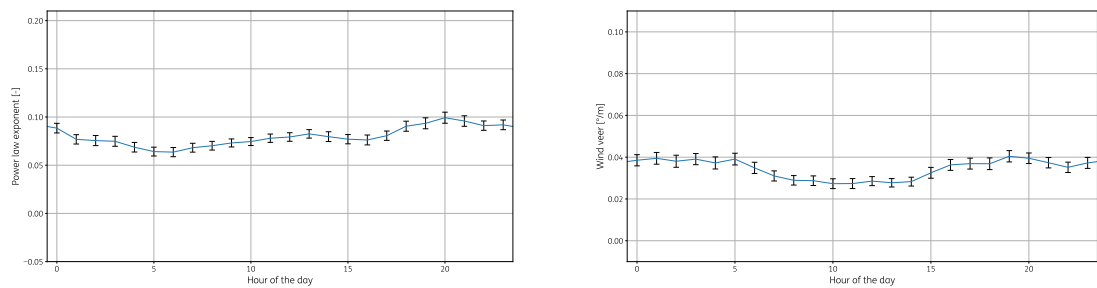


Figure A.11: Wind shear and veer as function the hour-of-day for 2024

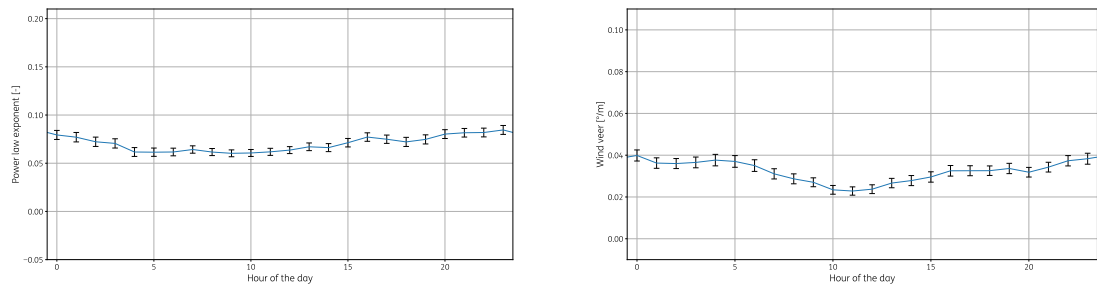


Figure A.12: Wind shear and veer as function the hour-of-day for 2025

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

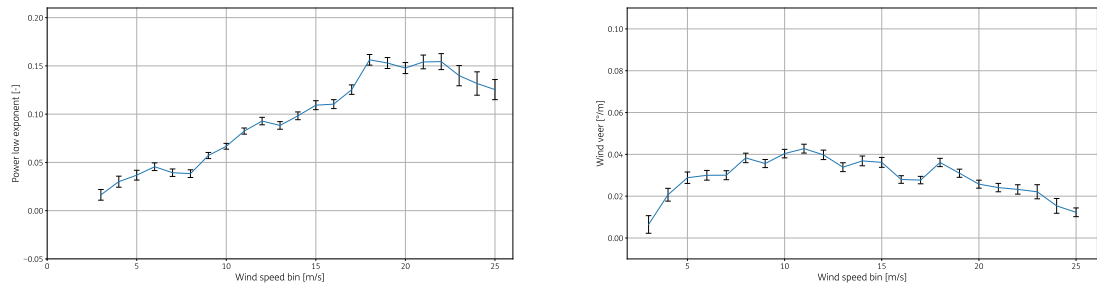


Figure A.13: Wind shear and veer as function of wind speed for 2023

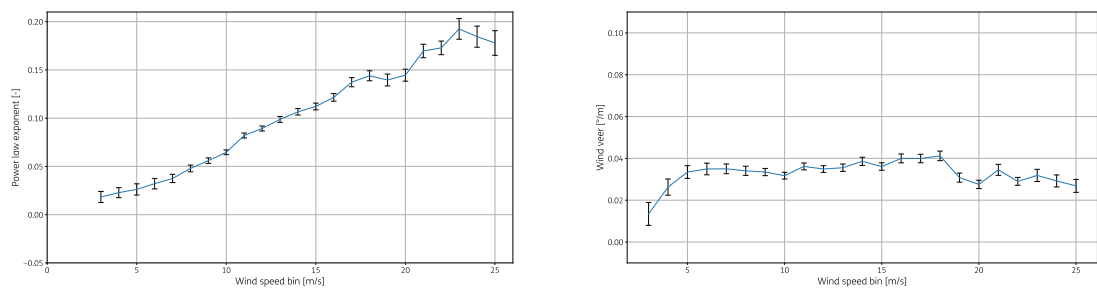


Figure A.14: Wind shear and veer as function of wind speed for 2024

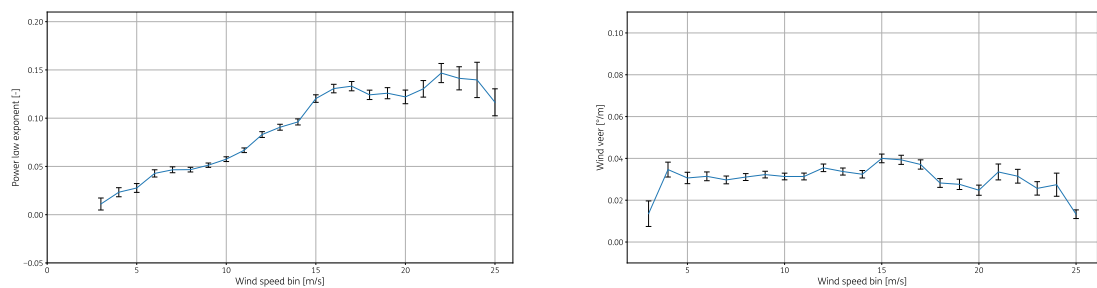


Figure A.15: Wind shear and veer as function of wind speed for 2025

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

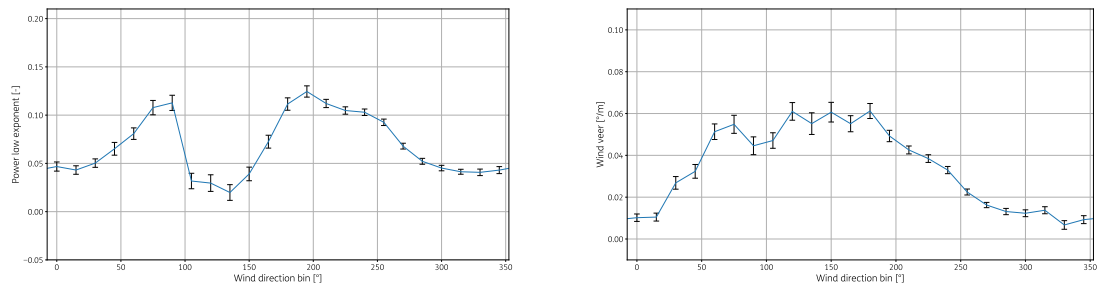


Figure A.16: Wind shear and veer as function of wind direction for 2023

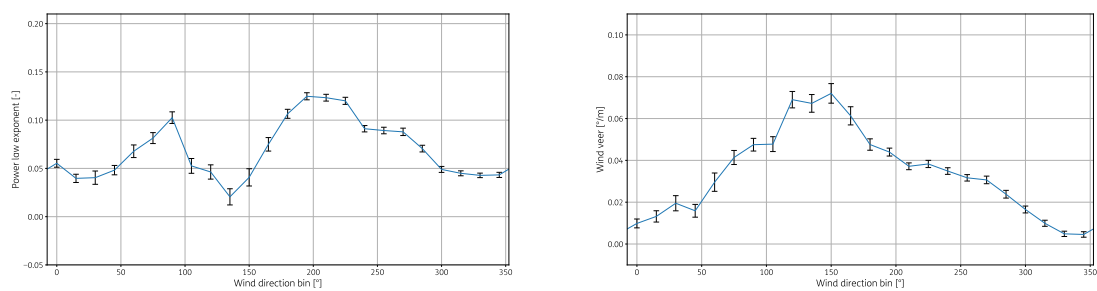


Figure A.17: Wind shear and veer as function of wind direction for 2024

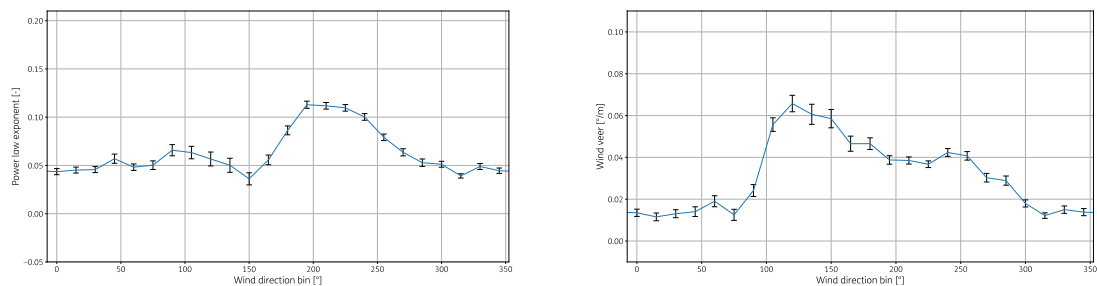


Figure A.18: Wind shear and veer as function of wind direction for 2025

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

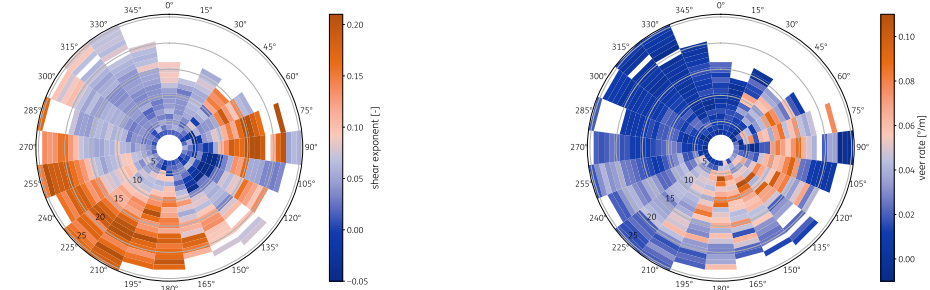


Figure A.19: Wind shear and veer as function of wind speed and direction for 2023

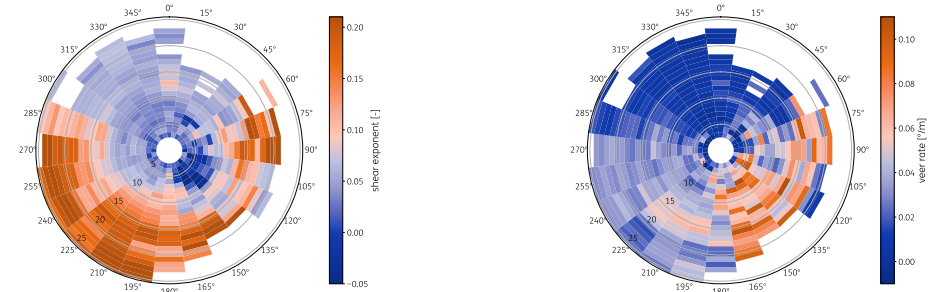


Figure A.20: Wind shear and veer as function of wind speed and direction for 2024

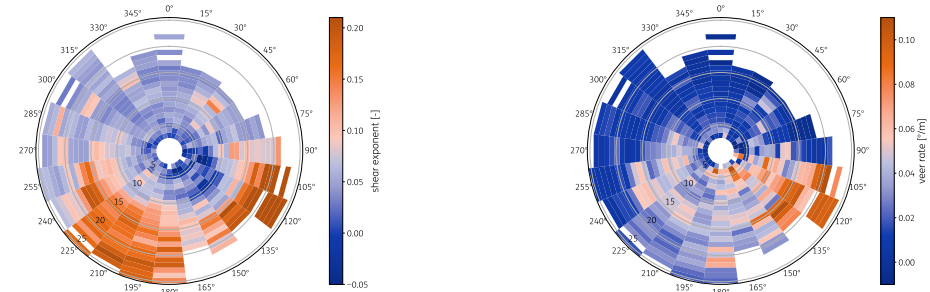


Figure A.21: Wind shear and veer as function of wind speed and direction for 2025

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