Offshore wind energy deployment in the North Sea by 2030: long-term measurement campaign. EPL, 2016-2022

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- NTF/NPC measurements according to IEC61400-12-2
- Mechanical loads measurements according to IEC61400-13
- Meteorological parameters (windspeed, wind direction, temperature, air pressure, relative humidity) conform to IEC 61400-12-1
- Verificaiton of ground-based or nacelle -mounted Remote Sensing Devices conform to IEC 61400-12-1, Appendix L
- Verification of Floating LiDAR conform to IEC 61400-12-1, Appendix L and IEA Recommended Practices 18

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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 add 4.5 GW by 2023 in a first phase, to further expand to 21.5 GW by 2030 . The Netherlands is moving ahead with yearly tendering rounds for upcoming development areas. Recently, the winners of the Hollandse Kust West development zones were announced at the end of 2022, and the most recent IJmuiden Ver tender has commenced in April 2023.

TNO has been performing offshore wind measurement campaigns at strategic locations in the North Sea since 2011 with the installation and data management of both a 100-meter met-mast and a co-located LiDAR situated 75 km west of IJmuiden. From 2014 onwards, TNO has further organized wind measurement campaigns with LiDARs on offshore platforms for the Dutch Ministry of Economic Affairs and Climate Policy. These campaigns are part of the “Wind op Zee” project to support the Dutch wind offshore roadmap. They consist of three longstanding locations: Lichteiland Goeree (LEG), Europlatform (EPL) and Wintershall platform K13a. Since March 15th 2023 a LiDAR has been deployed for wind measurements at a fourth platform, L2-FA-1, located north of the Wadden Islands. TNO is accredited for performing these measurements in accordance with IEC 61400-50-2.

This report refers to the offshore measurement campaign at the EPL platform where a ZX 300 LiDAR has been deployed, being continuously monitored, maintained, and providing high quality data since May of 2016. The data are publicly available, and can be retrieved by visiting www.windopzee.net.

At the EPL platform, the wind analysis for the 2016-2022 period shows that the wind profiles are dominated by the regional climate, mainly by the positive phase effect of North Atlantic Oscillation (NAO). The prevailing wind direction is from the southwest with a mean direction ranging from 228° to 237° across the different sensor heights (63 m to 291 m). The average calculated wind speed ranges from 9.05 m/s at the lowest measured height of 63 m up to 10.18 m/s at 291 m, increasing gradually.

The Weibull distribution, which describes the shape of measured wind frequency distribution and inter-annual variability, shows typical offshore wind shape and scale parameters for the North Sea (k = 2.052 and c = 10.945 m/s at the 141 m measurment height). The wind speed frequency distribution is flattened and moderately skewed right with higher heights, with more frequently occuring wind speeds greater than 26 m/s.

The resulting assessment of the shear profile shows an annualized range of 0.052 to 0.085 considering the entire data period between matched sequential sensor height pairs of the LiDAR. For the year 2022, the calculated day and night time shear was found to be approximately 0.08 and 0.07 respectively.

From February 16th to February 21st 2022, a triplet of storms hit the Netherlands with the most severe and powerful one being Storm Eunice on February 18th 2022. This storm was registered as the third most severe in the past 50 years. Wind speeds ranged between 25 and 35 m/s, and the sustained duration of extreme winds as a result of Storm Eunice dominates the entire top 10 list of recorded extreme wind speed timestamps, barring one occurrence on March 31st 2018.

Contents

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 add 4.5 GW by 2023 in a first phase, followed by deploying a further 21 GW by 2030 [2].The Netherlands is moving ahead with yearly tendering rounds for upcoming development areas. Recently, the winners of the Hollandse Kust West development zones were announced at the end of 2022, and the most recent IJmuiden Ver tender has commenced in April 2023 [3] [4].

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

One crucial requirement to evaluate the financing of a project is the wind resource assessment (WRAs) of a given site. Therefore, accurate long-term offshore wind measurements allow for improved estimations of WRAs by reducing uncertainties and increasing the financial success of a project. This increases the trust between the interested stakeholders including developers, consultants, the financial community, the government and policymakers. At the same time it allows the selection and identification of strategic locations.

TNO has been performing offshore wind measurement campaigns at strategic locations in the North Sea since 2011 with the installation and data management of both a 100-meter met-mast and a co-located LiDAR situated 75 km west of IJmuiden. From 2014 onwards, TNO has further organized wind measurement campaigns with LiDARs on offshore platforms for the Dutch Ministry of Economic Affairs and Climate Policy. These campaigns are part of the “MinvEZ 2023 Windconditions@northsea” project to support the Dutch wind offshore roadmap. They consist of three longstanding locations: Lichteiland Goeree (LEG), Europlatform (EPL) and Wintershall platform K13a. Since March 15th 2023, a LiDAR has been deployed at a fourth platform, L2-FA-1, located north of the Wadden Islands, is operational (**Figure 1**). TNO is accredited for performing these measurements in accordance with IEC 61400-50-2.

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

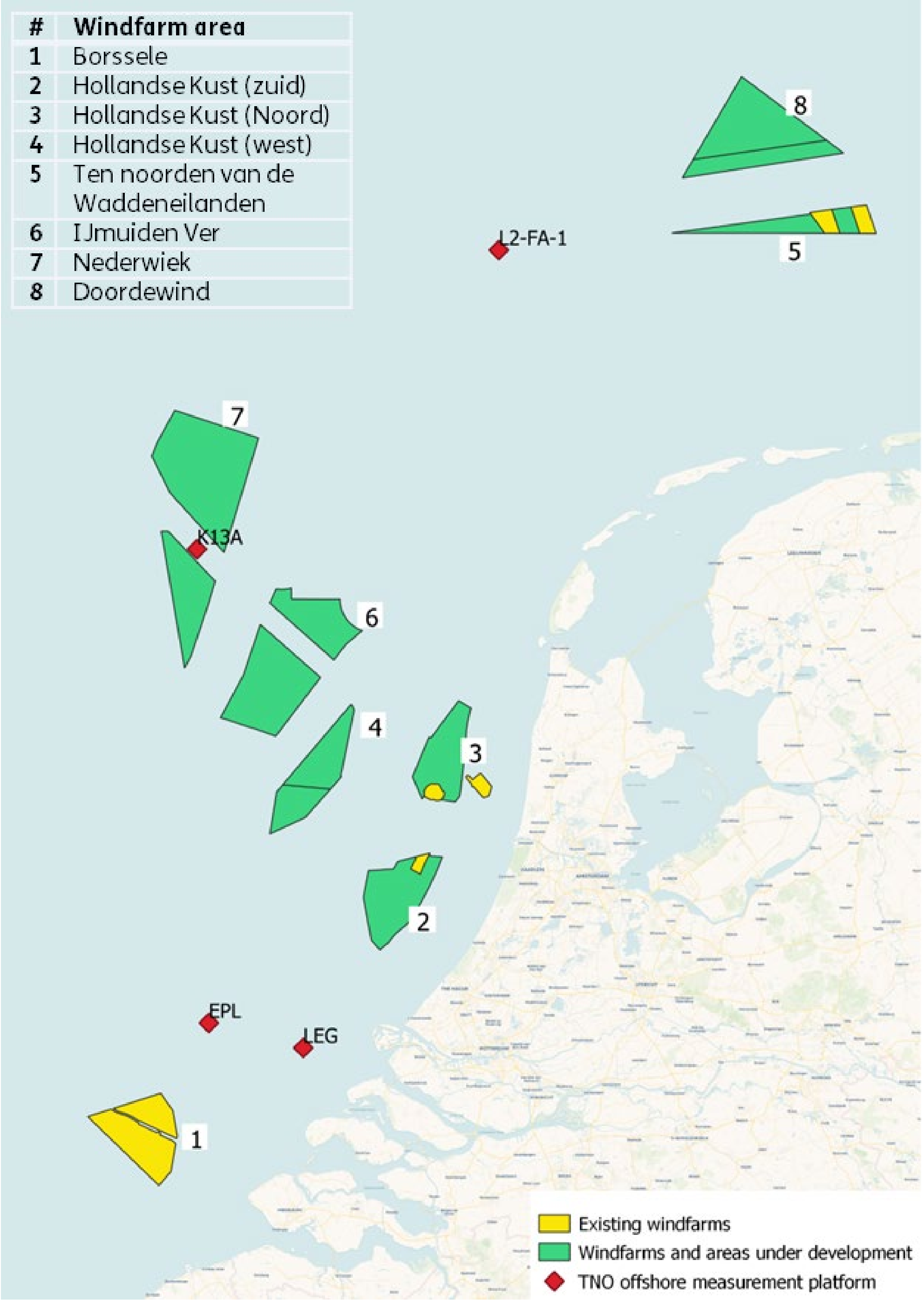

Figure 1:Illustration of TNO long-term offshore wind measurement campaign locations at Lichteiland Goeree (LEG), Europlatform (EPL) and Wintershall platform (K13a), and L2-FA-1, along with wind farm development zones in the Dutch North Sea

2 Wind Measurement Campaigns in the North Sea

2.1 TNO's leading role on offshore measurement campaigns

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

Onshore measurement campaigns are also part of the activities of TNO for more than 20 years, including independent ISO17025 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 (13MW). During the measurement campaign, TNO is responsible for the entire life cycle: from selection of the instrumentation and planning the installation, to the purchase, validation, installation, and maintenance of the LiDAR, as also analyzing, reporting and dissemination of the data.

2.2 Open-access and public datasets

TNO has published annual reports on the wind conditions for the Europlatform location (EPL) since 2020. These annual reports are referred to in Table 1, and they are available for download at https://www.windopzee.net/en/. This report includes the specific wind conditions for the period 2016-2022 at the EPL platform. This report has been updated with improved practices for deducing the wind direction, wind veer and wind shear.

Table 1 Publication History of Wind Conditions for EPL

Reference	EPL Wind Conditions Period
[5]	EPL platform for the periods 2016-2019
[6]	EPL platform for the periods 2016-2020
[7]	EPL platform for the periods 2016-2021

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

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

1. Citation to the instrumentation report *with the type of data used, location and date:*
   Bergman, G., Verhoef, J.P., Werkhoven E., P.A. van de Werff (2022) Europlatform LiDAR measurement campaign; Instrumentation Report 2022, TNO 2022 R11776
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The publication date at which the data have last been accessed must be indicated along the citations (e.g. *Last accessed April 2023*).

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

- Navigate to the web-service https://nimbus.windopzee.net/, select the platform of choice and log in (free registration)
- For monthly files: EPL-yyyy-mm.CSV
- After a quarter of a year is completed the monthly files will be replaced by: EPL-yyyy-Qx.CSV
- After the year is completed the quarterly files will be replaced by a yearly file as: EPL-yyyy.CSV.

3 Measurement campaign at EPL

3.1 Location and instrumentation

The Europlatform (EPL) is located about 60 km from the coast of Hoek van Holland (**Figure 1**). It includes both a helicopter pad and an accommodation deck (**Figure 2**). The platform is part of the North Sea Monitoring Network consisting of several permanent monitoring locations over the North Sea.

The LiDAR was in installed in May 2016 for measuring the wind conditions and other signals are collected as well. 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.

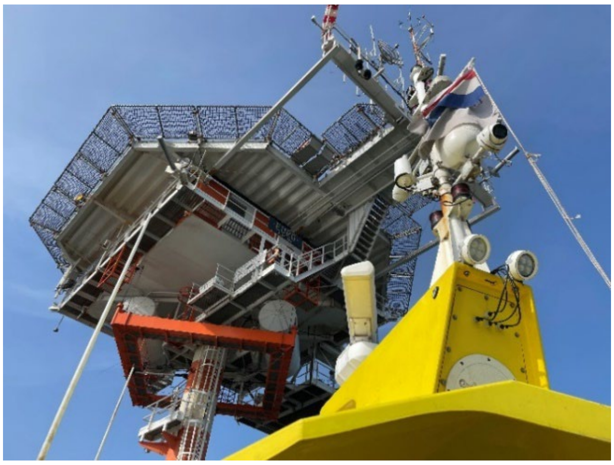


Figure 2: View of the Europlatform (EPL), March 2022

TNO has been conducting an ongoing measurement campaign at EPL since 2016, and has accumulated not only important meteorological data, but has also gathered a collection of imagery regarding installation practices, maintenance, replacement, and observations of weather conditions that have occurred at the site. **Figure 3** shows the LiDAR installed at its location on the platform, after being recently replaced on March 22nd, 2022.

Figure 3: View of LiDAR unit following replacement in March 2022 at EPL

3.2 Installation plan of instrumentation

The initial phase of a measurement campaign is formed by the evaluation of the platform to place the LiDAR on. This evaluation is described in the installation plan of the instrumentation, which provides a description of how the measurement equipment will be mounted and the agreement with Rijkswaterstaat about the installation and safety measures required. The second phase includes onsite installation, electrical infrastructure and the operational activities (control, maintenance and replacements of the instrumentation, quality control of the measured data). Health and safety aspects are also part of the measurement campaign activities.

To ensure good quality measurements it is crucial to select the right location for the LiDAR on the platform. The description and information regarding the installation at the EPL platform has been recently updated and described in the installation report [8]. At EPL, the suitable place was found in the west side of the platform in a newly built extension of near an escape ladder between the landing and the deck (**Figure 4** a, b). The LiDAR was installed with the 'North' marker pointing towards the platform North which is aligned to true North (**Figure 4** c, d).

Figure 4: a) Front and b) top view of EPL platform (geographical coordinates 51° 59' 52.512" N, 3° 16' 29.316" E) including a helicopter deck at a height of 18.78m above mean sea level with an accommodation deck below; c) original escape ladder location before the LiDAR installation and d) built extension to install the LiDAR.

3.3 Onsite installation and operational status

The LiDAR selected is a ZX 300 LiDAR. This remote sensing device measures wind profiles up to 10 different heights by conically emitting a laser beam into the air, even if an object blocks the laser beam at some positions (see Annex A for additional LiDAR specifications). Before the installation in 2016 and 2018, 2019 and 2022, the LiDAR was first verified at the LiDAR calibration facility, ECN Wind Energy Facilities B.V. [9] [10] [11] [12]. To ensure good quality measurements it is crucial to select the right location for the LiDAR on the platform.

The LiDAR was installed to provide measurements at 10 different heights between 63 m and 291 m above mean sea level. The data is timestamped at the start of the 10-minute time frame. This is the same configuration as for the LiDAR's at other measurement locations like LEG and K13a platforms. Manufacturers guarantee data quality up to 200 m above the LiDAR although the ZX300 can measure beyond that height. The analysis of the data at highest measurement levels shows the same quality patterns as at the guaranteed heights (see section 4 and 5).

Two different electrical connections are required in order to have the LiDAR fully operational:

- 230V AC power supply connection, provided at the computer room of the platform where the AC-DC power converter of the LiDAR is placed.
- A network connection, as the LiDAR is connected by ethernet cable to a TNO laptop located in the computer room.

As defined by TNO's ISO17025 quality system, the LiDAR should be serviced after one year of operation and replaced every two years (**Table 2**). All operational aspects with respect to installing and maintaining the LiDAR are recorded in a logbook of the team responsible for the measurement campaign.

During 2022, the overall availability at all heights was observed to be higher than in previous years, with improvements mainly due to the installation of the new lidar U315 from March 22nd 2022 following its schedule replacement cycle.

Table 2: Replacements of LiDAR at the EPL platform.

Id LiDAR	LiDAR in operation	Reason of replacement
U308	10-05-2016 to 02-08-2018	Periodical replacement , First LiDAR operational
U315	02-08-2018 to 23-10-2019	Malfunction power supply of LiDAR
U308	23-10-2019 – 22-03-2022	Periodic replacement with the original LiDAR inspected and verified its performance.
U315	22-03-2022 - Present	Periodic Lidar Replacement. Maintenance visit conducted on February 27th , 2023

3.4 Health and safety measures

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

- 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.

4 LiDAR performance assessment at EPL

Remote sensing devices bring many advantages such as ease of transportation, measurement capabilities beyond meteorological mast configurations, etc. 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. Data measured are classified into two categories of availability:

- **System availability**, not influenced by meteorological events, independent to the height: internal temperature of the LiDAR, availability and wiper activation count.
- **Signal availability** at different heights; wind speed and direction, horizontal and vertical and the standard deviation of wind and carrier to noise ratio. The heights considered are 63, 91,116,141,166,191,216,241,266 and 291 m.

The data is measured on a 10-minute basis. The data collection period started from 31st of May 2016 at 00:00 UTC (Universal Time Coordinates). This report considers the measurement period until the 31st of December 2022 at 23:50 (UTC). The campaign is still ongoing, with future yearly assessments envisioned.

Table 3: List of variables measured in the LiDAR during the experimental campaign. Where EPL is the platform; HXXX are the different heights measured above mean sea level(MSL): 63, 91,116,141,166,191,216,241,266 and 291 m.

Acronym	Signal name	Units
EPL_batvoltage	Battery Voltage	V
EPL_tempcpu	CPU temperature inside the LiDAR	deg C
EPL_humpod	Relative Humidity inside the LiDAR	%
EPL_bearing	LiDAR Bearing	Deg
EPL_tilt	LiDAR tilt angle	Deg
EPL_pair	Air Pressure at LiDAR position	hPa
EPL_wsmet	Wind speed measured by LiDAR meteo station	m/s
EPL_wdmet	Wind direction measured by LiDAR meteo station	Deg
EPL_HXXX_npts	Measuring points	
EPL_HXXX_missed	Missed points	
EPL_HXXX_npackets	Packets in fit	
EPL_HXXX_Wd	Wind direction	Deg
EPL_HXXX_Wshor_avg	Horizontal wind speed average	m/s
EPL_HXXX_Wshor_std	Horizontal wind speed standard deviation	m/s
EPL_HXXX_Wshor_min	Horizontal wind speed minimum	m/s
EPL_HXXX_Wshor_max	Horizontal wind speed maximum	m/s
EPL_HXXX_WsVer_avg	Vertical wind speed average	m/s
EPL_HXXX_cs	CS	

Acronym	Signal name	Units
EPL_HXXX_BackScatter	Back Scatter	

The ZX 300 does not determine the direction of the Doppler shift in the received signal and therefore there is a 180° ambiguity in the wind direction. The attached met station with wind speed and direction measurements (EPL_wsmet and EPL_wdmet, **Table 3**) is used by the LiDAR to correct the 180° offset (See Annex A for more specifications). The overall system availability and the overall data availability for the whole campaign is evaluated following [10], based on the Offshore Wind Accelerator roadmap [13].

Data over the whole period of the measurement campaign has been analysed in previous reports. The estimation of the measured availability follows the approach by [10]. As indicated in **Figure 5** and **Table 4** (and Annex A); the data availability with the ZX 300 at the EPL platform is independent of height from May 2016 to April 2019. **Table 4** also shows a lower availability of the all sensors from 2018 to 2021, ranging from 55% to 73% (despite the yellow colour which defines an availability lower than 80%). In 2022, the availability improves to a range of 75% (upper most sensor – 291m) to 84% (heights below 216m). This is due to the LiDAR replacement in March 2022, with higher reported data availability following the installation as observed in **Figure 5**.

Table 4: Data measured availability (in %) by height and by year. Data >80% available in green, <80% in yellow, and in red not available data.

Year	H 63 (%)	H 91 (%)	H 116 (%)	H 141 (%)	H 166 (%)	H191 (%)	H 216 (%)	H 241 (%)	H 266 (%)	H291 (%)
2016	87.9	87.9	87.9	87.9	88.0	88.0	88.0	88.0	88.1	88.1
2017	81.6	81.6	81.6	81.5	81.5	81.4	81.4	81.3	81.3	81.3
2018	68.0	68.0	68.0	68.0	68.0	68.0	67.9	67.9	67.9	67.9
2019	63.4	64.3	64.6	64.6	64.4	63.7	63.0	62.2	61.1	60.0
2020	68.4	71.1	72.3	72.4	71.9	70.7	69.3	67.3	64.4	61.6
2021	65.9	67.9	68.7	68.6	68.0	66.5	64.7	62.5	58.9	55.8
2022	80.8	82.8	83.9	84.0	83.8	83.1	81.8	79.6	77.2	75.1

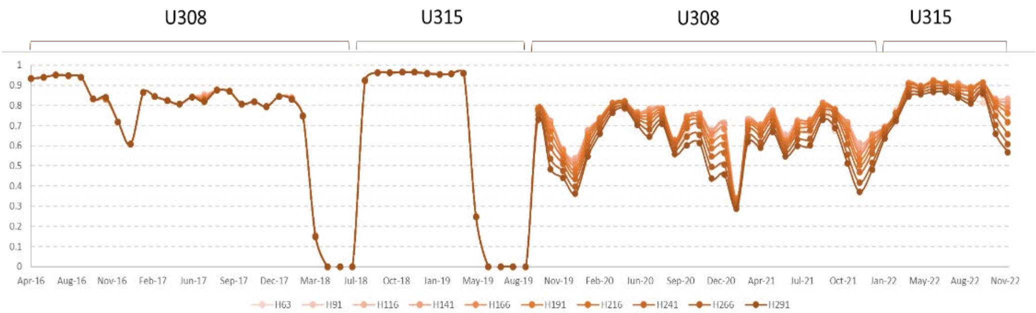


Figure 5: Monthly averages of the data available (fraction based) measured by the ZX 300 LiDAR by height at the EPL platform for the period 2016-2022.

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

Figure 6 shows the monthly average number of points measured, which also aligns with the overall number of packets used in the calculation of monthly availability shown in **Figure 5**.

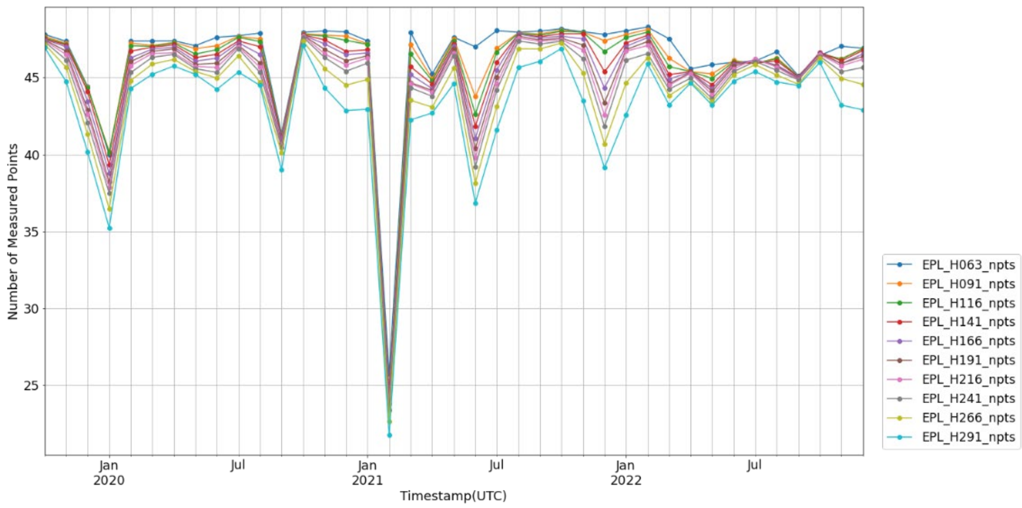


Figure 6: Monthly number of points measured over the measurement period of October 2019 to December 2022.

5 Wind conditions at EPL

This section presents the results following an assessment of the weather conditions during the measurement campaign at the EPL platform for the entire period of 2016-2022. The main meteorological characteristics are presented in the form of dominant wind directions and wind speed distributions for different heights; temporal variation and the descriptive statistics. Shear and veer were also assessed for different sensor heights. A complementary analysis on the annual and monthly weather conditions at EPL is included in Annex B.

5.1 Weather conditions during the period 2016-2022

Numerous oceanic effects influence the wind conditions on the North Sea including the large-scale atmospheric circulation North Atlantic Oscillation (NAO), the North Atlantic low pressure systems, and the tides. Continental effects in the form of freshwater discharge, heat flow, and input of pollutants can also effect ocean conditions, and further highlight how delicate and interconnected the climate system really is.

The atmosphere mainly controls the general circulation of the North Sea via heat fluxes and their variability. The dominant effect is the positive phase of NAO, which is characterized with higher air temperatures and stronger westerly winds over the North Sea. This induces both higher water temperatures and sea levels. A thermal stratification is generated in the northern and central parts during early summer and remains until early autumn, when stronger winds mix the water again [14] [15].

At the EPL platform, the weather analysis for 2016-2022 shows that the wind profiles are dominated by the effects of the positive NAO.

The calculated mean of monthly mean (MoMM) wind speed ranges from 9.05 m/s at the lowest measured height of 63 m up to 10.18 m/s at 291 m, increasing gradually. The wind direction was calculated considering the average unit wind direction vector. The dominant direction is from the southwest, measuring between 228° to 237° degrees (**Table 5**). The wind roses presented in **Figure 7** clearly show the dominant wind direction sector for all the heights from the southwest and also that wind speeds with higher intensities (mean wind speeds above 22 m/s) are observed at higher sensor heights.

Table 5: Average wind speed (Ws) and direction (Wd) at different heights for the 2016-2022 period at the EPL platform.

H (m)	63	91	116	141	166	191	216	241	266	291
Ws – Min	0.39	0.32	0.32	0.33	0.32	0.3	0.31	0.31	0.3	0.31
Ws - Mean	9.05	9.35	9.52	9.67	9.79	9.89	9.97	10.04	10.11	10.18
Ws - Max	39.07	39.16	38.56	38.17	39.22	36.86	42.47	47.06	56.89	44.28
Wd - Mean	227.7	228.5	229.3	230.4	231.5	232.7	234.0	235.0	235.8	236.6

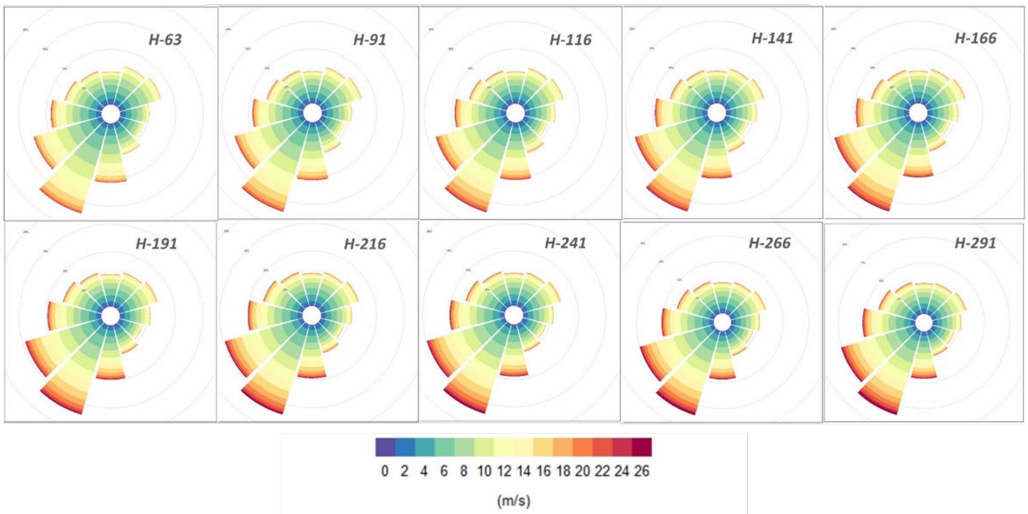


Figure 7: Wind roses at different heights showing the wind prevailing direction for the 2016 - 2022 period.

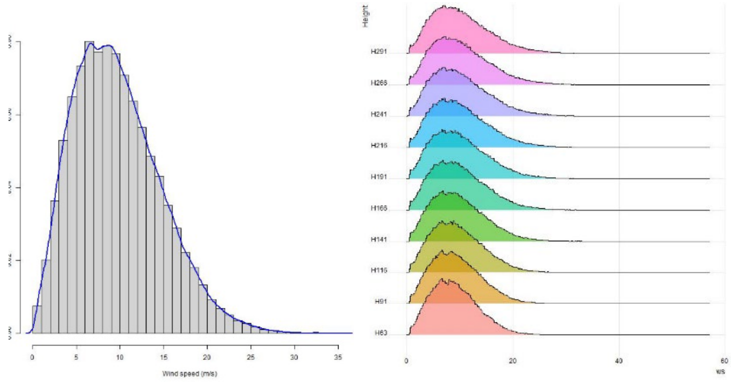
Wind regime frequency distributions and the intra-annual variability typically represented by the Weibull probability density function. This two-parameter relationship between probability of occurrence for a given wind speed v (in m/s), shape dimensionless parameter, k, and scale parameter, c (in m/s) is expressed by the following formula:

$$f(v;k,c) = \frac{k}{c}\left(\frac{v}{c}\right)^{k-1} \exp\left[-\left(\frac{v}{c}\right)^{k}\right] \text{ for } v > 0 \text{ and } k, c > 0 \quad (1)$$

The shape parameter (as implied from its name) provides information on the overall shape of the Weibull distribution and is inversely proportional to wind variability. This implies that a large k value indicates less wind variability. The scale parameter is proportional to the average of the wind speed of the distribution and therefore also increases with height.

Over the period 2016-2022 at EPL, the best approximation of the Weibull function at 141 m height yields a shape parameter of 2.052 and a scale parameter of 10.945 m/s (see the table of Figure 8). Due to the impact of seasonality on the results, the years 2016, 2018 and 2019 were excluded due to incomplete years caused by the start of the campaign or to poor overall availability over months. Figure 8 (left) shows the wind speed frequency distribution, and the Weibull probability density function fitted over the distribution.

Figure 8 (centre) indicates the frequency distribution of the wind speed for each measurement height and shows how the distribution is flatter and skewed right when increasing in sensor height, as reflected by the height specific shape and scale parameters presented in **Figure 8** (table). A reduction in the shape parameter implies less variability, while the increase in scale parameter indicates higher wind speeds, as expected. Typical shape parameters of approximately 2 are representative of the wind conditions of the Dutch part of the North Sea.



Height (m)	Shape (k)	Scale (c)
63	2.150	10.224
91	2.113	10.566
116	2.082	10.770
141	2.052	10.945
166	2.025	11.083
191	2.003	11.200
216	1.984	11.301
241	1.968	11.392
266	1.959	11.486
291	1.949	11.578

Figure 8: Frequency distribution and Weibull curve fitting at 141 m height (left), frequency distributions at different heights for the measurement campaign (centre) with k and c parameters (table) at EPL for 2016-2022. **Note:** The years 2016, 2018 and 2019 were excluded due to incomplete years caused by the start of the campaign or to poor overall availability.

The **Figure 9** presents the seasonal variation on both annual and diurnal cycle at different sensor heights. Timestamps with a wind speed of less that 3m/s were also excluded from the wind direction data considered . Then, the wind speed and wind direction timeseries of each height were matched together to established a common data period across all heights. The data were then grouped and averaged to the required period (hourly, monthly). A pattern can be observed both for wind speed and direction at different heights. The wind direction was calculated considering the average unit wind direction vector.

On an annual cycle, there is a decrease in the mean monthly wind speed of approximately 6 m/s from winter to summer months, due to the change in temperatures over the sea surfaces along the year. The seasonal changes of the wind resource are mainly dominated by the heat flux and by vertical mixing caused by the lower-atmosphere and land energy balance. The wind direction is quite consistent at approximately 200 - 250 degrees year round, except for the month of April, where the winds predominantly come from the northeast.

Considering the diurnal cycle at the EPL platform, the offshore wind speeds vary within margins of about 1.0 m/s and of approximately 20 degrees in wind direction depending on height. The average wind direction is higher in the afternoon hours of the diurnal cycle, and more consistent among heights that in the evening and morning hours.

The wind conditions analysed in this report are in line with the assessment presented in [16], [17]. Such studies present additional description over the temporal variability of horizontal and vertical wind profiles at different offshore locations over the Dutch part of the North Sea.

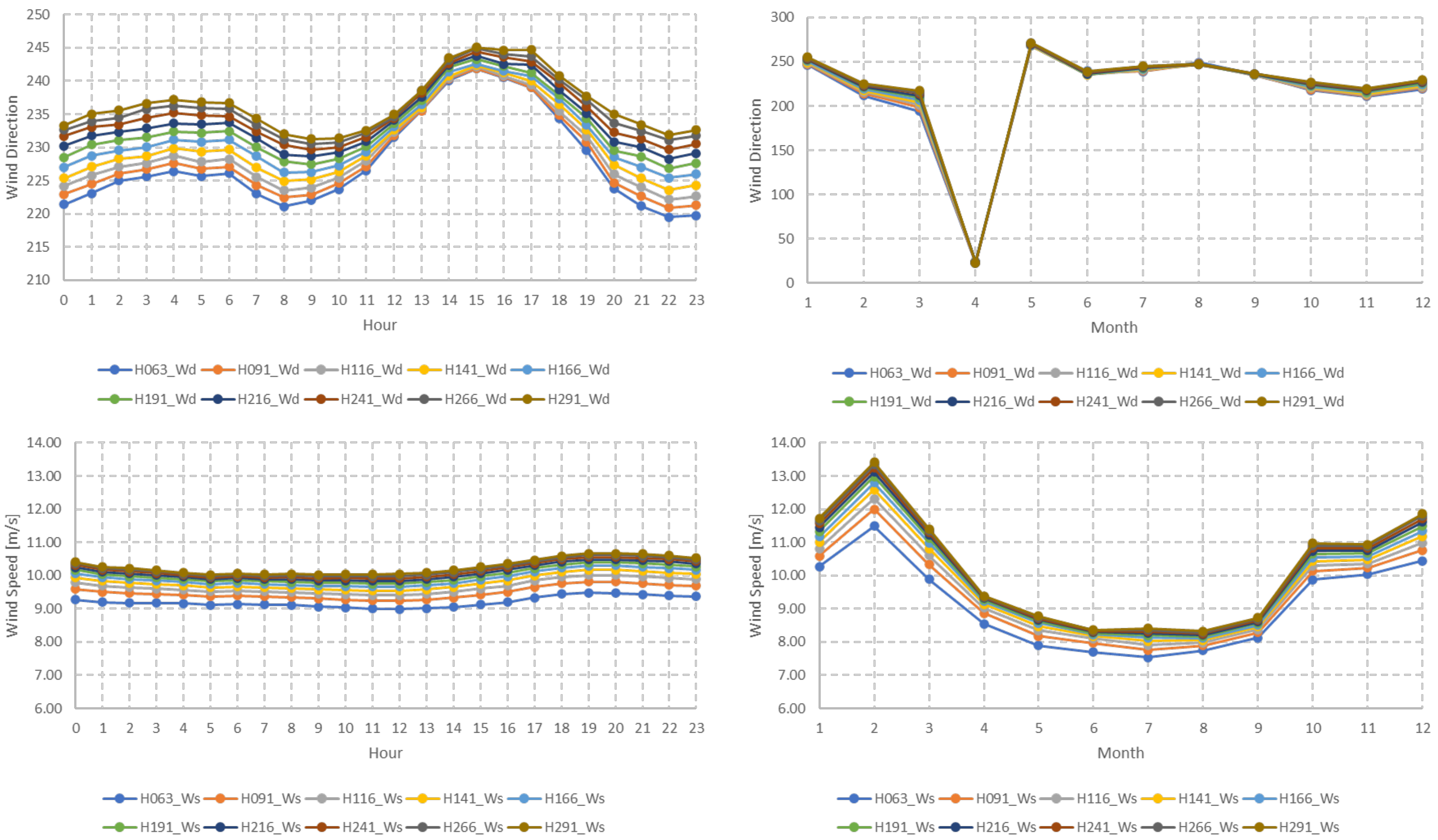


Figure 9: Matched and filtered wind speed and direction monthly averages (right) and average diurnal cycles (left) at different heights for the 2016-2022 period.

5.2 Annual wind statistics

In regards to the wind regimes and intra-annual variability; **Figure 10** presents the annual Weibull distribution shape and scale parameters for all heights of each successive year to the present one. It is possible to observe the variability in both parameters for each year compared to the entire period. Data from the year 2022 shows higher scale values compared to 2021 values, but are still lower compared to the windiest years of 2018-2020. However, the data from 2018 and 2019 were limited in data availability during the summer months when the wind speed tends to be lower, thus higher overall values were observed. For the shape parameter, which is inversely proportional to wind variability, the year 2022 measurement period is in line with the year 2020 showing lower values, and thus meaning higher wind availability. Again, the year 2018 and 2019 show very high values due to low data availability in the summer periods.

The annual measured frequency distributions at different heights are shown for 2022 in **Figure 11**, with previous years presented in Annex B. Annual statistics are further provided in **Table 6**. These statistics are influenced by the available months of data, and do not account for seasonality.

Assessing the temporal evolution, **Figure 12** shows the monthly averaged wind speeds for each individual year. Monthly trends are in line with expectations - the months with highest wind speeds occurred in winter periods. The year 2022 is characterized as mentioned above by lower wind speeds in the winter months of December and January compared to the previous years, and with exceptionally higher wind speeds observed in November and February. The lowest wind speeds were registered in summer in June, and were below most summer months compared to other years. Annex B includes additional annual wind analysis and statistics for the EPL platform.

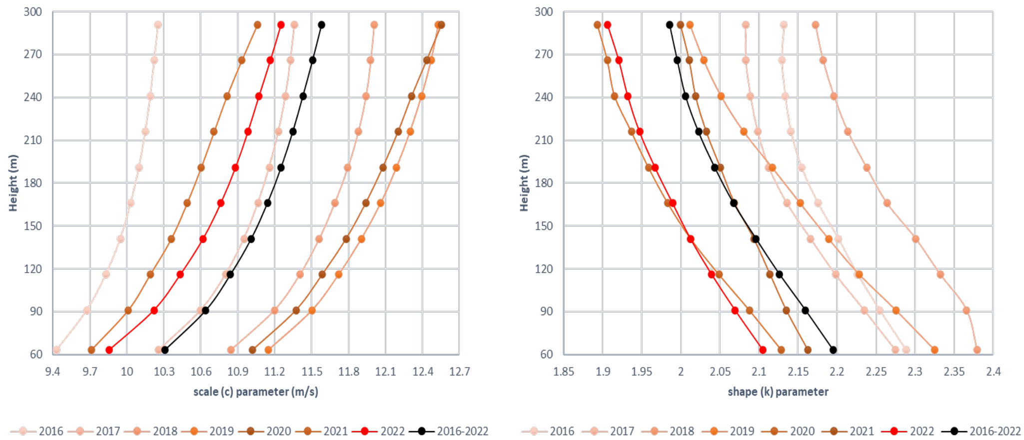


Figure 10: Annual Weibull (left) scale and (right) shape parameters at different heights at the EPL platform from 2016 to 2022.

Table 6: Descriptive annual statistics of the wind speed (Ws) and wind direction (Wd) at 141 m height at the EPL platform.

H141 (m)	2016	2017	2018	2019	2020	2021	2022
Ws (m/s)- Min	0.68	0.68	0.66	0.45	0.34	0.33	0.38
Ws (m/s)– 1st q	5.94	6.10	6.75	6.84	6.31	5.76	5.66
Ws (m/s)- Median	8.95	9.24	9.85	9.97	9.96	8.65	8.70
Ws (m/s)- Mean	9.43	9.70	10.25	10.54	10.45	9.17	9.40
Ws (m/s)- 3rd q	12.46	12.92	13.41	13.85	13.96	11.84	12.45
Ws (m/s)– Max	31.85	30.16	38.17	29.10	33.23	29.74	35.46
Wd (°)- Mean	220.2	238.9	207.6	221.2	224.6	265.9	232.0

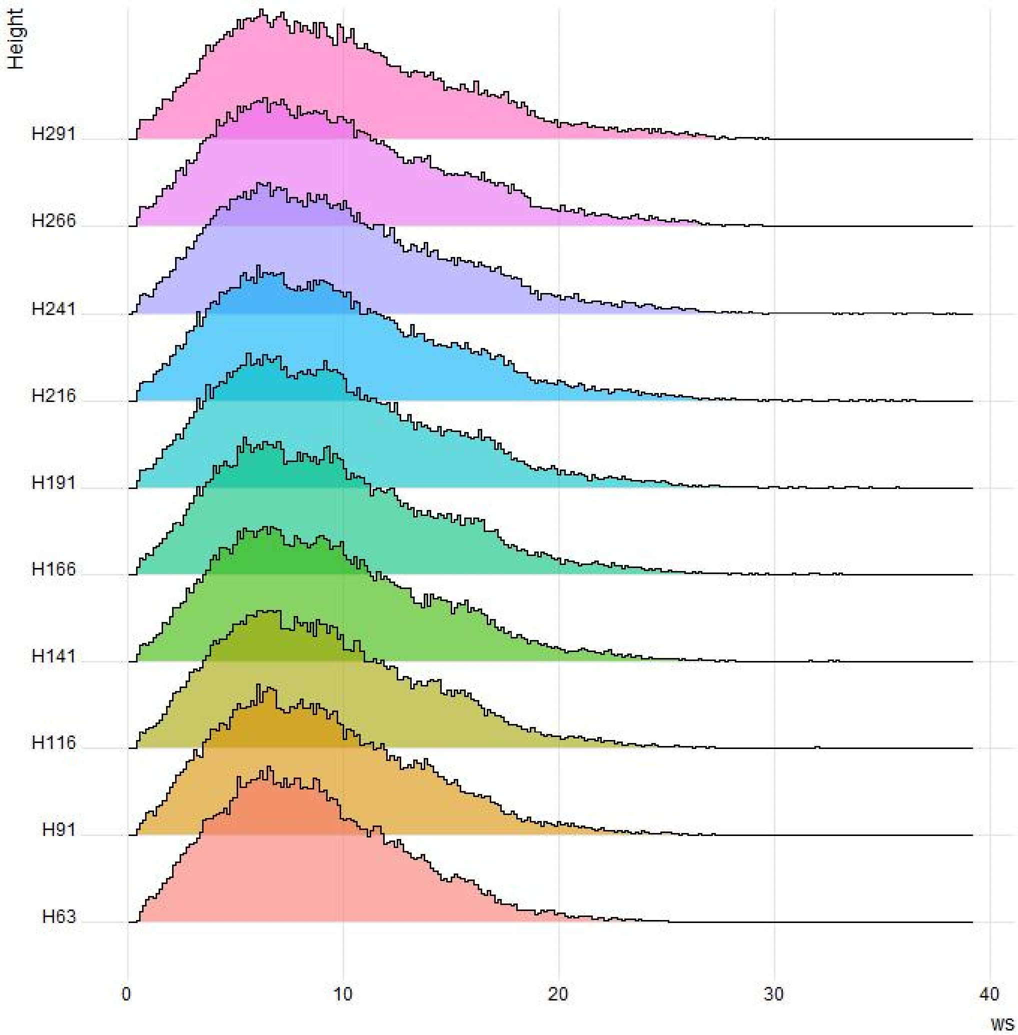


Figure 11: Annual frequency distribution derived for different sensor heights for the year 2022.

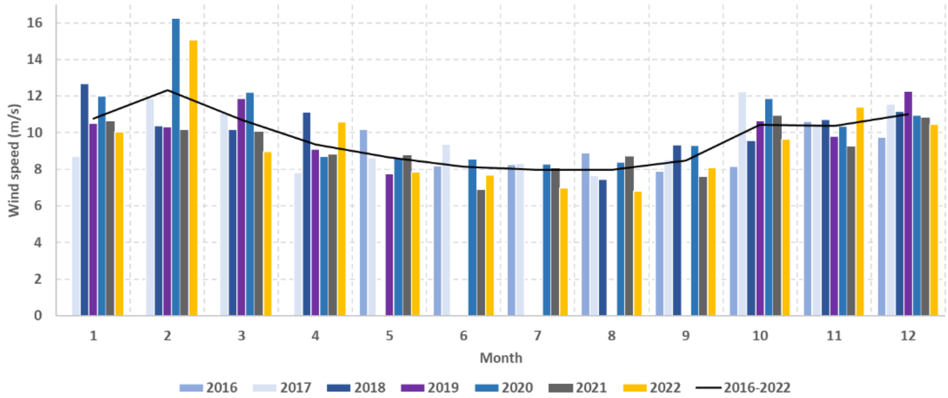


Figure 12: Annual wind speed (m/s) monthly average bars at 141 m height and 2016-2022 monthly average (black line). **Note:** low availability in 2018 and 2019 between May and August.

5.3 Analysis of wind shear and veer

Wind shear is described as the variations of wind speed with respect to height, and is an important characteristic of the wind resource since it impacts the assessment of wind speeds from measurement heights to the proposed hub heights for wind turbine technologies. Furthermore, as wind turbines are designed to operate at taller hub heights and with larger rotor blades, the impact of shear on both energy production and loading needs to be accounted for in the design process.

Wind shear can be described by the power law. This function relates the ratio of wind speeds, V_o and V_h, between their respective heights, H_o and H_h, by the shear exponent, α, as expressed below:

$$\left(\frac{V_h}{V_o}\right) = \left(\frac{H_h}{H_o}\right)^{\alpha} \quad (2)$$

There are complementary reports with data verification comparing with other wind resource measurements. In particular, [16] examines the wind speed and direction measurement campaigns at eight offshore measurement locations distributed throughout the North Sea, including the EPL platform. The study focuses on comparing the wind shear and veer from 2012 to the first quarter of 2018 with the aim of better understanding the wind conditions over the North Sea. The analysis is also a part of the data verification process.

LiDAR measurement data is programable to collect wind speed data at many more heights compared to standard meteorological measurement towers, and thus important insights into the shear profile between different levels can be acquired. The data between consecutive pairs were first matched to established a common data period (adjusting for availability of the timeseries) then wind speeds were grouped and aggregated over different periods (hourly, monthly, yearly). Finally the shear exponent was calculated using Equation 2 on the average values of the chosen period.

Table 7 shows the sensor pairs and the resulting matched annualized shear values over the entire data period (based on the wind speed mean of monthly means). Here the matched annualized shear exponent regardless of direction, range from 0.052 to 0.085, indicating possible shear relaxation with an increase in height.

Figure 13 shows the directional shear profile for different sensor height pairings for the entire data period of 2016 to 2022. The variation of shear exponent by direction is noticeable, ranging from over 0.10 from southwest direction to negative shear in the northeastern and south eastern directions. Shear exponents are tightly bound and consistent from the south to north western directions, which are in line with the prevailing wind regime for the site. Larger variations in shear are seen from the north east to the south east, with higher sensor pairs demonstrating negative shear, hence a reduction of wind speed with height.

Shear can be observed on a monthly and hourly basis. **Figure 14** presents these variations for each sensor level pairing. It can be seen that shear is highest in the evening and night hours, and lowest in the early mornings. Shear exponents were higher in the winter months, while lower in the summer months.

Figure 15 presents the extrapolated shear exponent considering the average wind speeds for each height for the year 2022, distinguishing between daytime and nighttime hours. During the night a lower shear exponent and higher wind speeds are observed. This observation can be explained by the lower part of the atmosphere being more stable during the night.

Table 7: Annualized shear exponent for different sensor height pairings at EPL over the entire data period, 2016 to 2022.

Shear Pairing	Shear exponent
63 m to 91 m	0.085
91 m to 116 m	0.075
116 m to 141 m	0.076
141 m to 166 m	0.071
161 m to 191 m	0.067
191 m to 216 m	0.064
216 m to 241 m	0.059
241 m to 266 m	0.054
266 m to 291 m	0.052

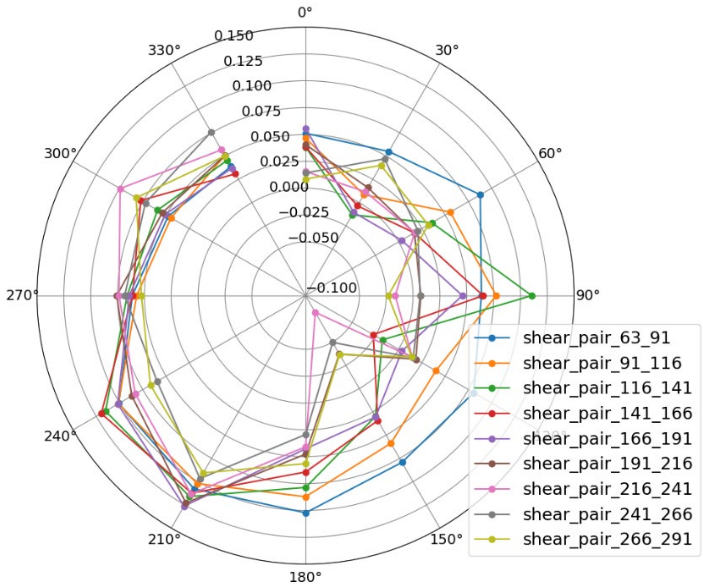


Figure 13: Directional shear profile trends for LiDAR sensor pairings for the entire data period 2016-2022

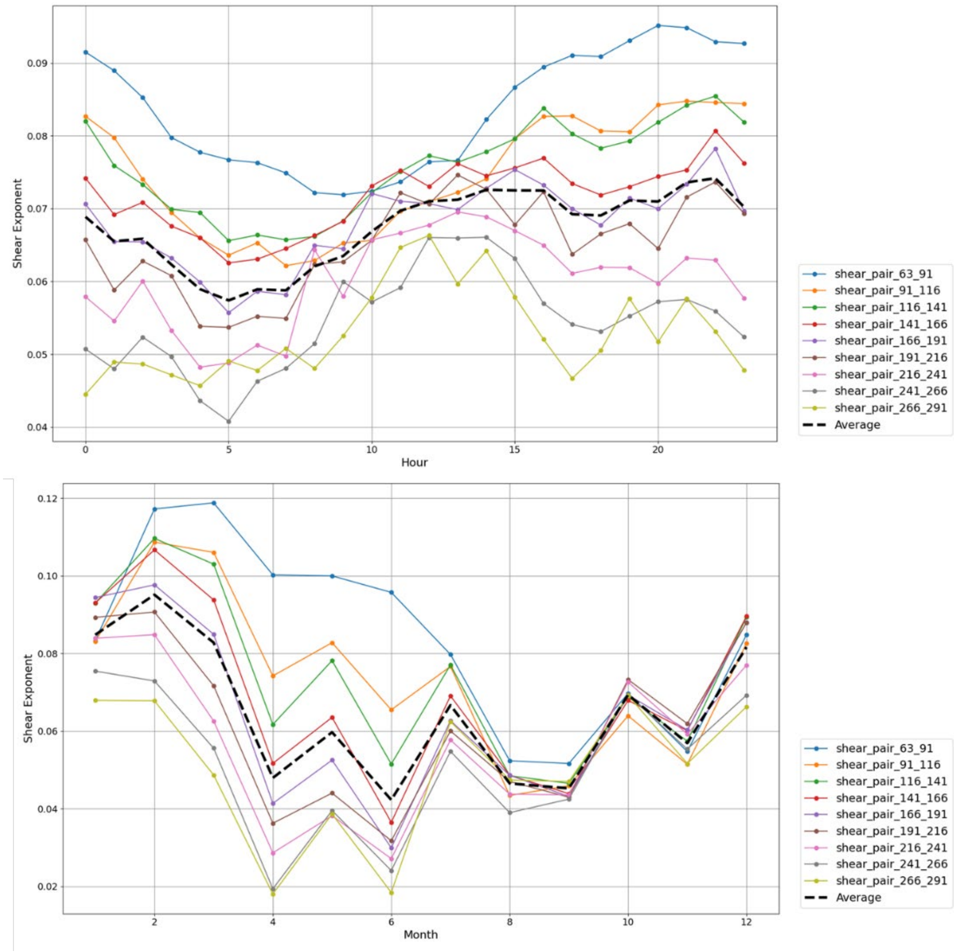


Figure 14: Shear profiles for LiDAR sensor pairs showing diurnal (top) and annual (bottom) trends for the data period of 2016 to 2022

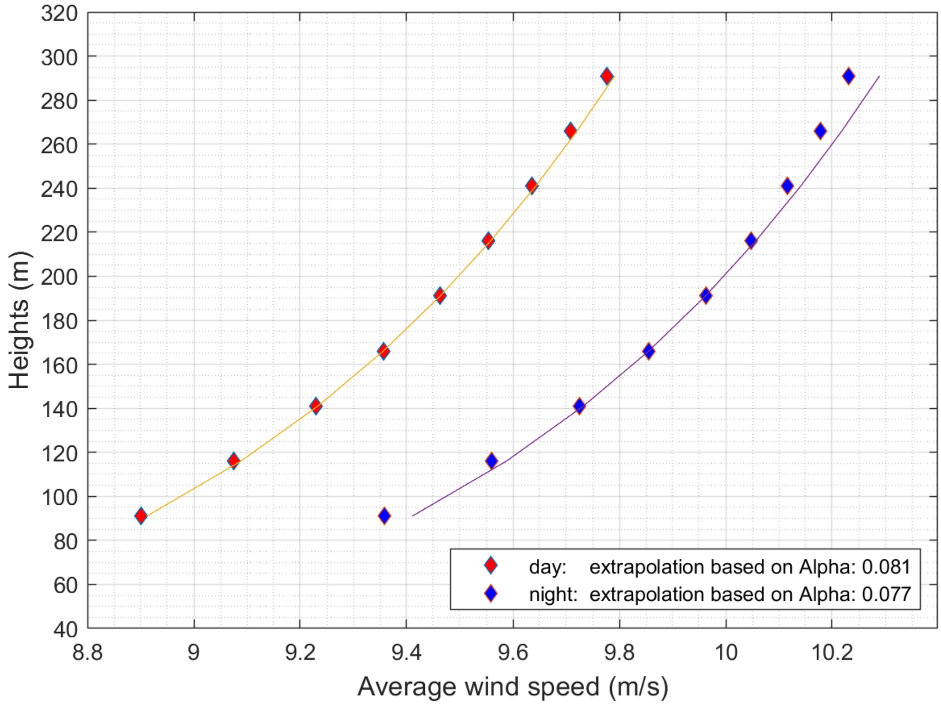


Figure 15: Day and night shear profiles at EPL for the year 2022

Wind Veer is the variation in wind direction with height, which is also an important atmospheric input and phenomenon that can impact the overall performance and loading of wind farms. Wind turbines have yaw based controls that allow them to align into the oncoming wind direction. Wind veer can lead to misalignments in the flow along the blades, and could lead to underperformance if the blade rotation is opposing the wind direction at higher heights. Positive values indicate a clockwise direction difference, also known as “veering”, as opposed to negative values that would indicate counter-clockwise direction known as “backing”. An analysis on the wind veer pattern has been conducted, and is summarized in the following figures.

The data was filtered by removing timestamps with a wind speed of less than 3 m/s. Then the timeseries of each height were matched together to established a common data period across all heights to account for availability. The unit vector wind direction data were then grouped and averaged to the required period (hourly, and monthly), and finally the veer between consecutive heights was calculated.

Figure 16 shows the average wind direction for all sensor heights at EPL considered only over the year 2022. At the lowest measured height of 63 m, the matched and filtered average wind direction was calculated to be approximately 228 degrees, while at the highest sensor height of 291 m the average wind direction was found to be approximately 241 degrees. That results in a difference of approximately 13 degrees between these levels. The figure demonstrates an average clockwise increase in wind direction (hence veering) with height.

Figure 17 presents the annual and diurnal variations in veer of the average wind direction over the entire matched and filtered data period considered . Here, it can be seen that the average wind direction changes throughout the hours of the day by approximately 1 degree. Over the months, veer varies mostly between +3 to – 2 degrees, with the largest veer coming in the month of March to June. The 91-63 pair varies from +4 and -2 degrees.

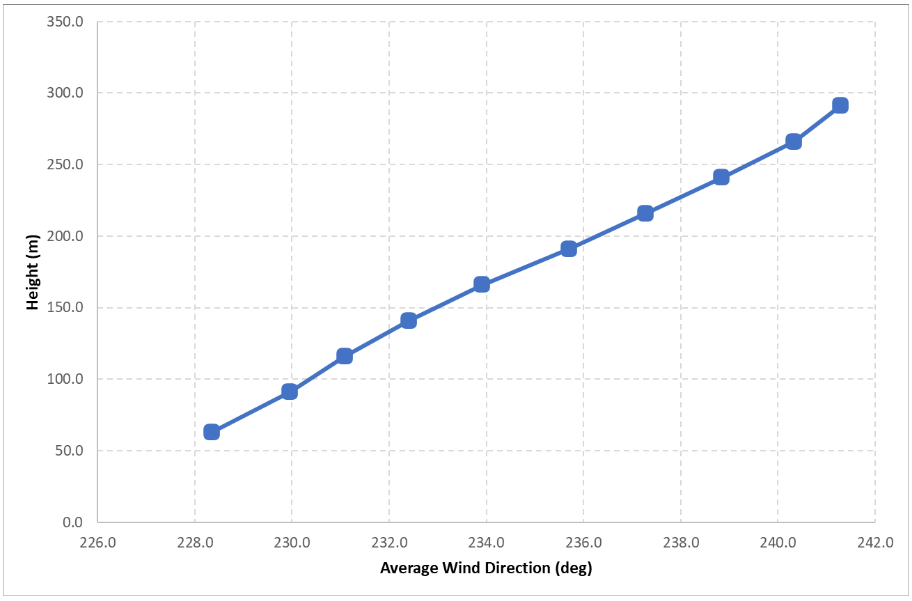


Figure 16: Variations in the matched and filtered average wind direction for different sensor heights over the year 2022

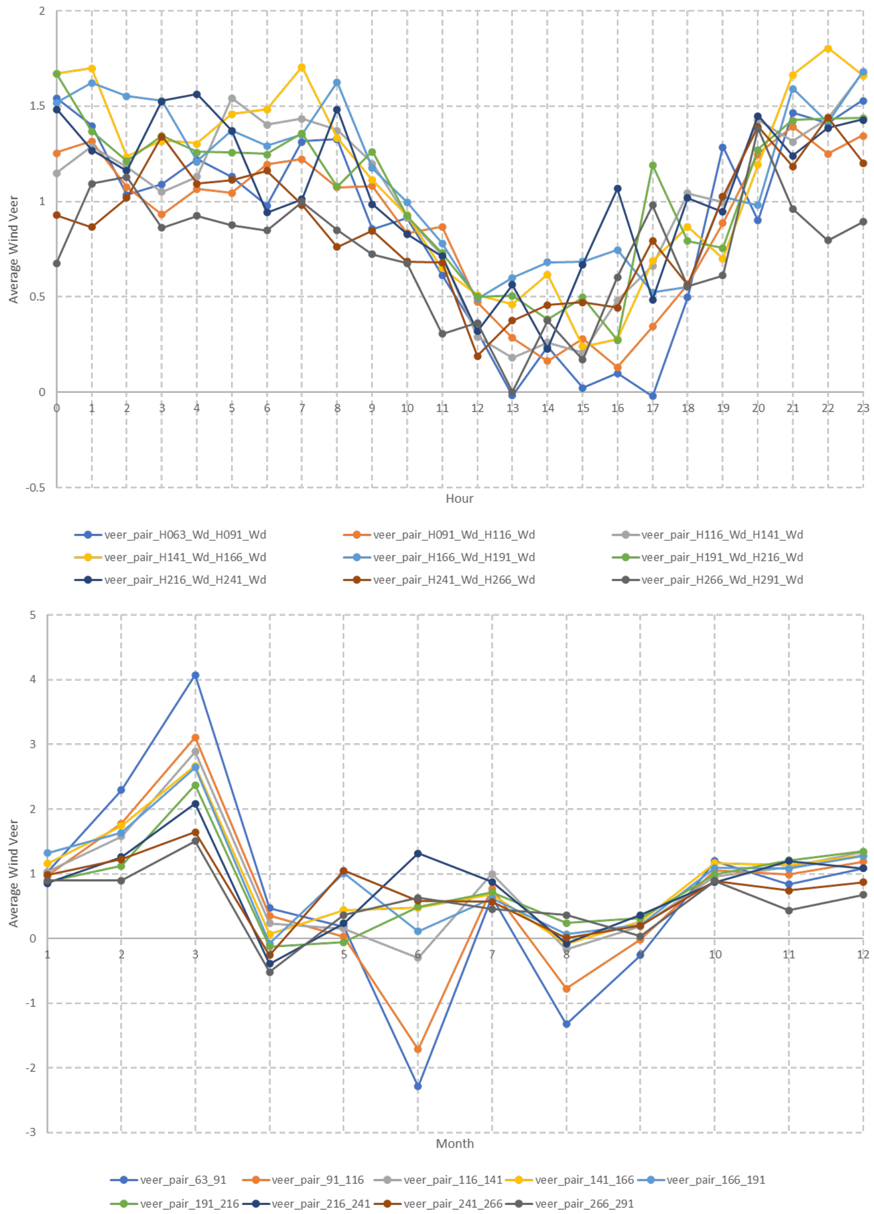


Figure 17: Matched and filtered veer profiles for LiDAR sensor pairs showing hourly (top) and monthly (bottom), trends for the data period of 2016 to 2022

5.4 Past extreme weather events

Building on the analysis of the wind measurements from 2022 presented in this report, it is noticeable that 2022 was characterized by similar wind speed trends as 2021 along most of the year.

However one noticeable exception is February 2022, over which higher wind speeds were observed and are similar to the year 2020. From February 16th to February 20th 2022, a triplet of storms hit the Netherlands, with the most severe and powerful one being Storm Eunice on February 18th. This storm, for which a code orange was issued for most of the Netherlands, was registered as the third most severe in the past 50 years [18]. **Figure 18** shows the time series for the wind speed at the 141 m sensor height, where wind speeds ranged between 25 and 35 m/s. This is also more visually represented in the wind rose and frequency distribution for that particular time period. The sustained duration of extreme winds as a result of Storm Eunice are further highlighted in the **Table 8**, as it dominates the entire top 10 list of recorded extreme timestamps, barring one occurrence on March 31st 2018.

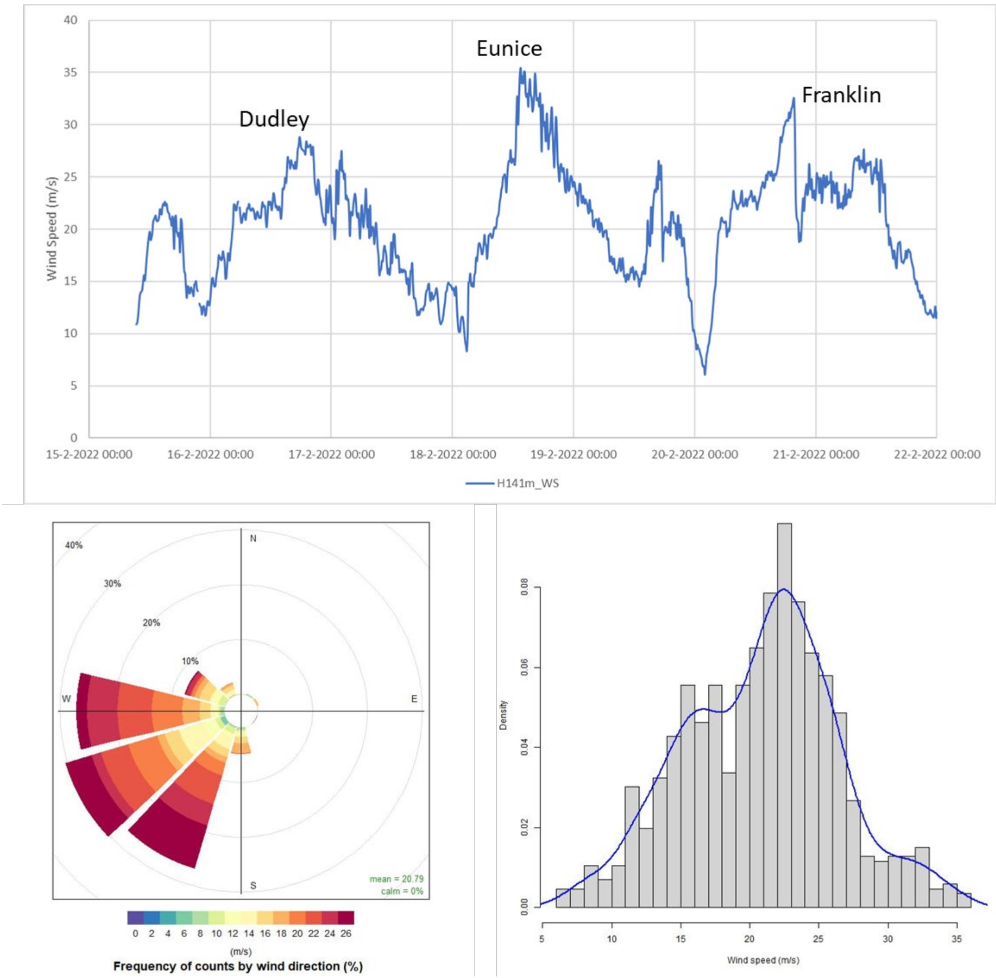


Figure 18: 10-minute wind speed timeseries (top), wind rose (bottom-left), and frequency distribution (bottom-right) measured by the LiDAR at a 141 m at the EPL platform during the triplet of storms Dudley, Eunice and Franklin in February 2022

Table 8: Top 10 windiest 10-minute averaged recorded timestamps at 141 m height at the EPL platform from 2016-2022

Rank	Timestamp	Wind Speed Recorded [m/s]
1	31-3-2018 15:00	38.2
2	18-2-2022 13:30	35.5
3	18-2-2022 14:10	35.1
4	18-2-2022 14:20	35.1
5	18-2-2022 16:20	34.9
6	18-2-2022 13:20	34.7
7	18-2-2022 13:50	34.7
8	18-2-2022 15:20	34.4
9	18-2-2022 16:30	34.0
10	18-2-2022 13:40	34.0

6 Conclusions and recommendations

This report refers to the measurement campaign at the EPL platform where a ZX 300 LiDAR has been deployed, and recently replaced in March 2022, providing high quality data. The data are publicly available to be used for further purposes (www.windopzee.net).

At the EPL platform, the wind analysis for the 2016-2022 period shows that the wind profiles are dominated by the regional climate, mainly by the positive phase effect of North Atlantic Oscillation (NAO). The prevailing wind direction is from the southwest with a mean direction ranging from 228° to 237° across the different sensor heights (63 m to 291 m). The average calculated wind speed ranges from 9.05 m/s at the lowest measured height of 63 m up to 10.18 m/s at 291 m, increasing gradually.

The Weibull distribution, which describes the shape of measured wind frequency distribution and inter-annual variability, shows typical offshore wind shape and scale parameters for the North Sea (k = 2.052 and c = 10.945 m/s at the 141 m measurement height). The wind speed frequency distribution is flattened and moderately skewed right with higher heights, with more frequently occurring wind speeds greater than 26 m/s.

The resulting assessment of the shear profile shows an annualized range of 0.052 to 0.085 considering the entire data period between matched sequential sensor height pairs of the LiDAR. For the year 2022, the calculated day and night time shear was found to be approximately 0.08 and 0.07 respectively.

Veer was found to be increasing in wind direction (hence veering) between all sequential pairs. An overall difference of approximately 13° between the lower and most upper sensor heights specifically for 2022.

From February 16th to February 20th 2022 a triplet of storms rolled troughed the Netherlands, with the most severe and powerful one being Storm Eunice on February 18th. This storm was registered as the third most severe in the past 50 years. Wind speeds ranged between 25 and 35 m/s. The sustained duration of extreme winds as a result of Storm Eunice dominates the entire top 10 list of recorded extreme timestamps, barring one occurrence on March 31st 2018.

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

- Long-term and accurate data sets can act as reference points for offshore wind atlases, and models.
- Serve as a basis for the development and validation of high fidelity models. It is necessary to improve the accuracy over a wide range of site conditions, with sufficient resolution in both time and space.

- Improving and reducing uncertainties of the variability due to renewable resources and their increase penetration in the power sector. The adequate modelling of high RES-E penetration systems crucially depends on the accurate representation of the spatial and temporal characterization of the weather conditions. Variability and uncertainty of the wind resource is translated into datasets that inherently bear the risk of being imperfect, inappropriate or incomplete. This might lead to errors in power system studies which in turn could result in either overstating or downplaying the possible role of wind energy in the future energy mix.
- Capturing extreme weather events for developers and wind turbine manufactures to help develop, certify and validate new models under site specific conditions.
- Filtering the data can influence the interpretation of period trends, and averaged results.

7 Acknowledgements

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

References

[1] Government of the Netherlands, “Offshore wind energy,” 2023. [Online]. Available: https://www.government.nl/topics/renewable-energy/offshore-wind-energy. [Accessed 20 April 2023].

[2] Ministerie van Economische Zaken en Klimaat, “Aanvullende routekaart windenergie op zee 2030,” 10 June 2022. [Online]. Available: https://open.overheid.nl/documenten/ronl-4a5f7a5116d647b18150a5692f00f2b29c5edad7/pdf. [Accessed 19 April 2023].

[3] Netherlands Ministry of Economic Affairs and Climate Policy, “Hollandse Kust (west) Wind Farm Zone,” Netherlands Ministry of Economic Affairs and Climate Policy, 19 January 2023. [Online]. Available: https://english.rvo.nl/information/offshore-wind-energy/hollandse-kust-west-wind-farm-zone. [Accessed 21 April 2023].

[4] Wind Op Zee RVO, “Windenergiegebied IJmuiden Ver,” Wind Op Zee RVO, 6 April 2023. [Online]. Available: https://www.rvo.nl/onderwerpen/windenergie-op-zee/ijmuiden-ver. [Accessed 21 April 2023].

[5] I. Gonzalez-Aparicio, J. P. Verhoef, G. Bergman en P. A. Van der Werff, „Offshore wind energy deployment in the North Sea by 2030: long-term measurement campaign Europlatform, 2016-2019,” TNO R10511, 2020.

[6] I. Gonzalez-Aparicio, A. Pian, J. P. Verhoef, G. Bergman en P. A. Van der Werff, „Offshore wind energy deployment in the North Sea by 2030: long-term measurement campaign. EPL 2016-2020,” TNO R10919, 2021.

[7] A. Pian, J. A. Vitulli, J. P. Verhoef, G. Bergman, P. A. Van der Werff en I. Gonzalez-Aparicio, „Offshore wind energy deployment in the North Sea by 2030: long-term measurement campaign. EPL 2016-2021,” TNO R10909, 2022.

[8] G. Bergman, J. P. Verhoef en P. A. van der Werff, „Europlatform LiDAR measurement campaign; Instrumentation Report 2022,” TNO 2022 R11776, 2022.

[9] J. W. Wagenaar en D. A. J. Wouters, „Validation of the ZephIR 300 LiDAR at the ECN LiDAR Calibration Facility for the offshore Europlatform measurement campaign,” ECN, 2016.

[10] D. A. J. Wouters en J. P. Verhoef, „Verification of ZephIR 300 unit 315 at ECN part of TNO LiDAR Calibration Facility, for offshore measurements at Euro Platform (EPL),” ECN part of TNO R10762, 2018.

[11] G. Bergman, „Validation of the TNO ZX300 LiDAR system unit 308, at the TNO RSD Verification Facility Period: July 2019 to September 2019,” TNO 2021 R10132, 2021.

[12] G. Bergman, „Verification of the TNO ZX300 LiDAR system unit 315 at the RSD Verification Location near MM6 at the EWTW test site Period: September 2021 to February 2022,” TNO 2021 R11643, Petten, 2021.

[13] The Carbon Trust, “Carbon Trust Offshore Wind Accelerator roadmap for the,” Carbon Trust, 2013.

[14] M. Mathis, A. Elizalde, U. Mikolajewicz en T. Pohlmann, „Variability patterns of the general circulation and sea water temperature in the North Sea,” *Progress in Oceanography,* vol. 135, pp. 91-112, 2015.

[15] J. Sundermann en T. Pohlmann, „A brief analysis of North Sea physics," *Oceanologia,* vol. 53, nr. 3, pp. 663-689, 2011.

[16] J. B. Duncan, P. A. van der Werff en E. T. G. Bot, „Understanding of the Offshore Wind Resource up to High Altitudes (<315 m)," TNO R11592, 2019.

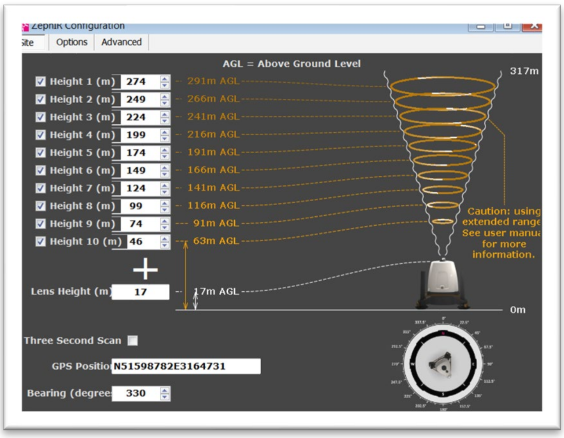
[17] G. G. A. Venkitanchalam, „High Altitude Wind Resource Assessment. A study of the North Sea wind conditions using the Dutch Offshore Wind Atlas.," TNO, 2020.

[18] KNMI, "Drielingstorm Dudley, Eunice en Franklin," 21 February 2022. [Online]. Available: https://www.knmi.nl/over-het-knmi/nieuws/drielingstorm-dudley-eunice-en-franklin. [Accessed 14 March 2023].

Appendix A
LiDAR specifications ZX 300

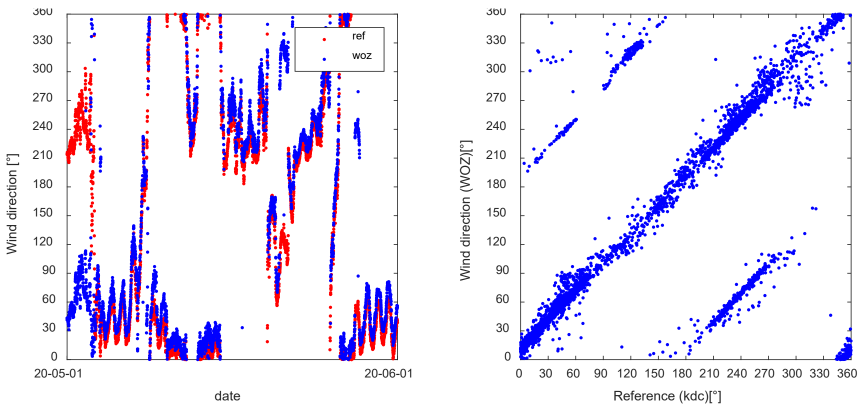
Setting and Configuration

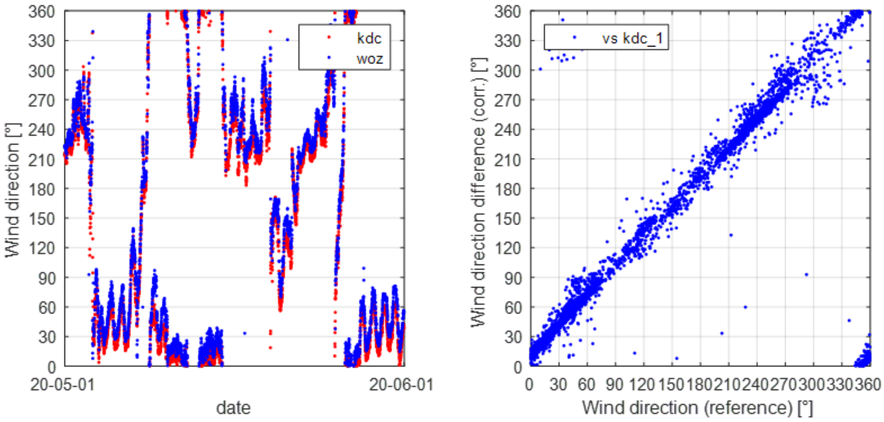
TNO is accredited for remote sensing device calibration (ISO 17025). The LiDAR is upfront verified against Meteorological Mast 4 at EWTW, in accordance with IEC 61400-12-1:2017. The validation is performed by checking Key Performance Indicators (KPIs) [12]. The figure below shows an example of screen setting of the LiDAR configuration and adjustments.



Data correction – 180 degrees offset

As abovementioned, The ZX 300 does not determine the direction of the Doppler shift in the received series and there is a 180° ambiguity in the wind direction. Therefore, the attached met station with wind speed and direction measurements (EPL_wsmet and EPL_wdmet) is used to correct the 180° offset. Firstly, the difference of the two wind direction timeseries are considering; then, the solitary spikes from this difference in signal are removed and; identification of the periods where the LiDAR wind direction is reversed. The figures below show the wind direction time series (left figures) and the comparisons (right figures) from the LiDAR at EPL and from the KNMI met mast; before (top) and after (bottom) applying the correction methodology.





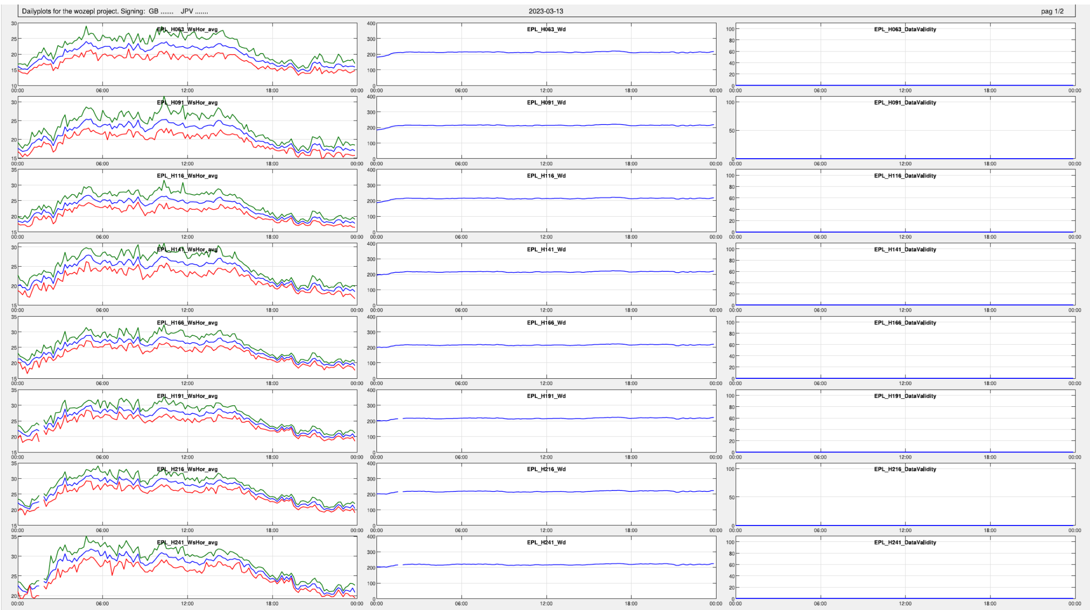
Data availability

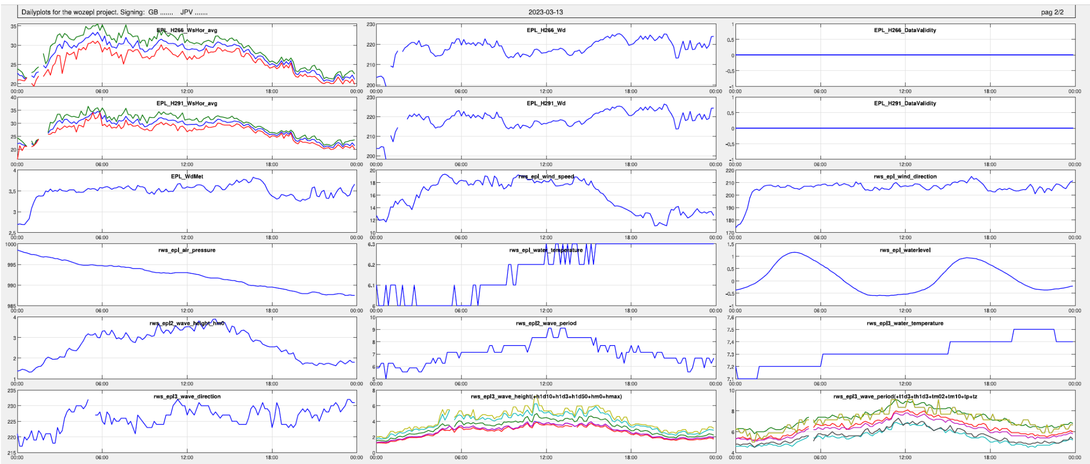
For the ZX 300 LiDAR, the quantification of the overall availability in a 10-minute interval (for a certain height), it is considered the number of packets by definition [11]. Due to different technology, the methodology to calculate data availability of the ZX 300 LiDAR is not comparable with the data availability of the LEOSPHERE LiDAR. Here, the number of packets in a 10-minute interval to 100% are normalized by:

$$Availability = \frac{n_{packets}}{Max(n_{packets})} * 100\%$$

Where max($n_{packets}$) is the maximum value for the number of packets metric observed in the entire data set and it depends on the type of the LiDAR.

Example of Daily Plot

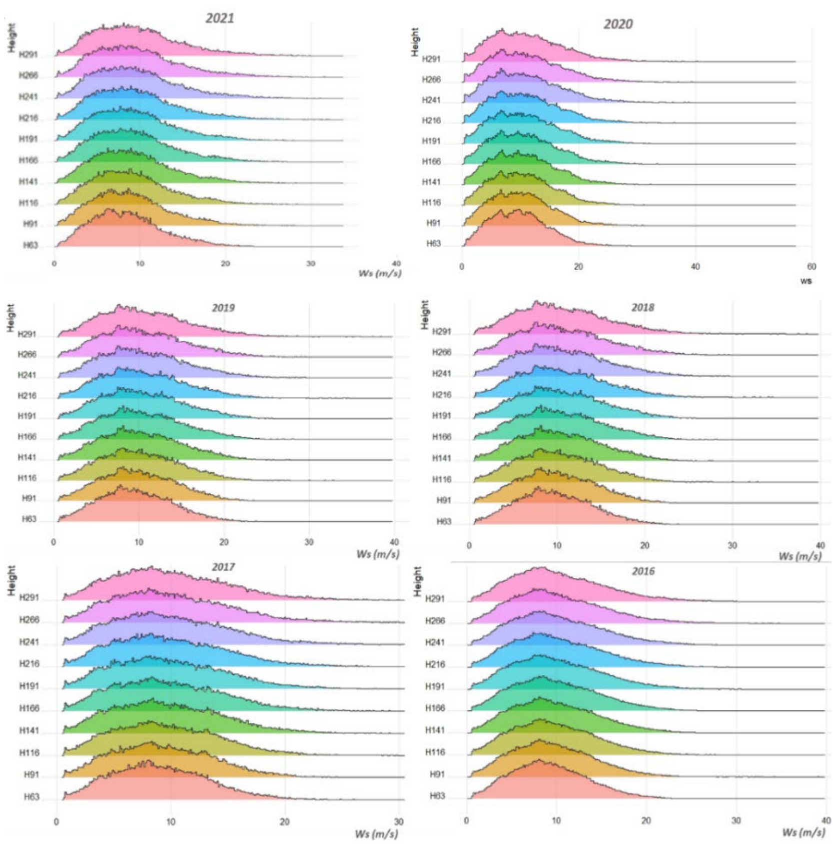




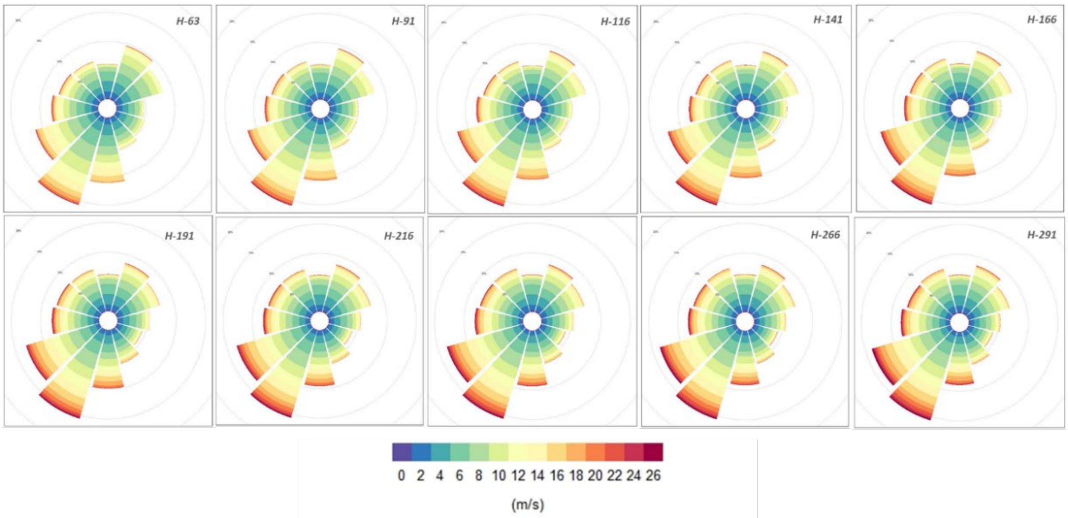
Appendix B
Annual weather conditions during the campaign at EPL

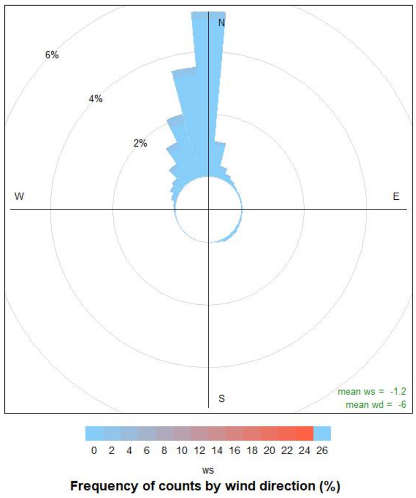
This section contains visual and statistical descriptive summary about the annual weather conditions per year at the EPL from 2022 backwards in time to 2016. These statistics are influenced by the available months of data, and do not account for seasonality. The annual prevailing wind direction recorded was South-West, at different heights, as indicated by the wind roses (top). The wind rose chart (bottom left) shows the difference on wind speed and direction between heights of 291 m and 63 m above MSL level. The main wind speed distributions (m/s vs. frequency) at 141 m (bottom right) and the descriptive statistics are also included. These data consider the available measured data, therefore the statistics are biased by the LiDAR availability.

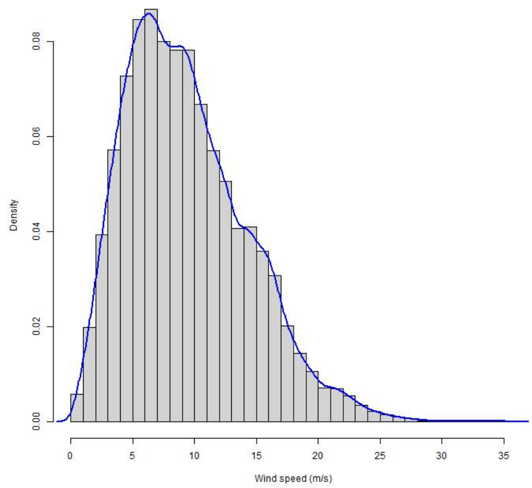
B.1 Yearly Frequency Distributions By Height (Previous Years)



B.2 2022

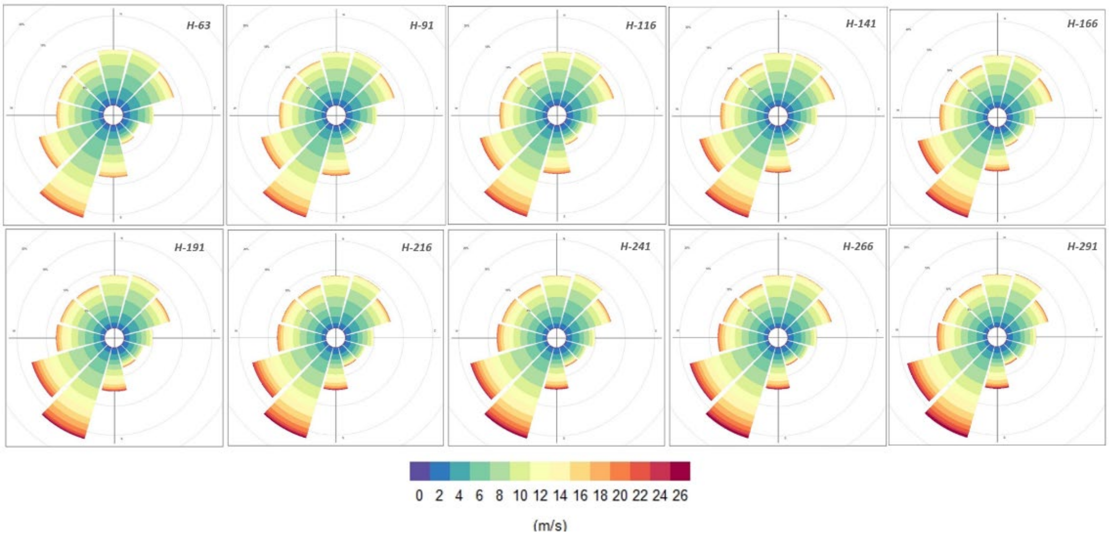


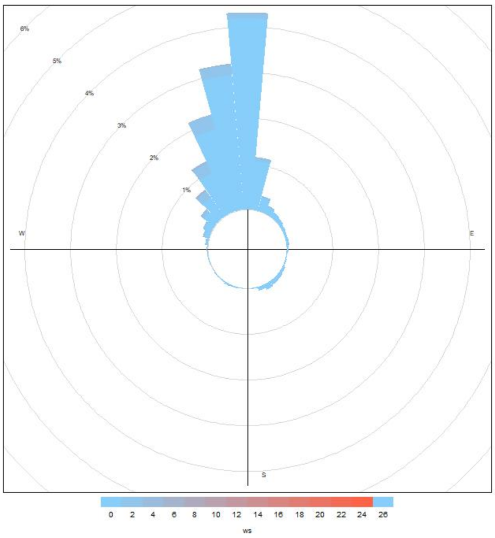


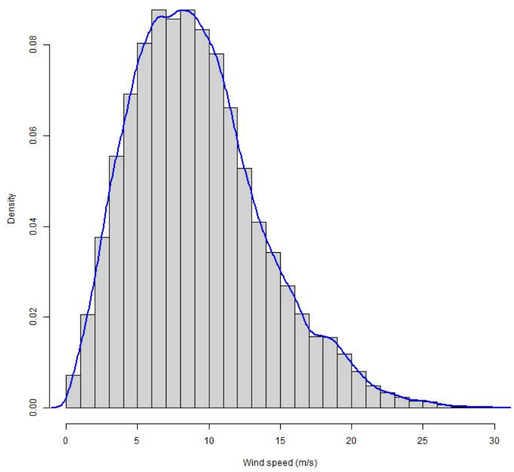


H (m)	63	91	116	141	166	191	216	241	266	291
Ws - Min	0.46	0.34	0.38	0.38	0.35	0.39	0.40	0.32	0.31	0.33
Ws – 1st q	5.48	5.58	5.62	5.65	5.68	5.71	5.74	5.78	5.81	5.82
Ws - Median	8.14	8.41	8.56	8.70	8.79	8.86	8.91	8.94	9.00	9.05
Ws - Mean	8.72	9.04	9.23	9.40	9.52	9.63	9.72	9.80	9.89	9.96
Ws - 3rd q	11.45	11.94	12.23	12.45	12.62	12.77	12.92	13.04	13.16	13.28
Ws – Max	32.52	33.92	34.63	35.46	36.05	36.86	37.86	38.32	38.75	38.99
Wd - Mean	228.2	230.0	230.8	232.0	233.5	235.4	237.2	238.7	240.3	241.7

B.3 2021

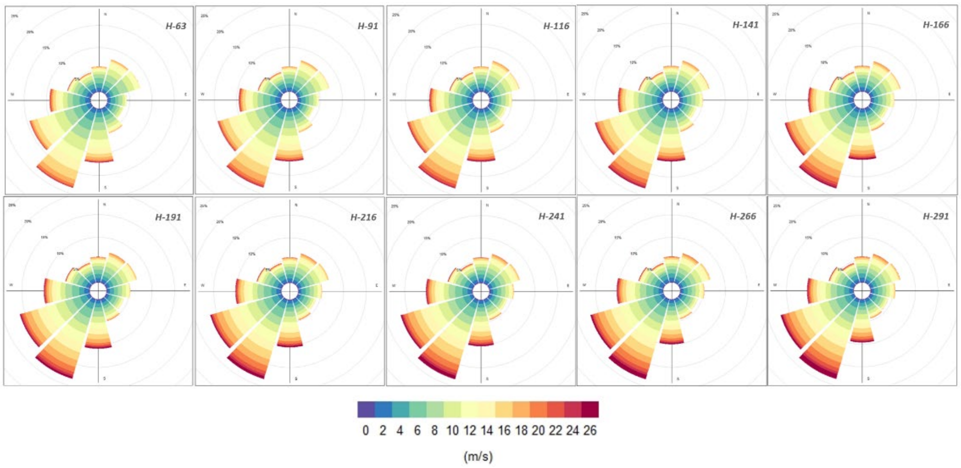


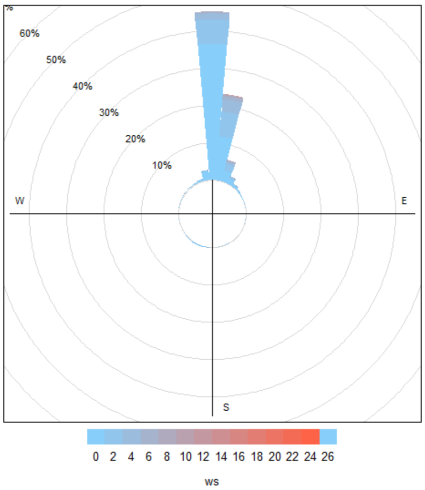


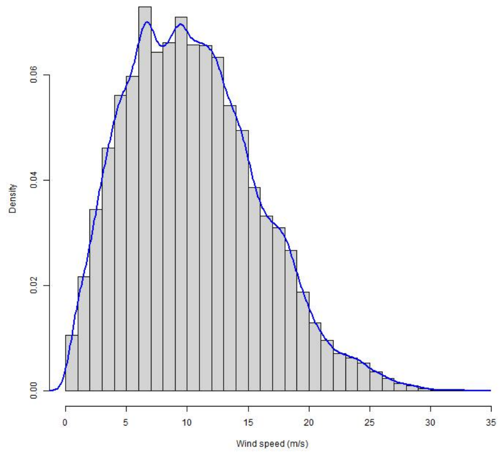


H (m)	63	91	116	141	166	191	216	241	266	291
Ws - Min	0.39	0.35	0.32	0.33	0.34	0.30	0.32	0.31	0.30	0.31
Ws – 1st q	5.50	5.64	5.71	5.76	5.77	5.79	5.82	5.84	5.89	5.93
Ws - Median	8.16	8.40	8.53	8.65	8.74	8.80	8.87	8.92	9.00	9.10
Ws - Mean	8.60	8.86	9.02	9.17	9.29	9.39	9.48	9.57	9.68	9.79
Ws - 3rd q	11.10	11.45	11.66	11.84	11.99	12.12	12.23	12.35	12.46	12.62
Ws – Max	26.98	28.06	29.03	29.75	30.71	31.48	32.13	32.81	33.28	33.57
Wd - Mean	269.9	267.5	266.6	265.9	266.0	266.1	266.9	267.2	266.3	264.7

B.4 2020

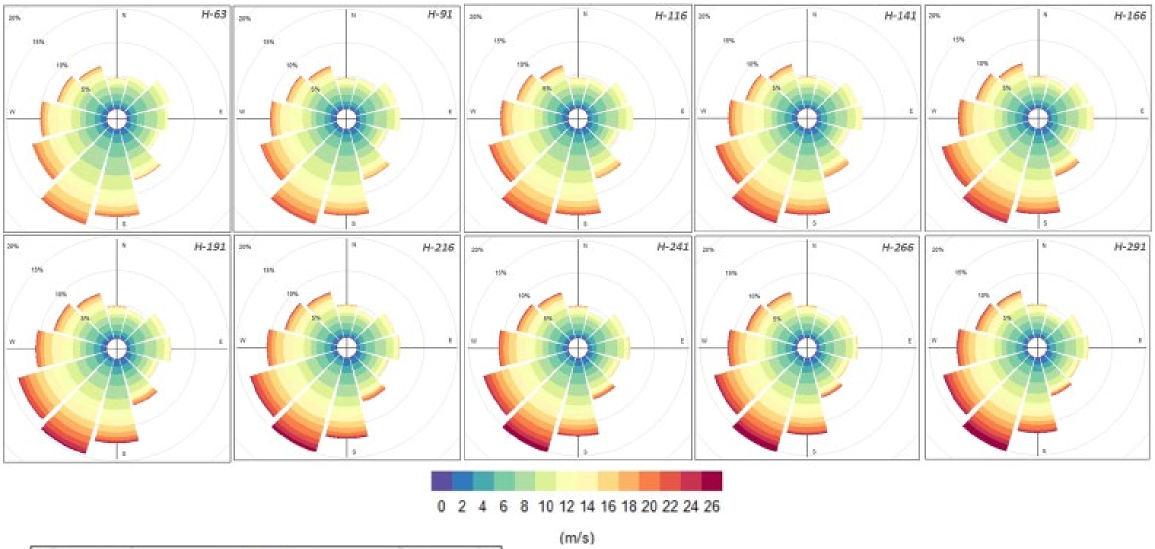


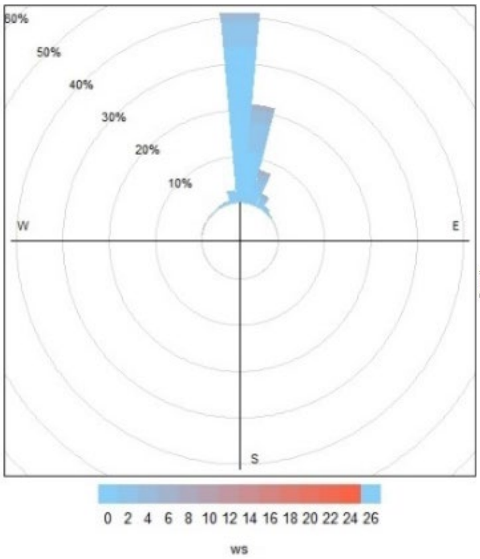


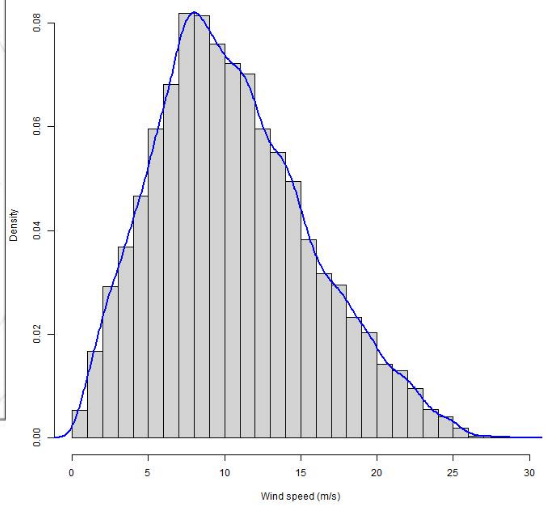


H (m)	63	91	116	141	166	191	216	241	266	291
Ws - Min	0.42	0.32	0.33	0.34	0.32	0.313	0.307	0.32	0.31	0.31
Ws – 1st q	6.08	6.21	6.27	6.31	6.33	6.345	6.373	6.39	6.45	6.47
Ws - Median	9.45	9.72	9.84	9.96	10.05	10.12	10.18	10.23	10.30	10.39
Ws - Mean	**9.76**	**10.08**	**10.27**	**10.45**	**10.59**	**10.72**	**10.83**	**10.93**	**11.04**	**11.15**
Ws - 3rd q	12.87	13.37	13.68	13.96	14.18	14.36	14.51	14.64	14.77	14.94
Ws – Max	28.99	30.89	31.85	33.23	34.12	36.28	42.47	47.06	56.89	44.28
Wd - Mean	222.9	223.0	223.6	224.6	225.7	226.7	227.6	228.5	229.1	229.9

B.5 2019

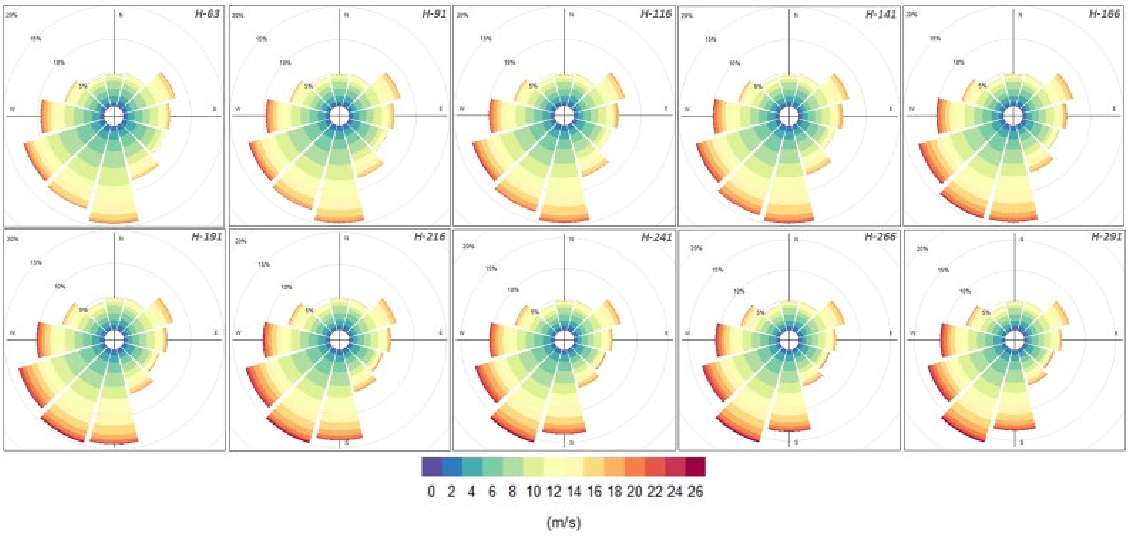


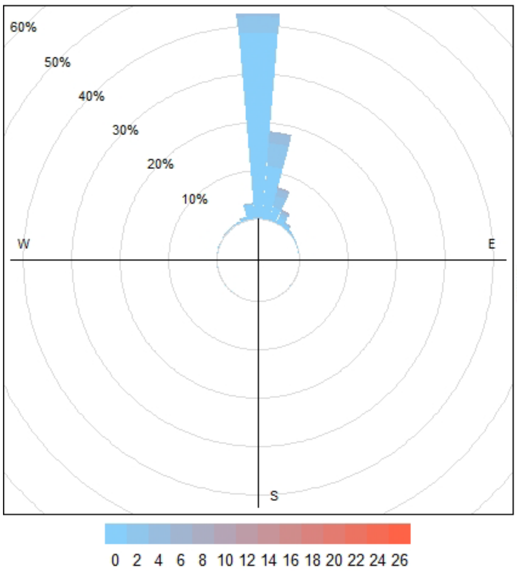


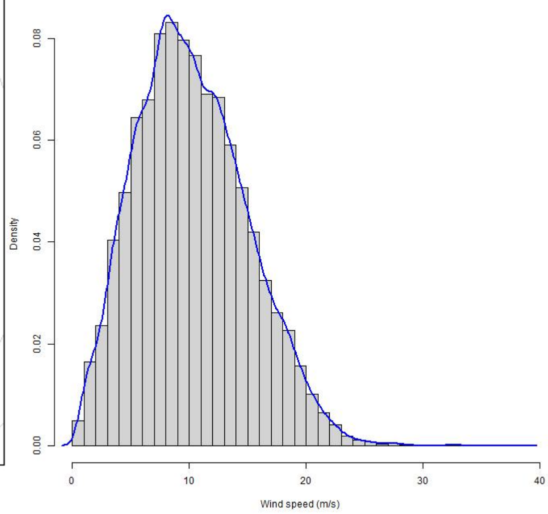


H (m)	63	91	116	141	166	191	216	241	266	291
Ws - Min	0.472	0.413	0.381	0.452	0.426	0.319	0.320	0.363	0.370	0.335
Ws – 1st q	6.685	6.768	6.820	6.840	6.868	6.878	6.872	6.868	6.878	6.877
Ws - Median	9.441	9.729	9.865	9.968	10.039	10.085	10.072	10.097	10.118	10.135
Ws - Mean	**9.883**	**10.194**	**10.383**	**10.543**	**10.679**	**10.791**	**10.887**	**10.969**	**11.037**	**11.090**
Ws - 3rd q	12.752	13.235	13.563	13.845	14.055	14.242	14.399	14.521	14.601	14.662
Ws – Max	27.000	28.300	28.500	29.100	29.600	31.600	34.100	34.600	34.400	34.900
Wd - Mean	217.6	218.5	219.7	221.2	222.8	224.5	225.8	226.9	227.9	229.4

B.6 2018

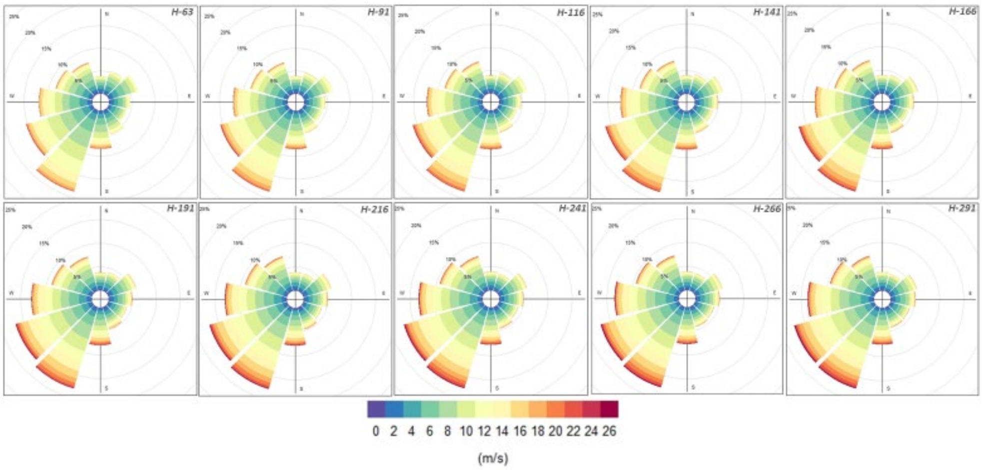


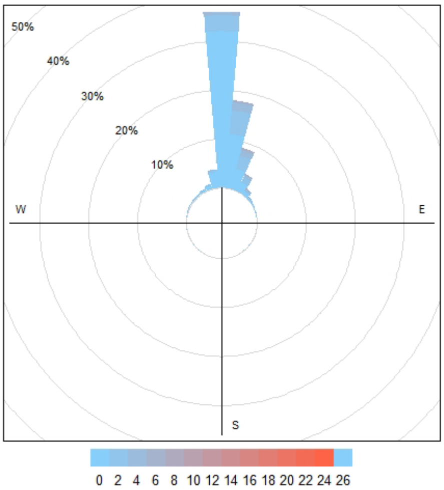


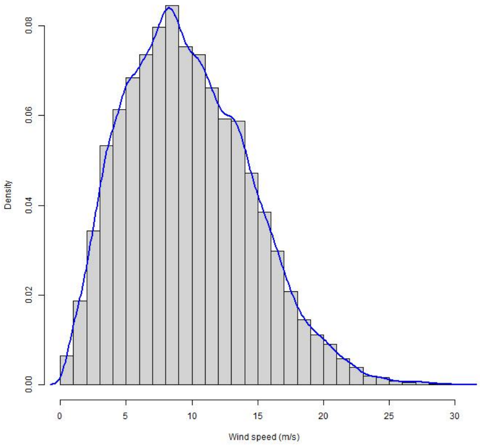


H (m)	63	91	116	141	166	191	216	241	266	291
Ws - Min	0.658	0.661	0.662	0.661	0.664	0.669	0.669	0.667	0.663	0.661
Ws – 1st q	6.497	6.659	6.713	6.754	6.780	6.795	6.820	6.821	6.838	6.842
Ws - Median	9.319	9.608	9.766	9.852	9.905	9.960	9.988	10.008	10.006	10.009
Ws - Mean	**9.621**	**9.931**	**10.110**	**10.246**	**10354**	**10.446**	**10.519**	**10.572**	**10.605**	**10.628**
Ws - 3rd q	12.526	13.011	13.241	13.410	13.541	13.662	13.757	13.821	13.844	13.872
Ws – Max	39.066	39.156	38.559	38.174	39.251	35.442	38.869	38.414	39.557	38.480
Wd - Mean	**201.2**	**203.8**	**205.7**	**207.6**	**209.1**	**210.9**	**212.4**	**213.8**	**214.6**	**215.7**

B.7 2017

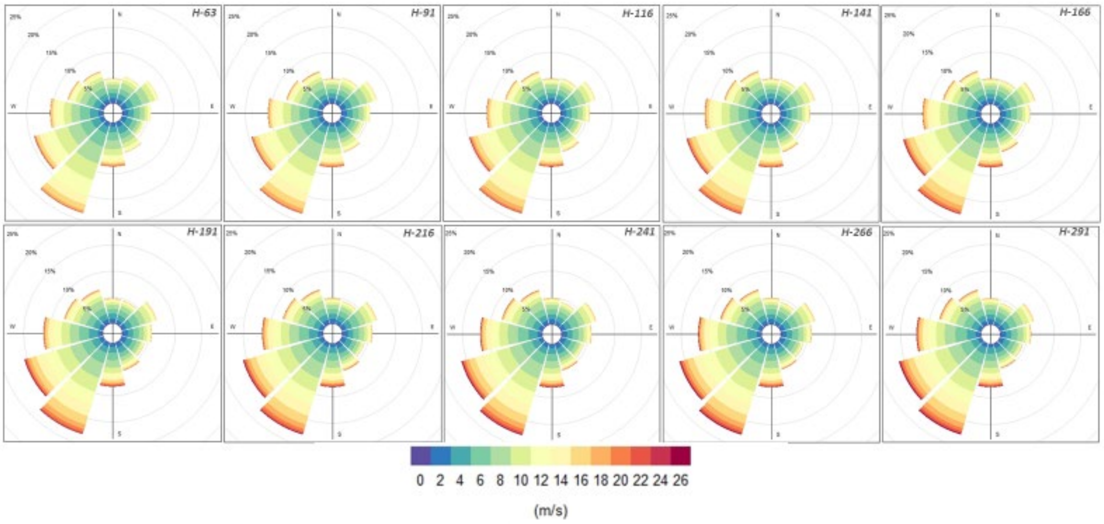


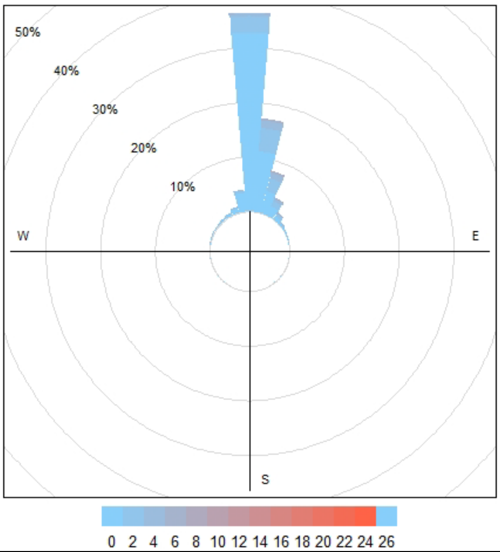


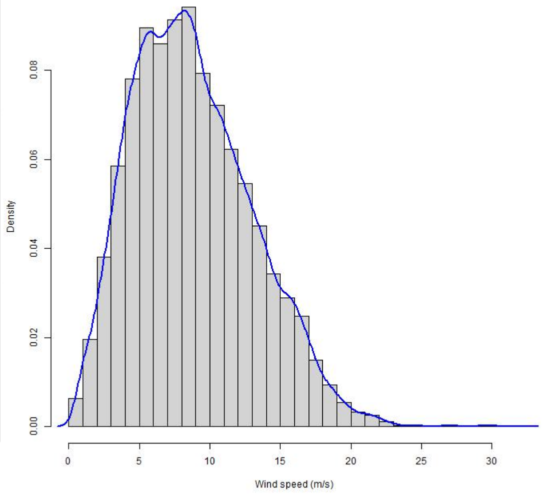


H (m)	63	91	116	141	166	191	216	241	266	291
Ws - Min	0.671	0.673	0.668	0.675	0.678	0.678	0.647	0.677	0.678	0.678
Ws – 1^{st} q	5.947	6.033	6.069	6.097	6.118	6.151	6.181	6.218	6.238	6.281
Ws - Median	8.732	9.016	9.155	9.241	9.301	9.342	9.353	9.381	9.400	9.396
Ws - Mean	**9.089**	**9.389**	**9.566**	**9.697**	**9.796**	**9.876**	**9.942**	**9.992**	**10.026**	**10.054**
Ws - 3^{rd} q	11.907	12.439	12.720	12.918	13.055	13.135	13.205	13.244	13.267	13.263
Ws – Max	28.572	29.424	29.759	30.164	30.079	30.355	30.668	30.852	31.715	31.938
Wd - Mean	**236.4**	**237.5**	**238.2**	**238.9**	**239.6**	**240.4**	**241.2**	**242.0**	**243.1**	**243.7**

B.8 2016







H (m)	63	91	116	141	166	191	216	241	266	291
Ws - Min	0.669	0.673	0.668	0.675	0.678	0.678	0.647	0.675	0.676	0.678
Ws – 1st q	5.770	5.859	5.895	5.938	5.960	5.993	6.023	6.053	6.082	6.127
Ws - Median	8.527	8.759	8.874	8.952	8.987	9.020	9.030	9.034	9.033	9.048
Ws - Mean	**8.876**	**9.145**	**9.307**	**9.426**	**9.516**	**9.588**	**9.646**	**9.692**	**9.724**	**9.753**
Ws - 3rd q	11.595	12.043	12.301	12.464	12.593	12.672	12.742	12.771	12.785	12.785
Ws – Max	30.475	31.225	32.339	31.854	31.808	31.895	32.476	32.030	32.636	33.029
Wd - Mean	216.8	217.7	218.9	220.2	221.3	222.6	224.4	225.5	226.1	227.0

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