Offshore wind energy deployment in the North Sea by 2030: long-term measurement campaign. K13A, 2016-2022

TNO Public ⟩ TNO 2023 R10580
27 June 2023

Energy & Materials
Transition
www.tno.nl
+31 88 866 50 65
info@tno.nl

TNO 2023 R10580 – 27 June 2023

Offshore wind energy deployment in the North Sea by 2030: long-term measurement campaign. K13A, 2016-2022

Author(s)	J.A. Vitulli C.B.H. Eeckels E.T.G. Bot J.P. Verhoef G. Bergman P.A. Van der Werff
Classification report	TNO Public
Number of copies	TNO Public
Report text	TNO Public
Appendices	TNO Public
Number of pages	45 (excl. front and back cover)
Number of appendices	3
Sponsor	Dutch Ministry of Economic Affairs and Climate Policy
Project name	2023 Wind Conditions @ North Sea
Project number	060.55419

All rights reserved
No part of this publication may be reproduced and/or published by print, photoprint, microfilm or any other means without the previous written consent of TNO.

© 2023 TNO

RvA is participant in the ILAC-MRA.

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

- Power performance measurements according to IEC 61400-12-1, Measnet Power Performance measurement procedure, FGW TR2, FGW TR5
- 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

Revision

Rev. No.	Date	Description of change	Page	Background **(*)**
1.0	27 June 2023	First release	-	-

*(a) request customer, (b) correction, (c) addition

Archiving

https://city.tno.nl/teams/T93134/TeamDocuments/Team/Work/Reports/General%20reports/WindConditions_K13a/2022

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 measurement campaign at the K13a platform where a ZX 300M LiDAR has been deployed, providing high quality data since November 2016. The data are publicly available to be used for further purposes (www.windopzee.net).

At the K13a 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 241° to 251° across the different sensor heights (63 m to 291 m). The average calculated wind speed ranges from 9.29 m/s at the lowest measured height of 63 m up to 10.44 m/s at 291 m, increasing gradually.

The Weibull distribution, indicating wind regimes and inter-annual variability, shows wind speed distributions with typical offshore wind k, and c parameters (k = 2.155 and c = 11.389 m/s at 141 m height). The wind speed frequency distribution is flattened and moderately skewed right with higher heights, with more frequent wind speeds greater than 26 m/s.

The resulting assessment of the shear profile shows an annualized range of 0.026 to 0.111 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 is not properly represented by the fitted shear exponent, indicating shear relaxation between heights.

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 was registered as the third most severe in the past 50 years. Wind speeds ranged between 20 and 35 m/s. The year 2020 dominates the entire top 10 list.

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 selected. 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 “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. (**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 Wintershall platform K13a , located about 101 km from northwest of Den Helder.

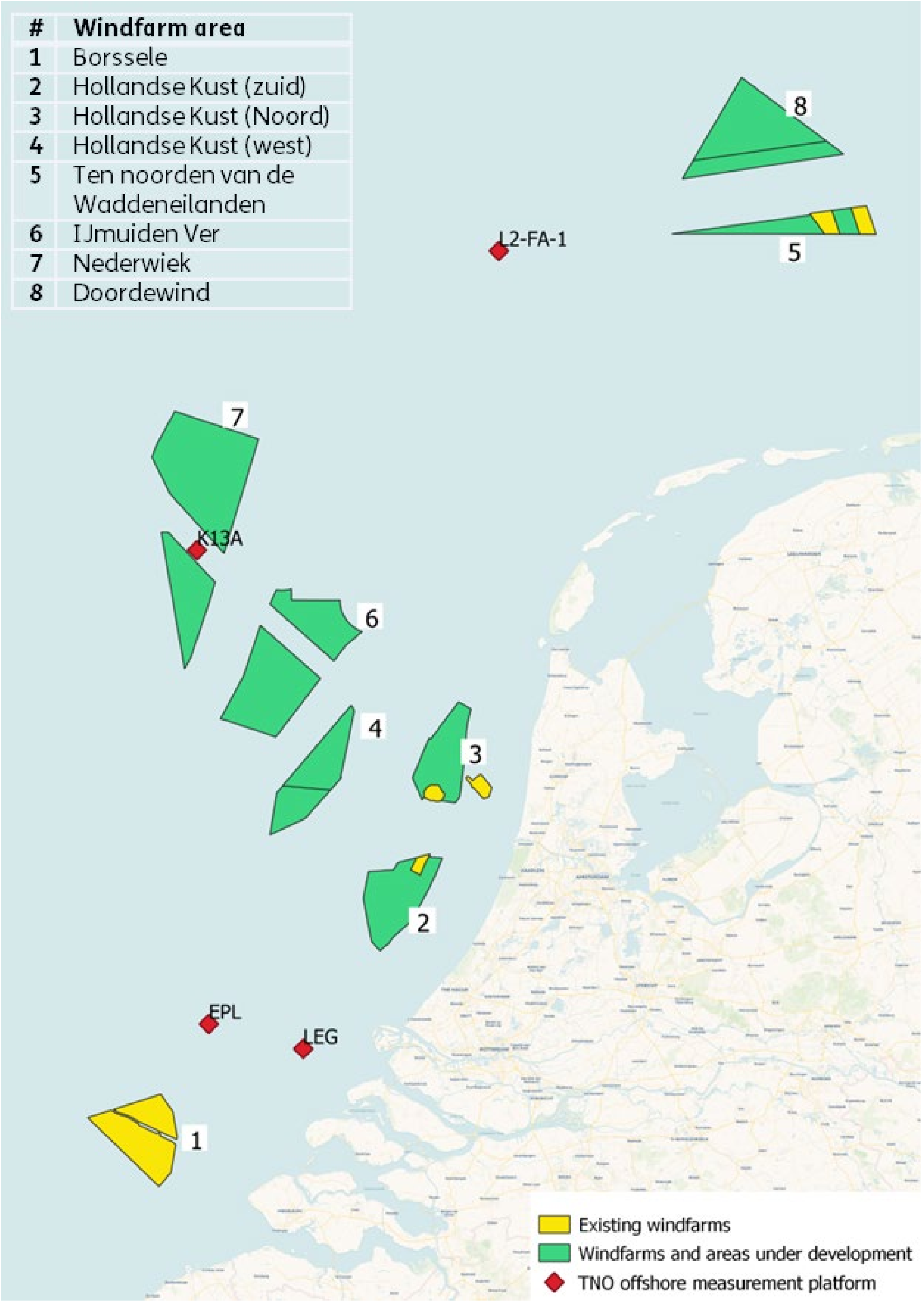


Figure 1:Illustration of TNO long-term offshore wind measurement campaign locations at Lichteiland Goeree (LEG), Europlatform (EPL) and Wintershall platform (K13a), and L2-FA-1, along with wind farm development zones in the Dutch North Sea

2 Wind Measurement Campaigns in the North Sea

2.1 TNO leading role on offshore measuring 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 analysing, reporting and dissemination of the data.

2.2 Open-access and public datasets

Since 2020 TNO has published annually reports on the wind conditions for the Wintershall platform K13a location. They are referred to in the Table 1. These reports are available at https://www.windopzee.net/en/. This report includes the specific wind conditions for the period 2016-2022 at the K13a platform

Table 1 Publication History of Wind Conditions for K13a

Reference	K13a Wind Conditions Period
[5]	K13a platform for the periods 2016-2019
[6]	K13a platform for the periods 2016-2020
[7]	K13a platform for the periods 2016-2021

This report has been updated with improved practices for deducing the wind direction, wind veer and wind shear. 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., P.A. van de Werff (2022) K13-A LiDAR measurement campaign; Instrumentation Report 2023, TNO 2023 R10159
2. Citation of this report:
   Vitulli J.A., Eeckels C., Verhoef J.P., Bergman G., van der Werff P.A., (2023) Offshore wind energy deployment in the North Sea by 2030: long-term measurement campaign. K13a, 2016-2022. TNO 2023 R10580.

The publication date at which the data have last been accessed must be indicated along the citations(e.g. *Last accessed April 2022*).

The data is shared in .csv format. In the case of the K13a measurement campaign please adhere to the following information:
- https://www.windopzee.net/en/locations/K13a/data/
- For monthly files: K13A-yyyy-mm.CSV
- After a quarter of a year is completed the monthly files will be replaced by: K13A-yyyy-Qx.CSV
- After the year is completed the quarterly files will be replaced by a yearly file as: K13A-yyyy.CSV.

3 Measurement campaign at K13a

3.1 Location and instrumentation

The K13a offshore platform is located northwest of Den Helder, 101 kilometers from the coast (**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 K13a platform serves as a production platform for natural gas, but since November 2016, it has also servers for wind measurements using a platform-mounted (~35 m above MSL) 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 weather meteorological agency (KNMI) and Rijkswaterstaat, the Dutch Ministry of Infrastructure and the Environment.

Figure 2: View of the K13a platform during visiting in November 2022 (left), location of K13a in the Dutch North Sea (right)

TNO has been conducting an ongoing measurement campaign at K13a 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 November 11th, 2022, after 6 years of continuous operation.

Figure 3: View of LiDAR unit following replacement in November 2022

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. This evaluation is described in the installation plan of the instrumentation, which provides the description of how the measurement equipment will be mounted and the agreement with Wintershall about the installation and safety measures. 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 K13a platform has been recently updated and described in the installation report [8] . At K13a, the suitable place was found just aside the helipad of the platform (**Figure 4** b, c, d).

Figure 4: a) Front of K13a platform (geographical coordinates 53° 13'N, 3° 13'E); b) c) and d) location of the LiDAR installation (2016)

3.3 Onsite installation and operational status

The LiDAR selected is a ZX 300M 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, the LiDAR was first verified at the LiDAR calibration facility, ECN Wind Energy Facilities B.V. [9] [10] . To ensure good quality measurements it is crucial to select the right location for the LiDAR on the platform. At K13a, the suitable place was found just aside the helipad of the platform (**Figure 4** b, c, d).

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 EPL platforms. Manufacturers guarantee data quality up to 200 m above the LiDAR although the ZX300 can measure beyond that height too. 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**). However, since the start of the campaign at this location, daily control and monitoring of the data show that the device is measuring at the same accuracy without any major issues. All operational aspects with respect to installing and maintaining the LiDAR are recorded in a logbook of the team responsible for the measurement campaign. WinterShall personnel, the oil and gas company working at the platform, supports monitoring and control of the LiDAR.

During 2022, there were no observable events that would suggest downtime and reduce data availability. The availability due the installation of the new lidar U1524 from November 11th 2022, remains similar to the previous period.

Table 2: Replacements of LiDAR at the K13a platform.

Id LiDAR	LiDAR in operation	Reason of replacement
U563	1 - 11 – 2016 to 11-11-2022	Replacement after 6 years of service
U1524	11-11-2022 to Present	Presently onsite recording data

3.4 Health and safety measures

Health, safety and environment are main priorities at TNO. TNO follows a strict program to train the employees for the measurement campaigns, more detailed information in the Annex A. Additional agreed safety measures with Wintershall 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 (Helicopter Underwater Escape Training). Only in case a visit was planned using a helicopter.

4 LiDAR performance assessment at K13a

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 the 1st of November 2016 at 00 UTC (Universal Time Coordinates). This report includes a 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 K13a 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
K13a_batvoltage	Battery Voltage	V
K13a_tempcpu	CPU temperature inside the LiDAR	deg C
K13a_humpod	Relative Humidity inside the LiDAR	%
K13a_bearing	LiDAR Bearing	Deg
K13a_tilt	LiDAR tilt angle	Deg
K13a_pair	Air Pressure at LiDAR position	hPa
K13a_wsmet	Wind speed measured by LiDAR meteo station	m/s
K13a_wdmet	Wind direction measured by LiDAR meteo station	Deg
K13a_HXXX_npts	Measuring points	
K13a_HXXX_missed	Missed points	
K13a_HXXX_npackets	Packets in fit	
K13a_HXXX_Wd	Wind direction	Deg
K13a_HXXX_Wshor_av	Horizontal wind speed average	m/s
K13a_HXXX_Wshor_std	Horizontal wind speed standard deviation	m/s
K13a_HXXX_Wshor_min	Horizontal wind speed minimum	m/s
K13a_HXXX_Wshor_max	Horizontal wind speed maximum	m/s
K13a_HXXX_WsVer_avg	Vertical wind speed average	m/s
K13a_HXXX_cs	CS	

Acronym	Signal name	Units
K13a_HXXX_BackScatter	Back Scatter	

The ZX 300M 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 (K13a_wsmet and K13a_wdmet, **Table 3**) is used 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 [11], based on the Offshore Wind Accelerator roadmap [12].

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 [9]. As indicated in **Figure 5** and **Table 4** (and Annex A); the data availability with the ZX 300M at the K13a platform is independent of height from May 2016 to February 2022. Following this period, there are differences in the observed availability by sensor height, but is remains above 89%.

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	96.1	96.1	96.1	96.1	96.1	96.1	96.1	96.1	96.1	96.1
2017	96.7	96.7	96,7	96.7	96.7	96.7	96.7	96.7	96.7	96.7
2018	95.0	95.1	95.1	95.1	95.1	95.1	95.1	95.0	94.9	94.9
2019	95.5	95.5	95.5	95.5	95.5	95.5	95.5	95.5	95.5	95.5
2020	94.5	94.5	94.4	94.4	94.4	94.4	94.3	94.3	94.3	94.3
2021	93.1	93.1	93.1	93.1	93.1	93.1	93.1	93.1	93.1	93.1
2022	93.5	92.9	92.2	91.9	91.4	91.1	90.6	90.0	89.5	89.0

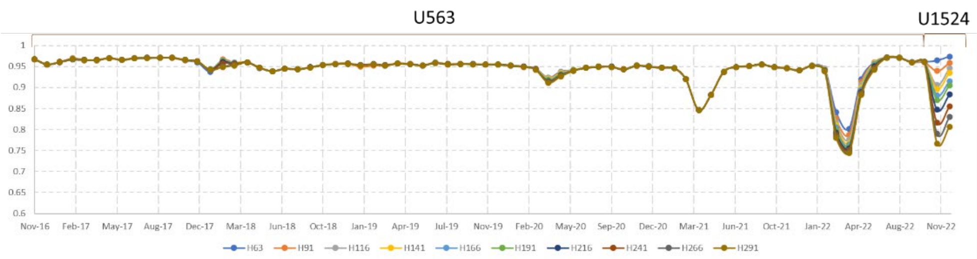


Figure 5: Monthly averages of the data available (fraction based) measured by the ZX 300M LiDAR by height at the K13a platform for the period 2016-2022.

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 missed points, which in February 2018 shift up to approximately between 2.5 and 4, and remain around that margin until present. This also corresponds to the observed reduction in availability shown in **Figure 5** where availability decreases from 97% to 95%. Noticeable drops in availability are also observed in April 2020 and 2021. While there is not enough direct information of the Lidar system due to limited site inspection, possible causes for reduced availability could be wiper system malfunctions or dirty lenses caused by lack of rainfall over those months. The number of missed points drops once the LiDAR is replaced in November 2022.

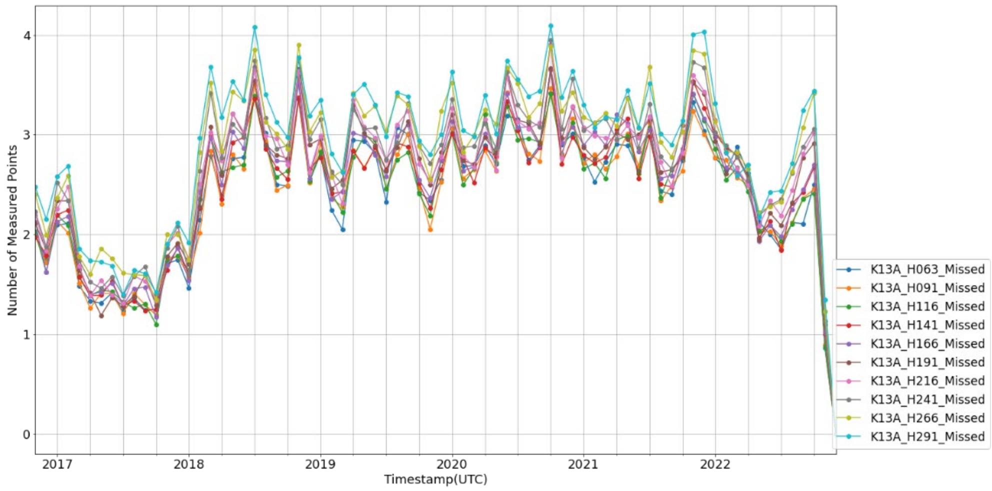


Figure 6: Monthly number of points missed over the measurement period of November 2016 to December 2022.

5 Wind conditions at K13a

This section presents the results following an assessment of the weather conditions during the measurement campaign at the K13a 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 K13a 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 [13] [14].

At the K13a 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 9.29 m/s at the lowest measured height of 63 m up to 10.44 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 241° to 251° (**Table 5**). The wind roses presented in **Figure 7** clearly show the dominant wind direction sector for all the heights 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 K13a platform.

H (m)	63	91	116	141	166	191	216	241	266	291
Ws – Min	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Ws - Mean	9.29	9.68	9.92	10.08	10.19	10.28	10.34	10.38	10.42	10.44
Ws - Max	32.41	34.02	34.88	35.77	36.43	36.84	37.27	37.67	38.00	38.09
Wd - Mean	241.2	243.0	244.3	245.4	246.4	247.5	248.5	249.4	250.1	250.8

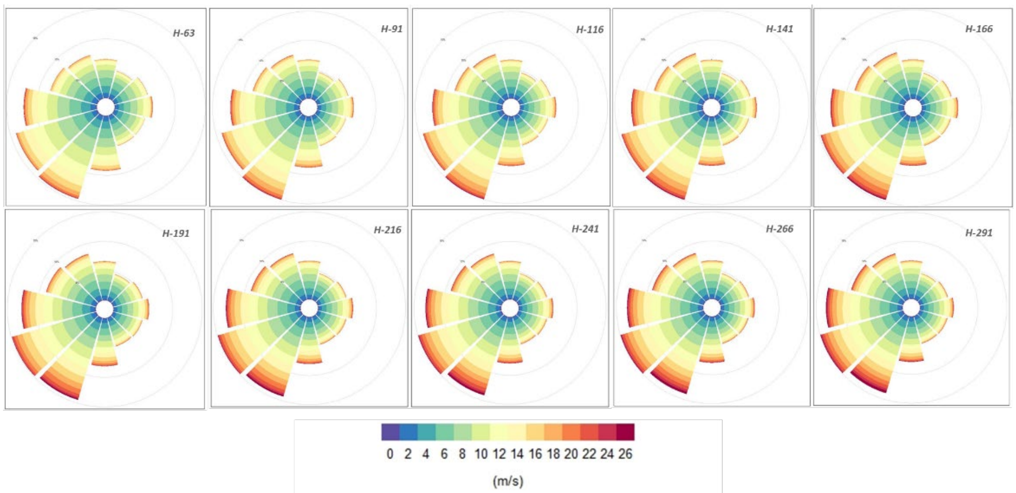


Figure 7: Wind roses at different heights showing the wind prevailing direction for the 2016 - 2022 period.

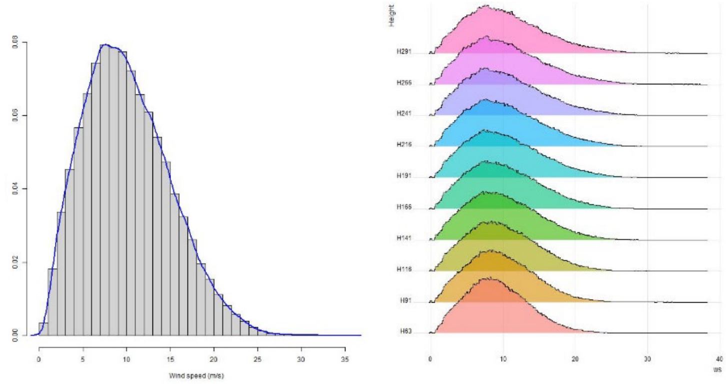
Wind regime frequency distributions and the intra-annual variability typically represented by the Weibull probability density function. This two-parameter relationship between probability of occurrence for a given wind speed v (in m/s), shape dimensionless parameter, k, and scale parameter, c (in m/s)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

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

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 during the period 2016-2022 at K13a, the best approximation of the Weibull function at 141 m height yields a shape parameter of 2.155 and a scale parameter of 11.389 m/s (see the table of Figure 8). Figure 8 (left) shows the wind speed frequency distribution, and the Weibull probability density function fitted over the distribution. Due to fairly complete years with proper seasonality in each, all the years were considered in the calculation.

The **Figure 8** (centre) indicates the frequency distribution of the wind speed for each measurement height and it 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 North Sea.



Height (m)	Shape (k)	Scale (c)
63	2.263	10.510
91	2.238	10.943
116	2.195	11.207
141	2.155	11.389
166	2.120	11.519
191	2.089	11.615
216	2.063	11.686
241	2.040	11.736
266	2.022	11.777
291	2.010	11.806

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 K13a for 2016-2022.

The **Figure 9** presents the seasonal variation on both monthly 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 7 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 general circulation of the North Sea via heat fluxes and by vertical mixing caused by the lower-atmosphere and land energy balance. The wind direction is quite consistent at approximately 220 - 260 degrees year round, except for the month of April, where the winds predominantly come from the northeast.

Considering the diurnal cycle at the K13a platform, the offshore wind speeds vary within margins of about 0.5 m/s on and of approximately 10 degrees in wind direction.

The wind conditions analysed in this report are in line with the assessment presented in [15], [16]. Such studies present additional description over the temporal variability of horizontal and vertical wind profiles at different offshore locations over the Dutch North Sea.

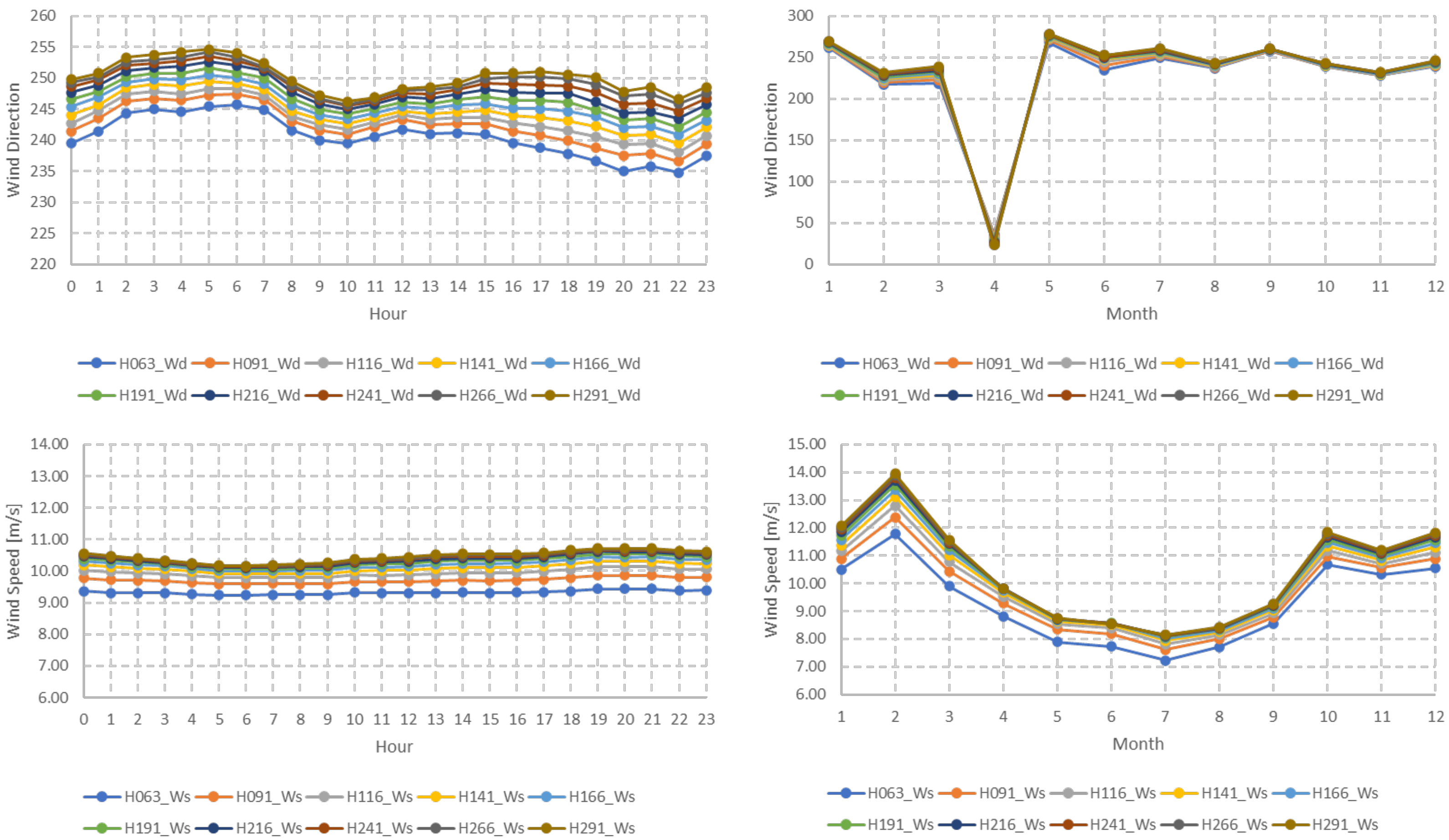


Figure 9: Matched and filtered wind speed and direction monthly averages (right) and average diurnal cycles (left) at different heights for the 2016-2022 period.

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 at all heights for each successive year to present. 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 2020. 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, it however lower compared to 2016, 2017 and 2018.

The annual frequency distributions at different heights are shown for each year in **Figure 11**, with previous years presented in the 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 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 similar wind speed throughout most of the year with exceptionally higher wind speeds in February and November, similar to the year 2020. The lowest wind speeds were registered in summer in August, and was the lowest recorded compared to other years. Annex B includes additional annual wind analysis and statistics for the K13a platform.

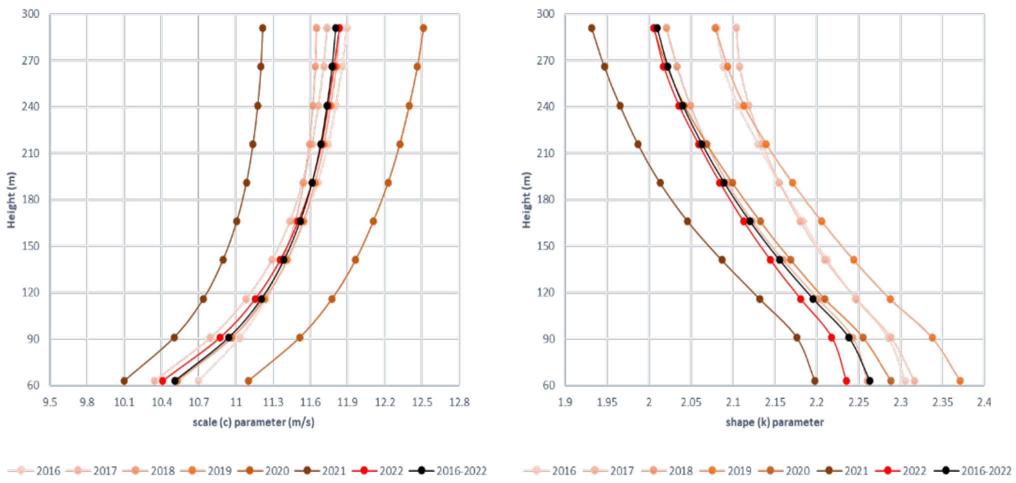


Figure 10: Annual Weibull (left) scale and (right) shape parameters at different heights at the K13a platform from 2016 to 2022.

Table 6: Descriptive annual statistics of the wind speed (Ws) and wind direction (Wd) at 141m height at the K13a platform.

H141 (m)	2016	2017	2018	2019	2020	2021	2022
Ws (m/s)- Min	0	0	0	0	0	0	0.642
Ws (m/s)– 1st q	6.62	6.39	6.35	6.699	6.573	5.947	6.255
Ws (m/s)- Median	9.75	9.66	9.52	9.721	10.016	9.094	9.424
Ws (m/s)- Mean	**10.17**	**10.00**	**10.08**	**10.305**	**10.575**	**9.655**	**10.044**
Ws (m/s)- 3rd q	13.21	13.30	13.42	13.457	13.765	12.607	13.326
Ws (m/s)– Max	26.74	31.72	32.34	29.492	35.765	27.693	33.877
Wd (°)- Mean	231.7	253.8	226.2	242.0	236.9	275.0	240.3

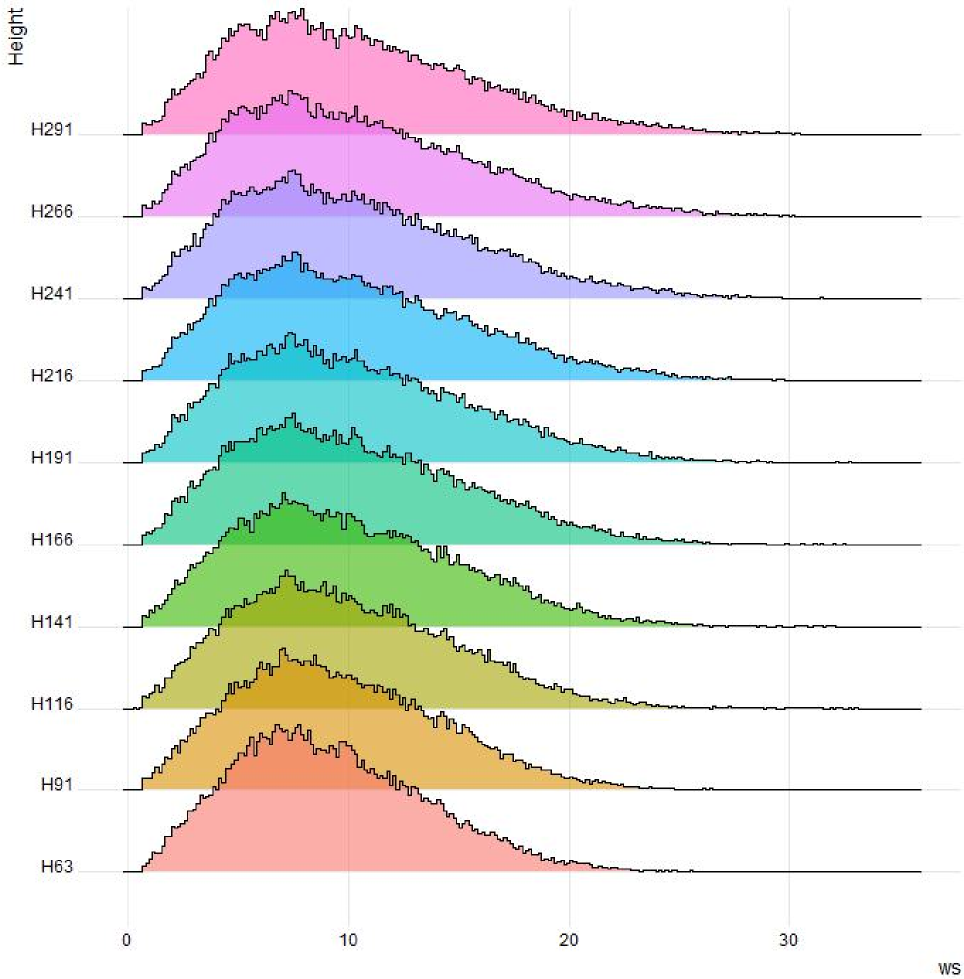


Figure 11: Annual frequency distribution derived for different sensor heights for the year 2022.

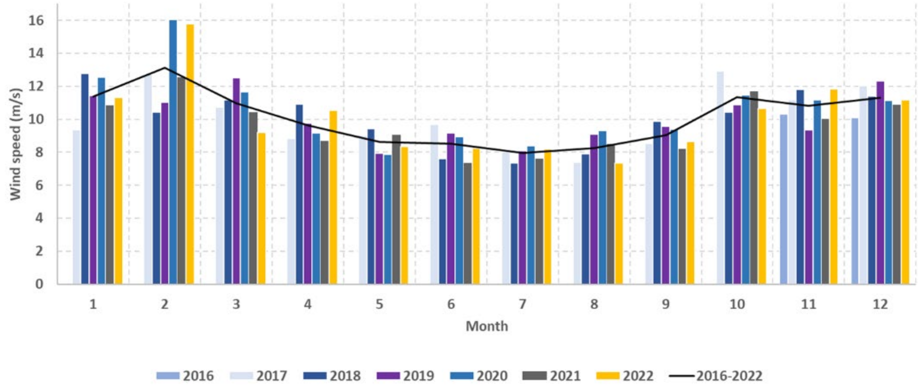


Figure 12: Annual wind speed (m/s) monthly averages bars at 141 m height and 2016-2022 monthly average (black line).

5.3 Analysis of wind shear and veer

Wind shear is described as the variations of wind speed with respect to height, and it is an important characteristic of the wind resource since it impacts the assessment of wind speeds from measurement heights to the proposed hub heights 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:

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

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 value 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 0.026 to 0.111, is decreasing with increasing sensor pair heights. This would indicate the present of shear relaxation, a slowing down of wind speeds 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 0.18 from southwest direction to negative shear in the eastern direction. Shear exponents are not tightly bound, as distinctions between curves demonstrate a reduction in shear between increasing sensor heights. Thus the directional variation and shape of the shear relaxation with height is captured and is non uniform across sectors. The largest discrepancy is noticed between 91 and 63 m pairs primarily from the south and southeast sectors. This can be due to the influence of the KNMI mast which is south of the lidar position on the K13a platform.

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. Once again, difference in shear between heights is noticeable, indicating shear relaxation is present.

Figure 15 presents the extrapolated shear exponent considering only the data for the year 2022, distinguishing between daytime and night-time hours. Wind speed profile does not follow a consistent shear exponent. Much like the values reported in **Table 7**, shear relaxation is observed, with larger changes in wind speeds at lower heights compared to higher heights.

Table 7: Annualized shear exponent for different sensor height pairings at K13a over the entire data period, 2016 to 2022.

Shear Pairing	Shear exponent
63 m - 91 m	0.111
91 m - 116 m	0.098
116 m - 141 m	0.082
141 m - 166 m	0.069
161 m - 191 m	0.058
191 m - 216 m	0.048
216 m - 241 m	0.038
241 m – 266 m	0.034
266 m – 291 m	0.026

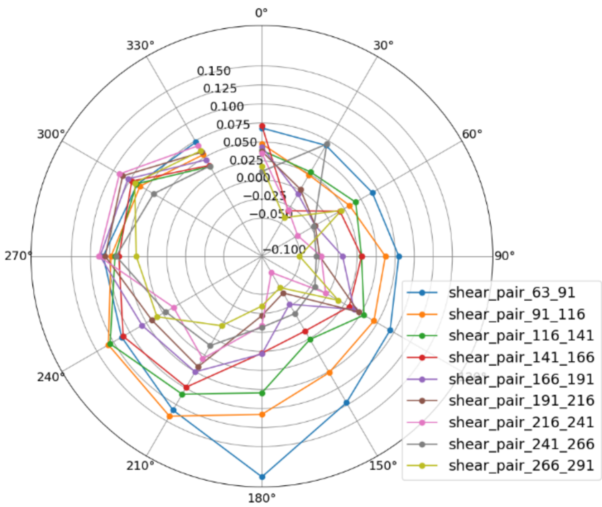


Figure 13: Directional shear profile trends for LiDAR sensor pairings for the entire data period 2016-2022

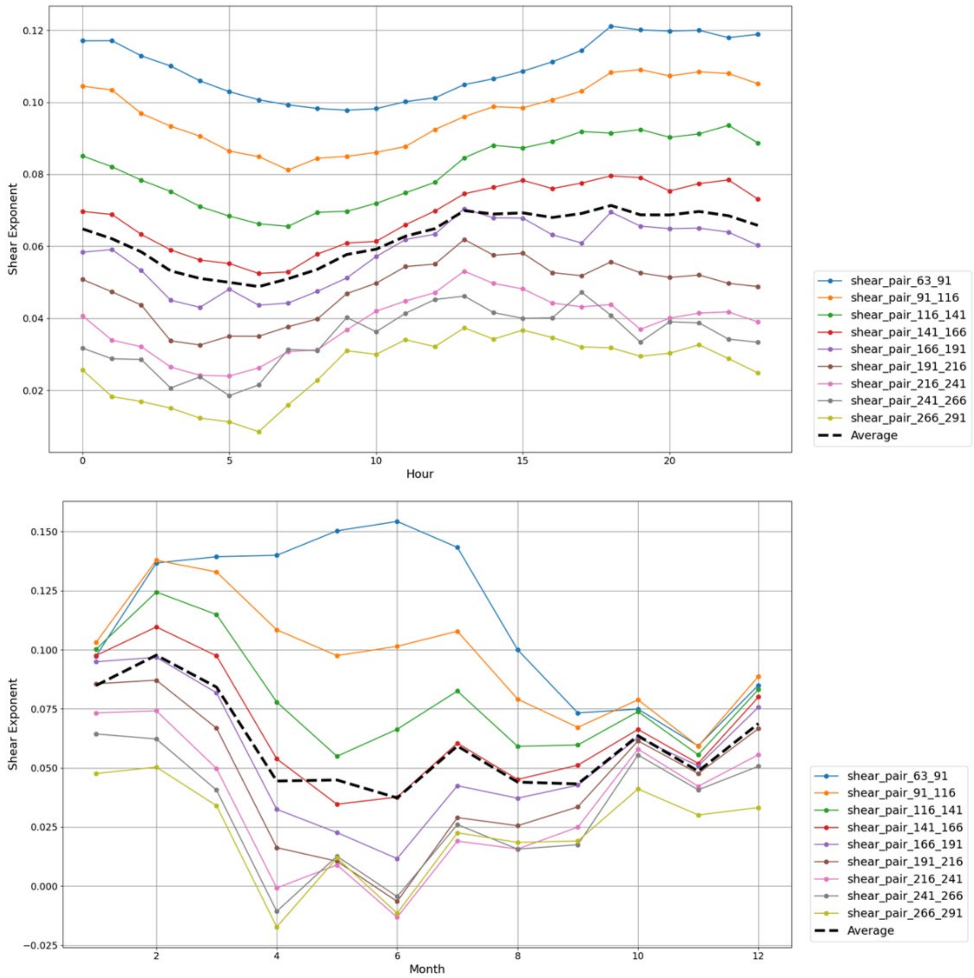


Figure 14: Shear profiles for LiDAR sensor pairs showing diurnal (top) and annual (bottom) trends for the data period 2016 to 2022

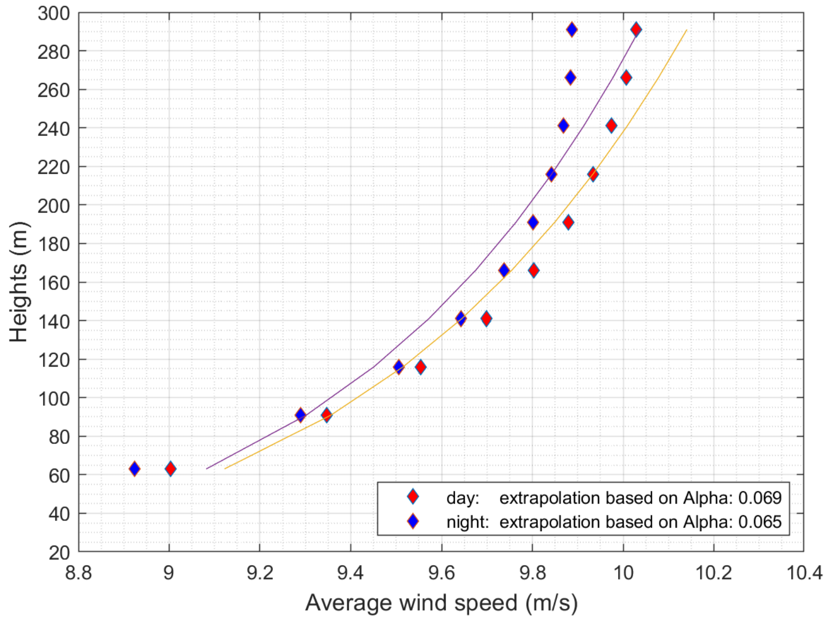


Figure 15: Day and night shear profiles at K13a for the year 2022

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 is 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 K13a considered only over the year 2022. At the lowest measured height of 63 m, the average wind direction was calculated to be approximately 234 degrees, while at the highest sensor height of 291 m the average wind direction was found to be approximately 245 degrees. That results in a difference of approximately 11 degrees between these levels. Larger variations at the lower heights are noticeable compared to higher heights.

Figure 17 presents the annual and diurnal variations in veer of the average wind direction over the entire 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 +0.25 to +1.5 degrees. The 91-63 senso pair fluctuates from +1.5 to +2.5 degrees

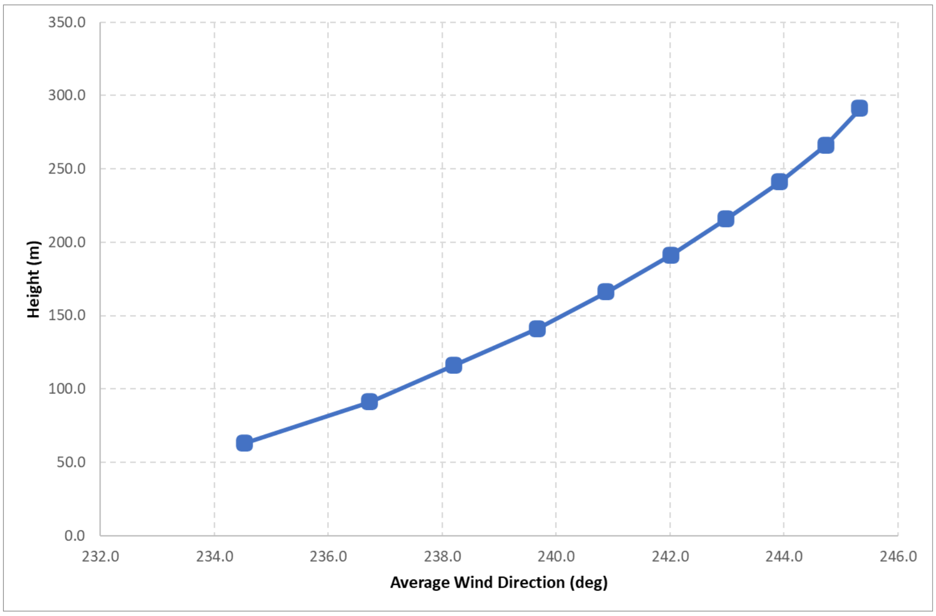


Figure 16: Variations in the matched and filtered average wind direction for different sensor heights over the year 2022

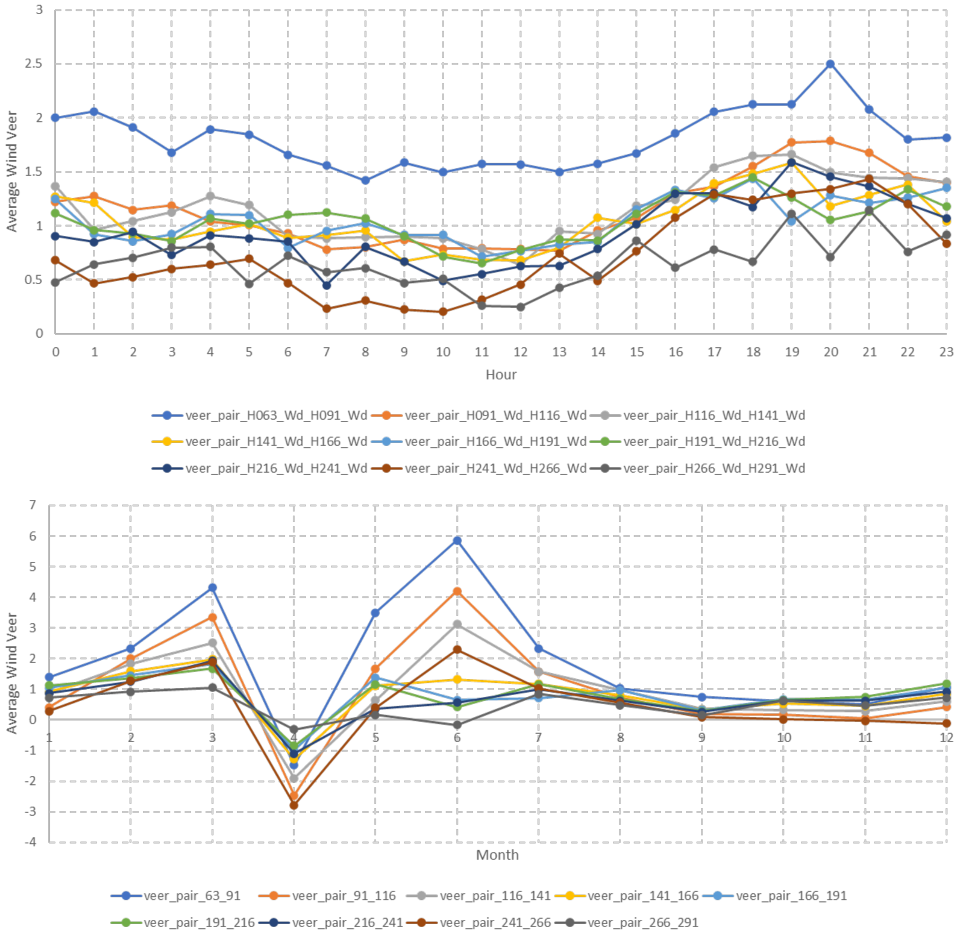


Figure 17: Matched and filtered veer profiles for LiDAR sensor pairs showing hourly (top) and monthly (bottom), trends for the data period of 2016 to 2022

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, and overall a windier 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 [17]. **Figure 18** shows the time series for the wind speed at the 141 m sensor height, where wind speeds ranged between 20 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 at this location are further highlighted in the **Table 8**, as the year 2020 still dominates the entire top 10 list. As shown previous, February 2022 was in line with February 2020 as being a high wind month, albeit slightly lower (**Figure 12**).

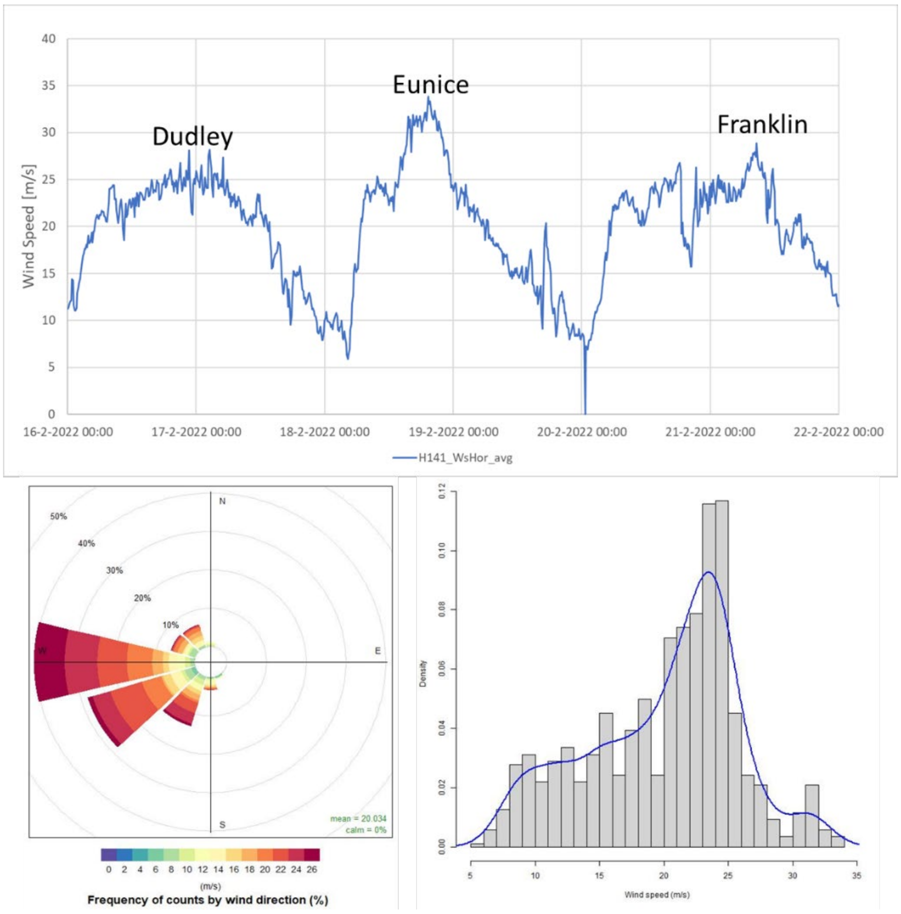


Figure 18: 10-minute wind speed timeseries (top), wind rose (bottom-left), and frequency distribution (bottom-right) measured by the LiDAR at 141 m at K13a platform during the triplet of storms Dudley, Eunice and Franklin in February 2022

Table 8: Top 10 windiest 10-minute averaged recorded timestamps at 141 m height at K13a from 2016-2022

Rank	Timestamp	Wind Speed Recorded [m/s]
1	9-2-2020 11:40	35.8
2	9-2-2020 12:00	35.6
3	9-2-2020 12:10	35.5
4	9-2-2020 12:50	35.2
5	9-2-2020 11:20	35.2
6	9-2-2020 13:30	34.8
7	9-2-2020 13:00	34.6
8	9-2-2020 15:40	34.6
9	9-2-2020 11:30	34.5
10	9-2-2020 12:30	34.4

6 Conclusions and recommendations

This report refers to the measurement campaign at the K13a platform where a ZX 300 LiDAR has been deployed, and recently replaced in November 2022, providing high quality data. The data are publicly available to be used for further purposes (www.windopzee.net).

At the K13a 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 241° to 251° across the different sensor heights (63 m to 291 m). The average calculated wind speed ranges from 9.29 m/s at the lowest measured height of 63 m up to 10.44 m/s at 291 m, increasing gradually.

The Weibull distribution, indicating wind regimes and inter-annual variability, shows wind speed distributions with typical offshore wind k, and c parameters (k = 2.155 and c = 11.389 m/s at 141 m height). The wind speed frequency distribution is flatter and moderately skewed to the right at higher sensor heights, with more frequent wind speeds greater than 26 m/s.

The resulting assessment of the shear profile shows an annualized range of 0.026 to 0.111 considering the entire data period between matched sequential sensor height pairs of the LiDAR. For the period year 2022, the calculated day and night time shear was does is not properly represented by the fitted shear exponent, indicating shear relaxation between heights.

Veer was found to increasing in a clockwise direction between all sequential pairs when considering the entire data period, with an overall difference of approximately 11° between the lower and most upper sensor heights specifically for 2022.

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 was registered as the third most severe in the past 50 years. Wind speeds ranged between 20 and 35 m/s. The year 2020 dominates the entire top 10 list.

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 K13a 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. K13a, 2016-2019,” TNO R11058, 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. K13a, 2016-2020,” TNO R10371, 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. K13a, 2016-2021,” TNO R11001, Petten, 2022.

[8] J. V. P. v. d. W. G. Bergmen, „K13-A LiDAR measurement campaign; Instrumentation Report 2023,” TNO 2023 R10159, Petten, 2023.

[9] J. V. D.A.H Wouters, „Verification of ZephIR 300M unit 563 at ECN part of TNO LiDAR Calibration Facility for offshore measurements at K13-A production platform,” TNO 2018 R10850, Petten, 2019.

[10] Z. Lidars, „ZX1525 Performance Verification,” ZX Lidars, 2022.

[11] 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.

[12] The Carbon Trust, „Carbon Trust Offshore Wind Accelerator roadmap for the,” Carbon Trust, 2013.

[13] 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.

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

[15] 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.

[16] 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.

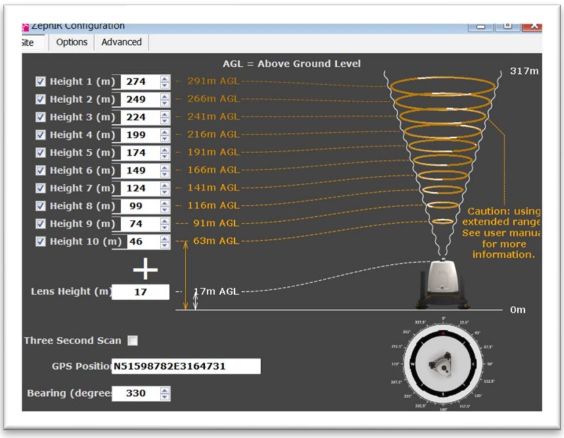
[17] KNMI, "Drielingstorm Dudley, Eunice en Franklin," 21 February 2022. [Online]. Available: https://www.knmi.nl/over-het-knmi/nieuws/drielingstorm-dudley-eunice-en-franklin. [Accessed 14 March 2023].

[18] 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.

Appendix A
LiDAR specifications ZX 300

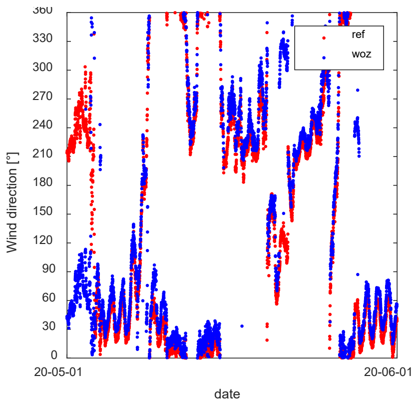
Setting and Configuration

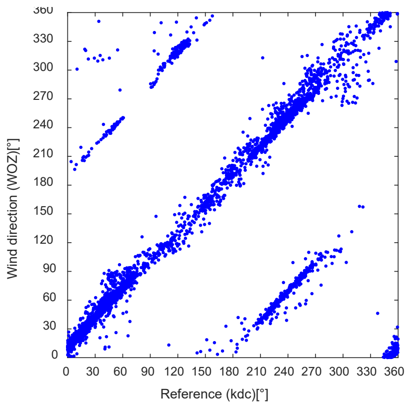
TNO is accredited for remote sensing device calibration (ISO 17025). The LiDAR is upfront verified against Meteorological Mast 4, in accordance with IEC 61400-12-1:2017. The validation is performed by checking Key Performance Indicators (KPIs) [8]. The figure below shows an example of screen setting of the LiDAR configuration and adjustments.

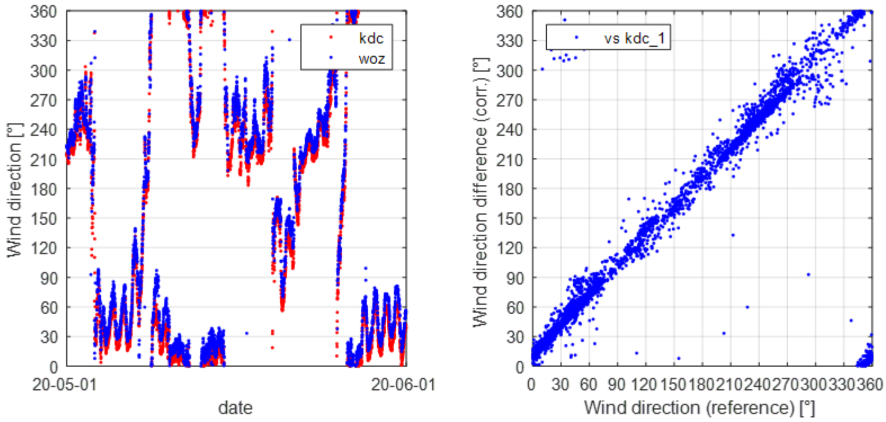


Data correction – 180 degrees offset

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 (K13a_wsmet and K13a_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 K13a and from the KNMI met mast; before (top) and after (bottom) applying the correction methodology.







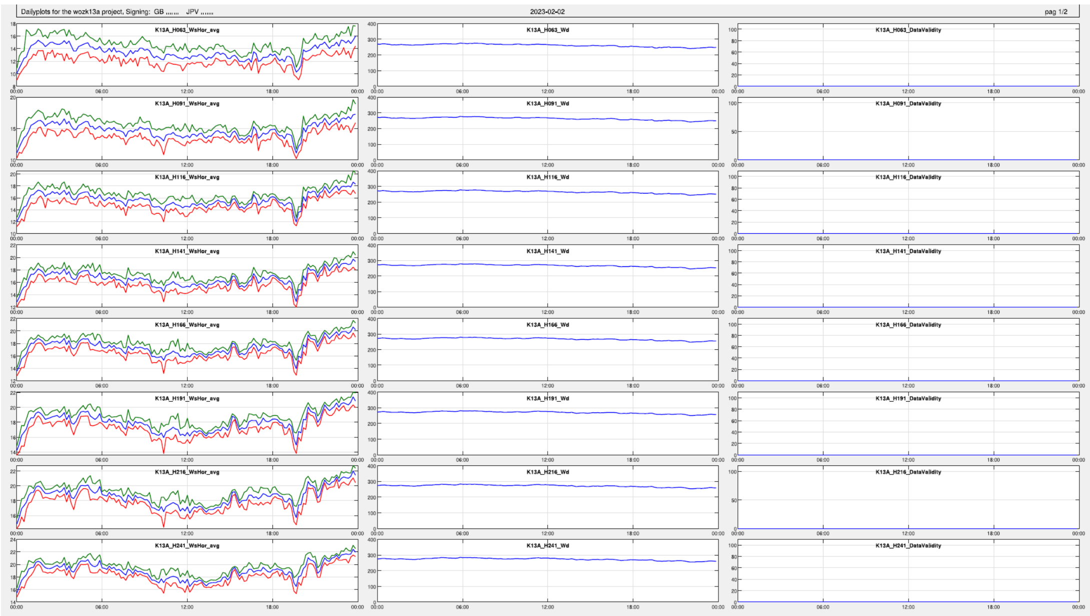
Data availability

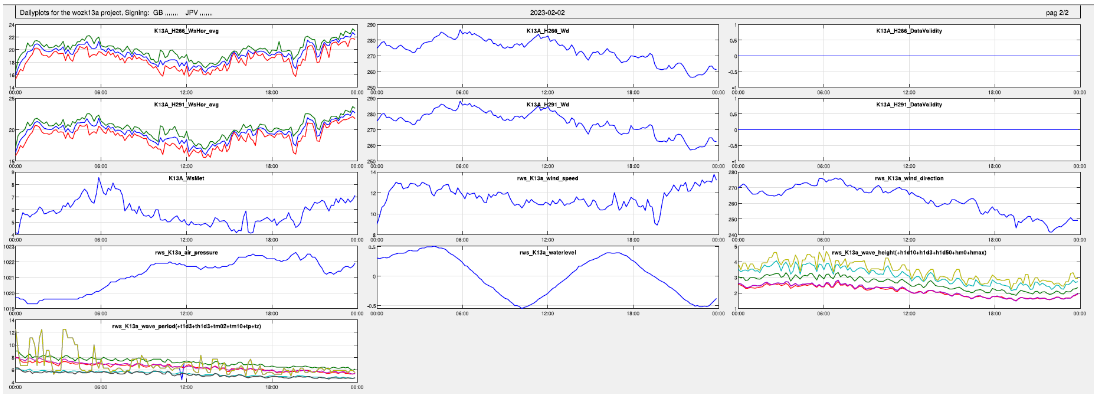
For the ZX 300 LiDAR, the quantification of the overall availability in a 10-minute interval (for a certain height), it is considered the number of packets by definition [15]. Due to different technology, the methodology to calculate data availability of the ZX 300 LiDAR is not comparable with the data 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

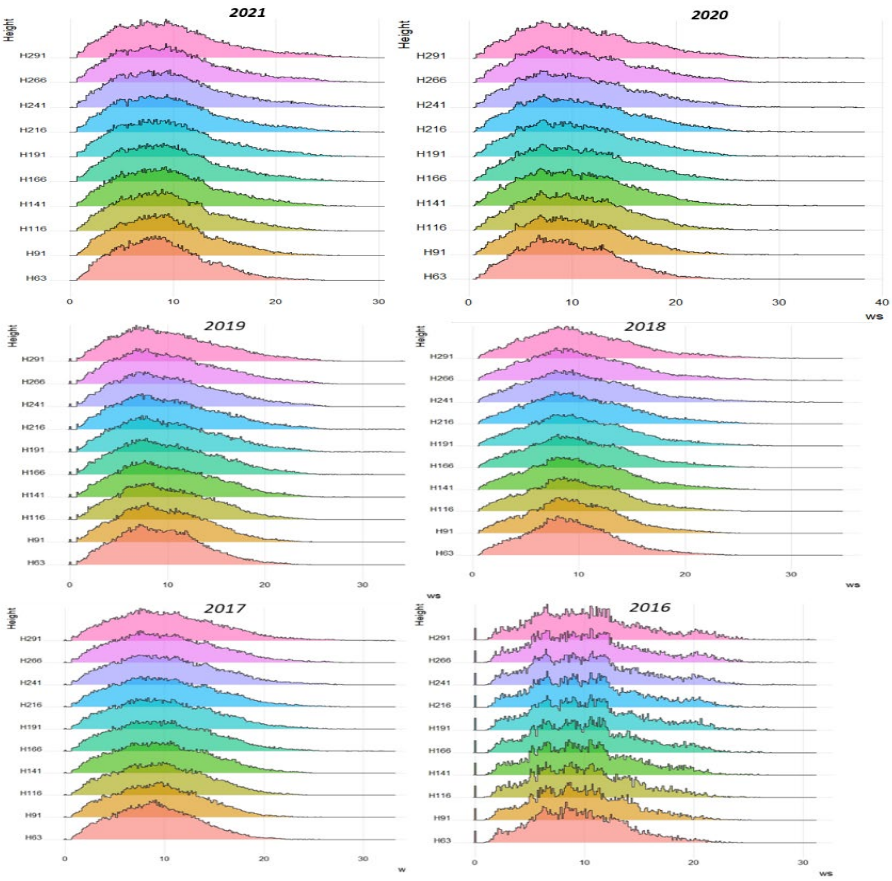




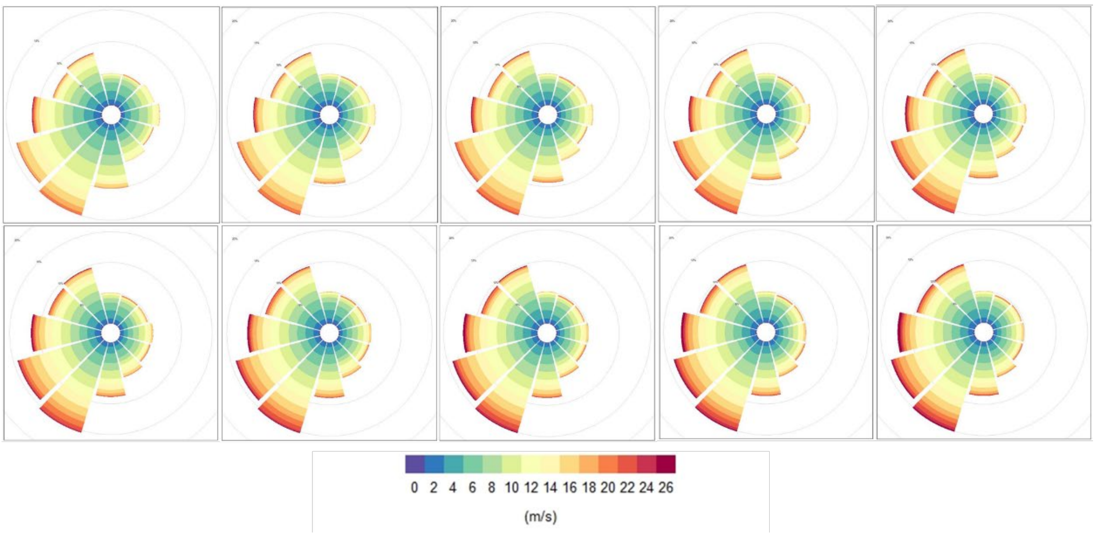
Appendix B
Annual weather conditions during the campaign at K13a

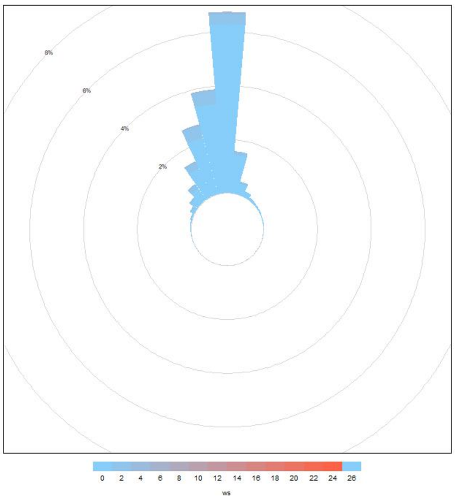
This section contains visual and statistical descriptive summary about the annual weather conditions per year at the K13a from 2022 backwards in time to 2016. These statistics are influenced by the available months of data, and do not account for seasonality. The annual prevailing wind direction recorded was South-West, at different heights, as indicated by the wind roses (top). The wind direction was calculated considering the average unit wind direction vector. 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.

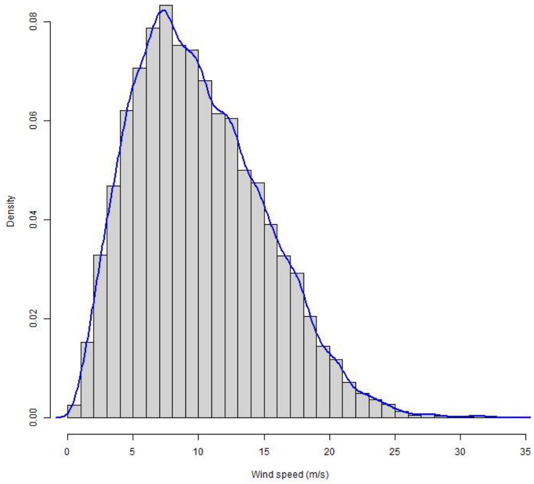
B.1 Yearly Frequency Distributions By Height (Previous Years)



B.2 2022

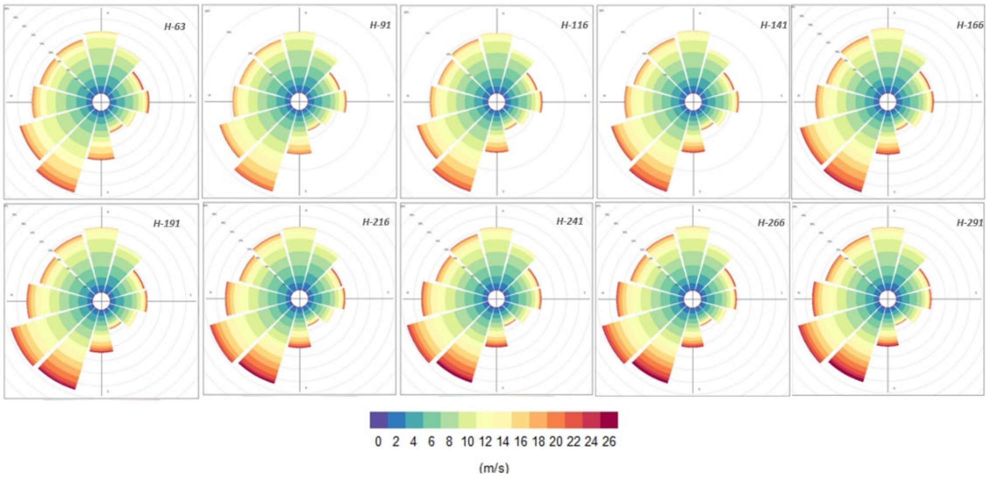


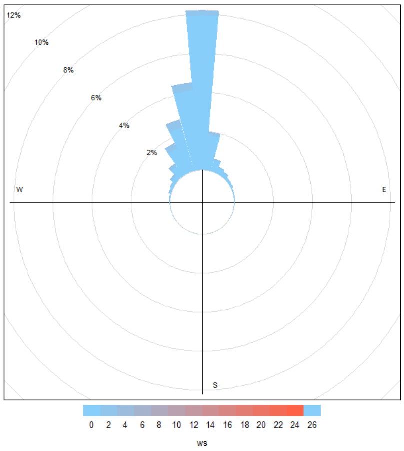


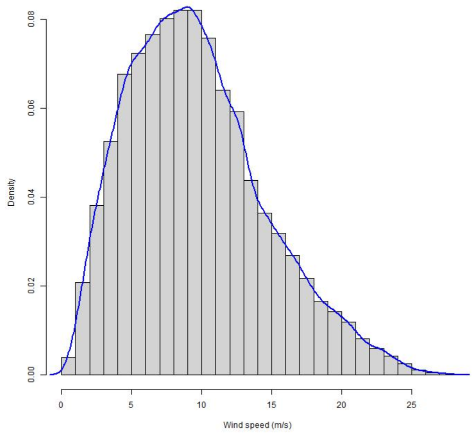


H (m)	63	91	116	141	166	191	216	241	266	291
Ws - Min	0.05	0.67	0.24	0.64	0.27	0.27	0.58	0.44	0.49	0.30
Ws – 1st q	5.95	6.16	6.23	6.26	6.26	6.27	6.26	6.24	6.25	6.27
Ws - Median	8.69	9.08	9.29	9.42	9.50	9.56	9.60	9.60	9.61	9.64
Ws - Mean	9.21	9.62	9.87	10.04	10.17	10.27	10.34	10.38	10.43	10.46
Ws - 3rd q	12.05	12.66	13.05	13.33	13.52	13.66	13.75	13.80	13.85	13.90
Ws – Max	30.51	31.96	33.06	33.88	34.17	34.10	34.29	34.65	35.16	35.81
Wd - Mean	234.8	237.2	238.9	240.3	241.6	242.8	243.9	244.8	245.8	246.5

B.3 2021

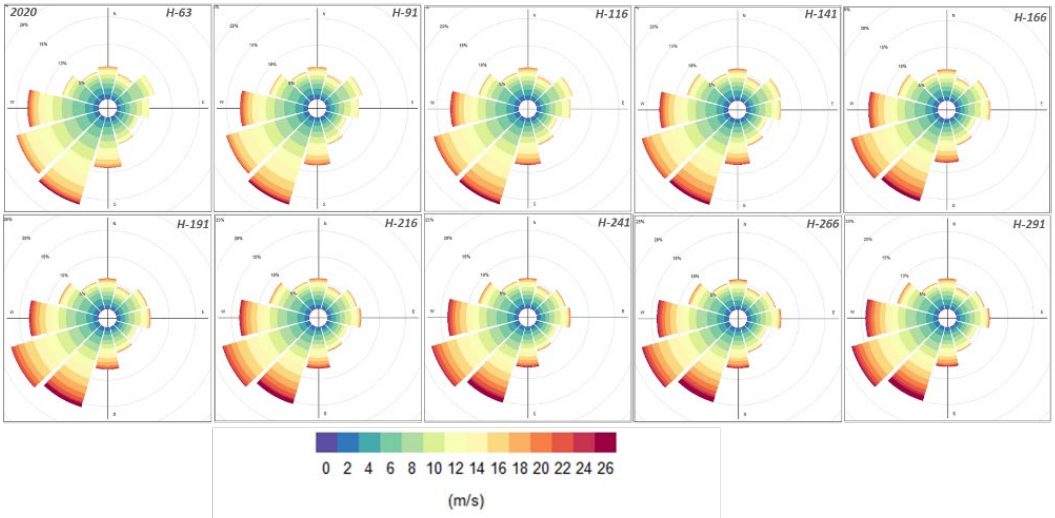


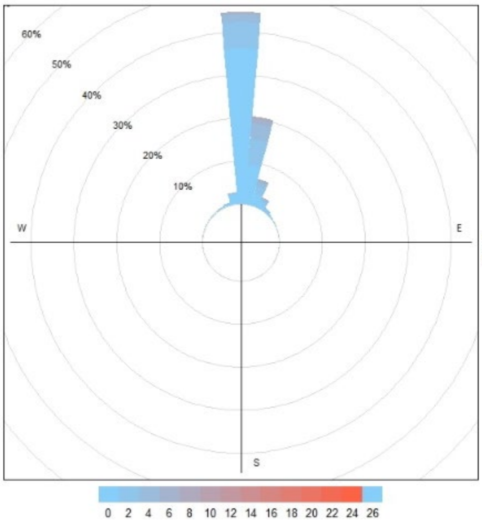


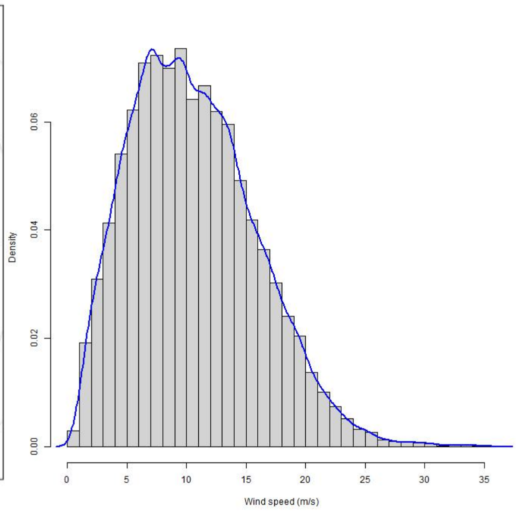


H (m)	63	91	116	141	166	191	216	241	266	291
Ws - Min	0.295	0.247	0.217	0.658	0.220	0.249	0.540	0.115	0.205	0.189
Ws – 1st q	5.718	5.891	5.933	5.947	5.938	5.919	5.904	5.886	5.874	5.866
Ws - Median	8.517	8.858	9.005	9.094	9.130	9.151	9.171	9.182	9.187	9.190
Ws - Mean	8.945	9.302	9.514	9.655	9.756	9.826	9.875	9.910	9.935	9.949
Ws - 3rd q	11.609	12.099	12.401	12.607	12.747	12.835	12.892	12.935	12.959	12.959
Ws – Max	25.97	26.71	27.37	27.693	28.64	29.90	30.32	30.74	31.52	32.71
Wd - Mean	271.2	273.2	274.2	275.0	275.8	276.6	277.4	278.3	278.9	279.4

B.4 2020

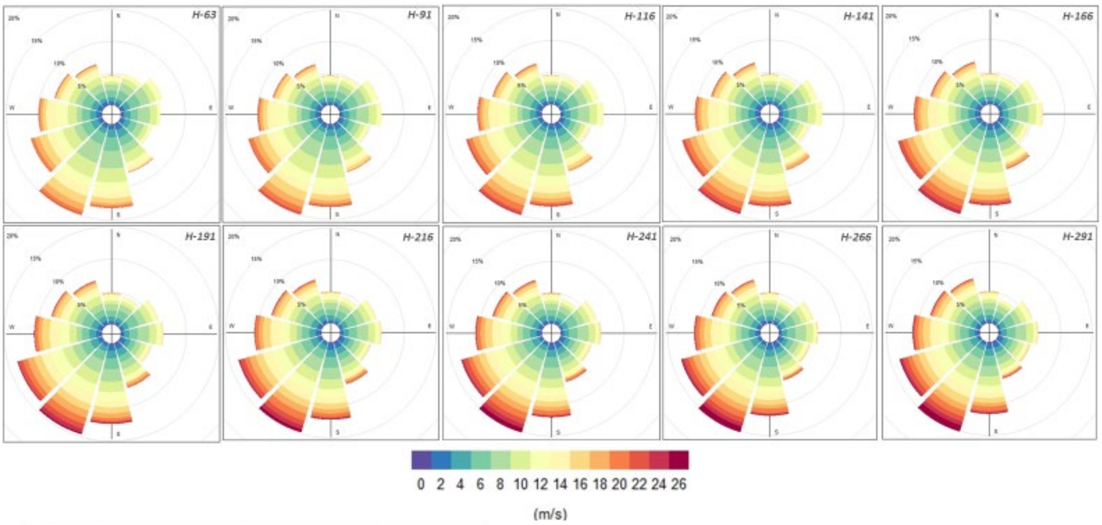


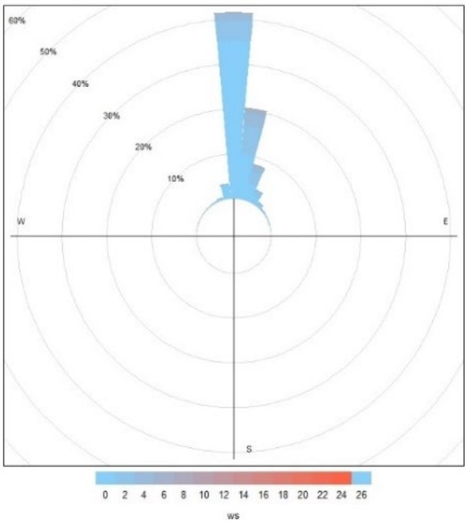


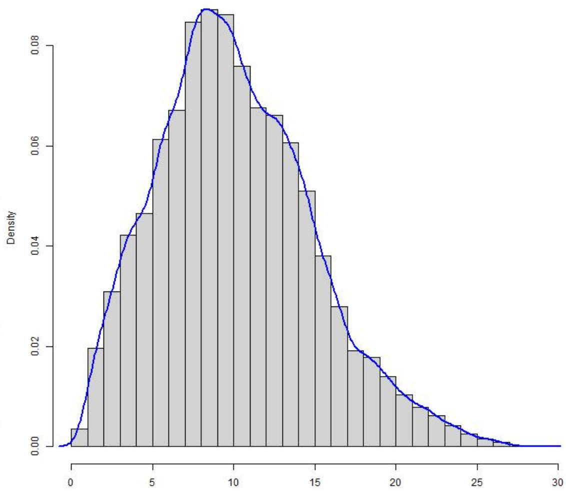


H (m)	63	91	116	141	166	191	216	241	266	291
Ws - Min	0.667	0.669	0.669	0.669	0.663	0.663	0.670	0.662	0.671	0.670
Ws – 1st q	6.329	6.474	6.537	6.573	6.574	6.587	6.582	6.580	6.587	6.591
Ws - Median	9.354	9.735	9.917	10.016	10.084	10.123	10.148	10.147	10.136	10.130
Ws - Mean	**9.815**	**10.180**	**10.410**	**10.576**	**10.702**	**10.807**	**10.890**	**10.957**	**11.016**	**11.060**
Ws - 3rd q	12.931	13.439	13.754	13.991	14.190	14.34	14.459	14.539	14.607	14.655
Ws – Max	32.405	34.016	34.879	35.764	36.432	36.839	37.273	37.669	38.003	38.091
Wd - Mean	234.4	235.4	236.0	236.9	237.8	238.9	239.9	240.7	240.9	241.7

B.5 2019

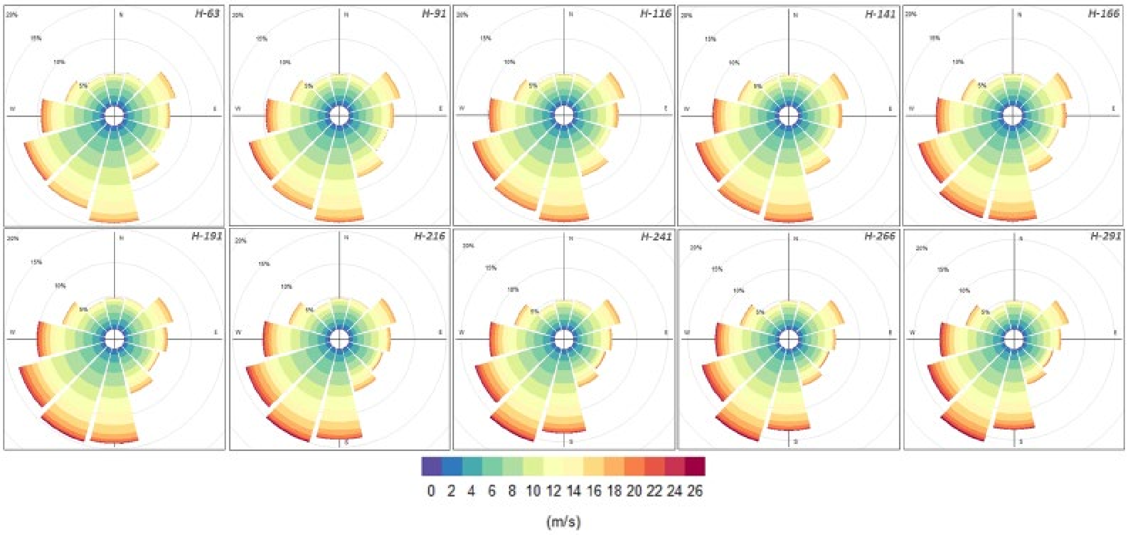


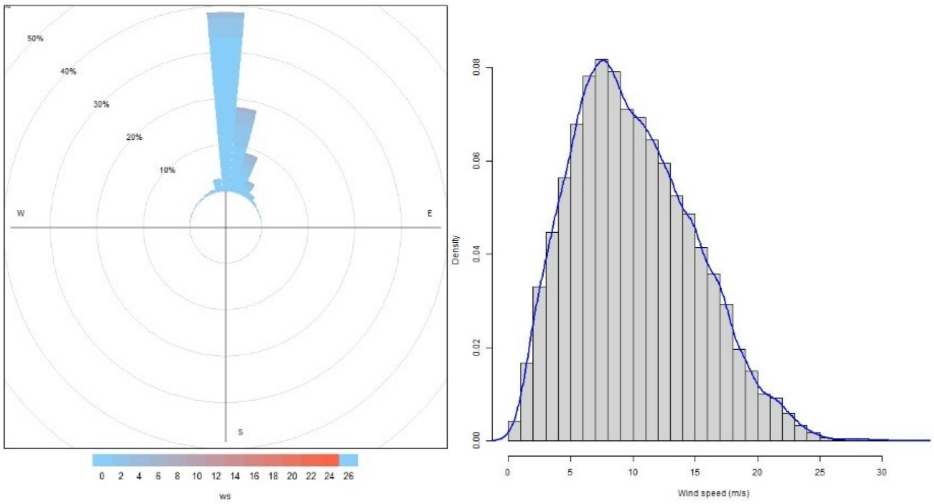




H (m)	63	91	116	141	166	191	216	241	266	291
Ws - Min	0	0	0	0	0	0	0	0	0	0
Ws – 1st q	6.44	6.64	6.685	6.68	6.69	6.69	6.70	6.68	6.68	6.68
Ws - Median	9.01	9.38	9.57	9.67	9.71	9.72	9.72	9.73	9.72	9.72
Ws - Mean	**9.33**	**9.72**	**9.95**	**10.11**	**10.22**	**10.30**	**10.36**	**10.41**	**10.45**	**10.47**
Ws - 3rd q	11.92	12.52	12.92	13.17	13.33	13.45	13.51	13.54	13.57	13.59
Ws – Max	26.73	27.06	27.95	28.68	29.18	29.49	30.98	32.98	33.80	34.55
Wd - Mean	238.2	239.8	240.9	242.0	243.0	244.1	245.1	245.8	245.8	246.3

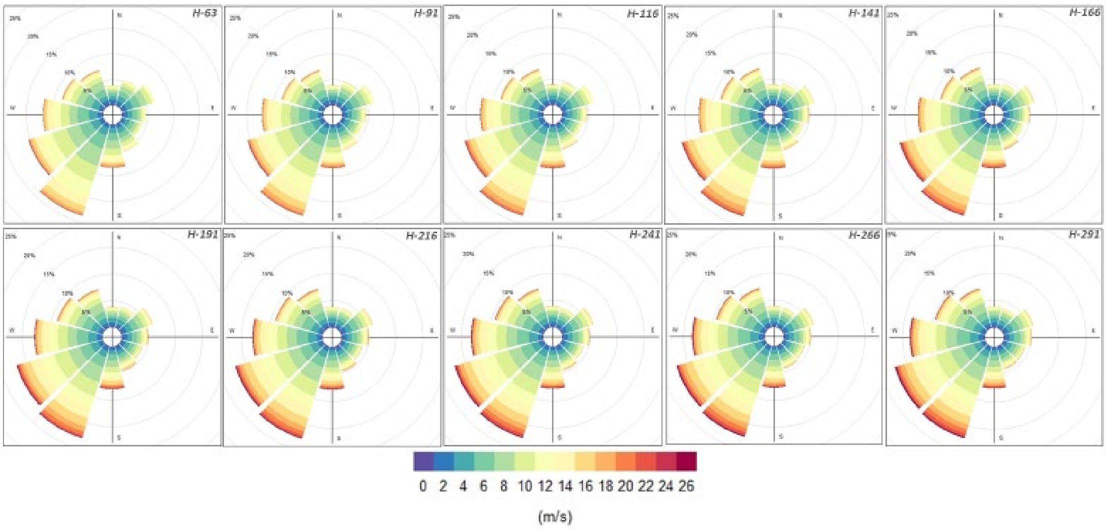
B.6 2018

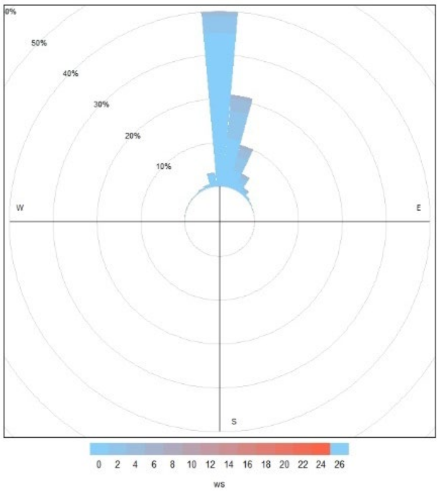


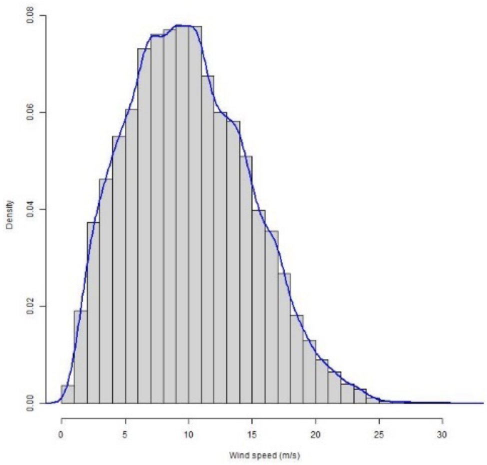


H (m)	63	91	116	141	166	191	216	241	266	291
Ws - Min	0	0	0	0	0	0	0	0	0	0
Ws – 1st q	6.10	6.30	6.34	6.35	6.35	6.32	6.13	6.30	6.29	6.28
Ws - Median	8.97	9.29	9.44	9.52	9.56	9.58	9.59	9.58	9.57	9.56
Ws - Mean	9.33	9.72	9.94	10.08	10.17	10.23	10.27	10.29	10.31	10.32
Ws - 3rd q	12.11	12.81	13.19	13.42	13.55	13.62	13.67	13.70	13.71	13.71
Ws – Max	29.50	30.69	31.64	32.34	32.65	33.35	34.61	35.39	35.78	35.98
Wd - Mean	221.2	222.5	224.2	226.2	227.3	228.7	229.7	230.7	232.8	233.7

B.7 2017

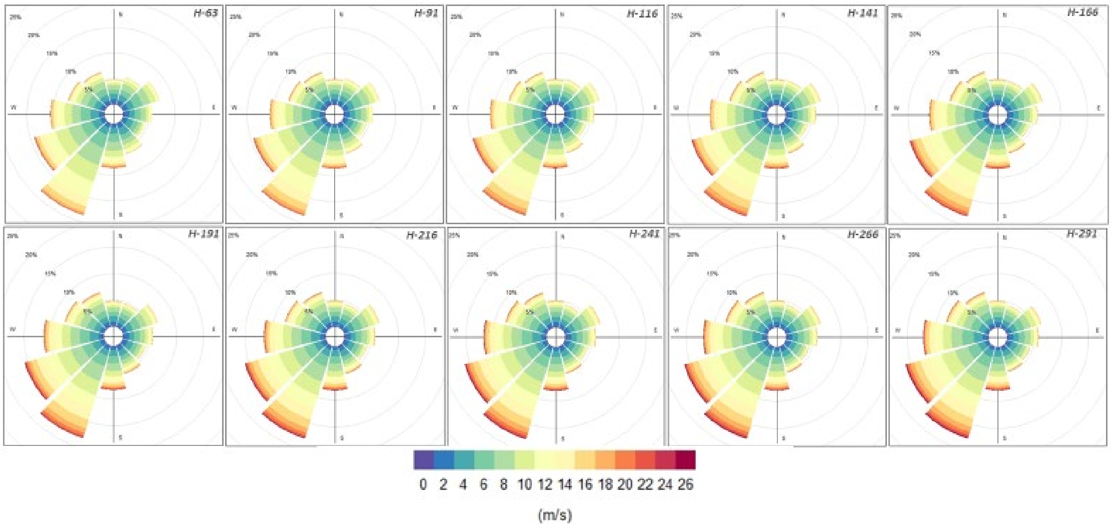


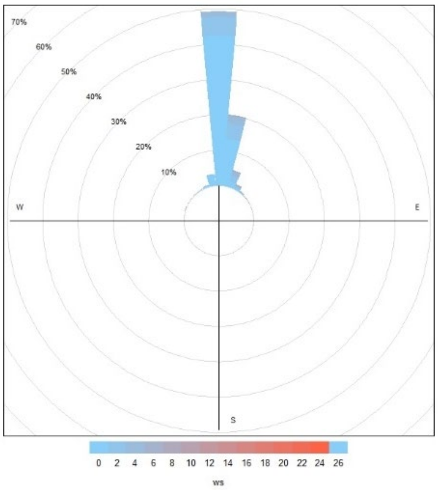


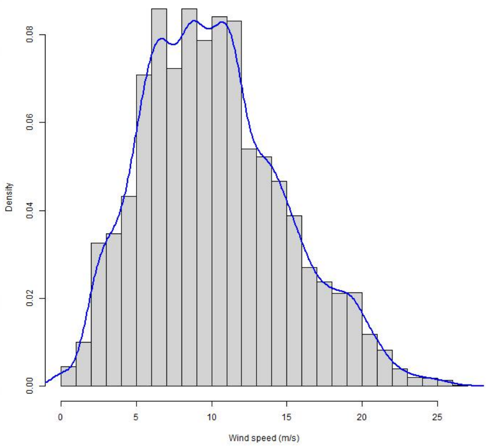


H (m)	63	91	116	141	166	191	216	241	266	291
Ws - Min	0	0	0	0	0	0	0	0	0	0
Ws – 1st q	6.07	6.26	6.34	6.39	6.42	6.43	6.46	6.46	6.49	6.51
Ws - Median	8.91	9.33	9.54	9.66	9.74	9.76	9.80	9.82	9.83	9.85
Ws - Mean	**9.16**	**9.56**	**9.82**	**10.00**	**10.13**	**10.22**	**10.28**	**10.33**	**10.36**	**10.39**
Ws - 3rd q	11.95	12.59	13.00	13.30	13.51	13.62	13.71	13.75	13.79	13.79
Ws – Max	29.39	30.21	30.98	31.72	31.97	32.40	32.55	32.78	32.83	32.96
Wd - Mean	**248.8**	**251.2**	**252.5**	**253.8**	**254.7**	**255.6**	**256.6**	**257.4**	**258.1**	**258.7**

B.8 2016







H (m)	63	91	116	141	166	191	216	241	266	291
Ws - Min	0	0	0	0	0	0	0	0	0	0
Ws – 1st q	6.40	6.58	6.60	6.62	6.654	6.651	6.643	6.613	6.62	6.629
Ws - Median	9.18	9.46	9.60	9.75	9.829	9.884	9.939	9.95	9.953	9.978
Ws - Mean	9.54	9.84	10.02	10.17	10.293	10.388	10.464	10.515	10.562	10.595
Ws - 3rd q	12.38	12.77	13.00	13.21	13.313	13.425	13.485	13.528	13.567	13.575
Ws – Max	24.42	25.11	25.96	26.74	26.997	27.305	27.485	29.262	30.378	30.983
Wd - Mean	229.3	230.8	231.4	231.7	232.8	234.1	235.6	237.0	236.1	237.0

Energy & Materials Transition

Westerduinweg 3
1755 LE Petten
www.tno.nl

innovation
for life