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TNO report

TNO 2022 R11001

Offshore wind energy deployment in the North Sea by 2030: long-term measurement campaign. K13a, 2016-2021.

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Contents

Executive summary

The North Sea plays a key role in the transformation to meet the European offshore wind plans of 75 GW by 2030. To further meet the revised European frameworks for 2050, in May 2022 four countries, Denmark, Germany, Belgium together with the Netherlands have signed the Esbjerg Offshore Wind Declaration, where they agreed on expanding their total capacity to 65 GW by 2030 and to 150 GW by 2050. The national government of the Netherlands had already further increased its envisioned installed offshored wind energy capacity targets, by designating new areas of development to facility the large scale deployment of offshore wind. These ambitions will make way for a total of installed capacity of 21.5 GW of to be offshore tenders be reached by 2030. The Netherlands continues its strong pace of offshore wind development, now reaching a total installed capacity of approximately 3 GW as of 2021.

TNO performs for The Dutch Ministry of Economic Affairs and Climate Policy measurement campaigns in the North Sea from 2014 until 2030 at different strategically locations. Currently, the locations of the measurements are Lichteiland Goeree platform (LEG), Europlatform (EPL) and Wintershall Noordzee B.V. platform K13a, under the project ‘2022 Wind Conditions @ North Sea”.

TNO is responsible for the entire life cycle during the measurements: from the installation plan at the platform to the purchase and selection of the instrumentation, monitoring, maintenance of the instrumentation, analysis, reporting and dissemination of the data. This report presents the overview of the measurement campaign at the K13a platform for the period 2016-2021 with a specific focus for the year 2021.

The weather analysis indicates that the measured data captures the variability of the local and regional climate of the area. Comparison with the KNMI measurement at K13a platform and with the wind measurement at EPL and LEG shows a good alignment and quality of the data along the entire period.

The average data availability over the 6 years of the measurement campaign is about 95% up to 200m. This renders the dataset valuable for additional applications in the energy sector. In addition, accurate and long term meteorological measurements are crucial for the feasibility and evaluation of wind farm sites and for financial decisions to ensure the profitability of the business plans.

At the K13a platform, the wind analysis for the 2016-2021 period shows that the wind profiles are dominated by the regional climate, mainly by positive NAO. Prevailing wind direction is South-West: mean of the distribution bell ranges 201° to 206° and the lower and upper quartiles range from 132° to 275° at all heights.

The analysis of shear shows an annualized range of 0.02 to 0.09 considering the entire data period between sequential sensor heights of the LiDAR. Shear relaxation is observed, with larger changes in wind speeds at lower heights compared to higher heights. This was found to be the case within all individual years as well.

Veer in 2021 shows a “backing” trend between the 141 and 241 m height. However considering the whole data period, the trend is still considered “veering”.

1 The importance of long-term wind measurement in the North Sea

1.1 Offshore wind energy deployment

Europe aims to become the first carbon neutral continent by 2050. To reach this goal, wind energy will play a fundamental role in the roll-out of renewable electricity and in the success of the Energy Transition in Europe (A European Green Deal [1]). In July 2021 the EU has proposed the “Fit for 55” framework, with targets to reducing greenhouse gases by 55% by 2030 compared to 1990 levels [2]. Furthermore, the recent and ongoing energy crisis due to Russia’s invasion of Ukraine has prompted further measures and targets outlined in the REPowerEU plan [3].Such new policies imply new efforts from all the European countries to further reduce their emissions and increase their development plans towards decarbonization, including the Netherlands. The North Sea has become a centre for industrial exploration of this technology, and is key for future transformation of the industry, since over 70% of existing and planned European offshore wind farms will be located in this area.

Presently, the national government has a current installed capacity of 2.9 GW [4] installed at the end of 2021. To address the revised EU efforts towards decarbonization, it 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 11.5 GW by 2030. The latter phase has been recently extended by an additional 10 GW, ensuring that a total of installed capacity of 21.5 GW of offshore tenders be reached by 2030 [4]. To achieve this, the government has planned to open 5 new areas for offshore wind farm development to accommodate these revised ambitions and targets (Figure 1). Recently, in May 2022 the Netherlands together with other three European countries, Denmark, Belgium and Germany has signed the Esbjerg Offshore Wind Declaration, agreeing to reach together an install capacity of 65 GW by 2030 and of 150GW by 2050 [5].

To successfully meet the ambitious target set by the EU polices and by the national government it is necessary to have profitable and viable wind farm business plans. One of the crucial parameter to evaluate the financing of a project is the wind resource assessment (WRAs) of a specific site selected. Therefore, accurate long-term offshore wind measurement allows for improved estimations of WRAs, reducing uncertainties and increasing the financial success of a project. This increases the trust between the interested stakeholders, from developers, consultants, the financial community, the government and policymakers. At the same time it allows the selection and identification of strategic locations.

In addition for the need of high quality and long-term measurement campaigns, having multiple measurement locations with high quality data are equally important. As wind farms are growing in size and in scale, one measurement source may not be enough to understand the wind resource across a vast area. Expanding measurement campaigns to include multiple measurement locations can help further reduce uncertainties, and assist project developers in the design of wind farms. At the same time, the presence of wind farms influence the wind measured by a meteorological mast or LiDAR. This influence depends on the location and size of the wind farm, and therefore a large roll-out of wind farms in the North Sea will also influence the measurement campaign. This further highlights the importance of having multiple locations to correct the influenced wind speeds from affected wind direction sectors.

Furthermore, the design conditions for developing an offshore wind farm are not limited to the wind speed and wind direction. Other sources of data can and should be acquired. Wave measurements can be used to inform loading calculations of turbines, while monitoring precipitation can inform degradation rates and impact turbine life cycles. All these measurements help characterize the conditions at sea, and can be useful to reducing the levelized cost of electricity of future offshore wind these suggested instrumentation to help characterize weather condition in deeper waters.

Figure 1 Locations of existing and planned wind farms (grey) and new designated zones for offshore wind farms (orange) to reach 21.5 GW over the Dutch North Sea by 2030, updated in March 2022 [6].

1.2 TNO leading role on offshore measuring campaigns

Before the integration of LiDARs in offshore wind resource assessments, meteorological masts (met mast) have been widely used at TNO: the met mast IJmuiden (MMIJ), as well as the met mast at Offshore Wind farm Egmond aan Zee (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 the installation plan at the platform; to the purchase and selection of the instrumentation, installation, analysing, reporting and dissemination of the data.

Since 2014, TNO is performing for the Dutch Ministry of Economic Affairs and Climate Policy measurement campaigns with LiDARs at three strategically locations in the North Sea. These campaigns are part of the *'2022 Wind Conditions @ North Sea"* project to support the Dutch wind offshore roadmap. These three locations are: Lichteiland Goeree (LEG), Europlatform (EPL) and Wintershall platform K13a (Figure 2).

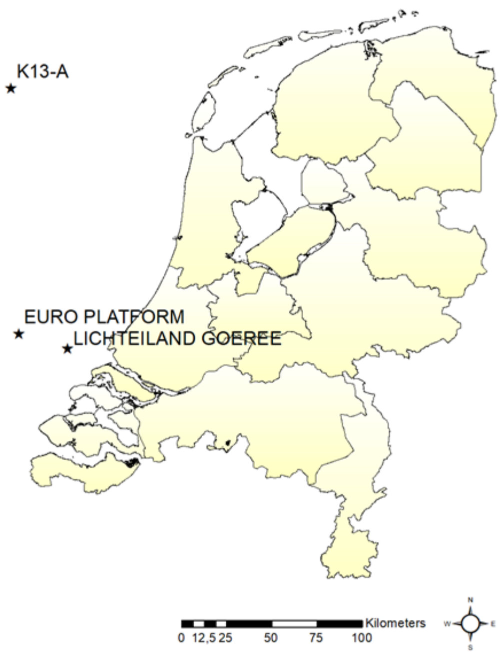


Figure 2 TNO locations of long term measurement campaigns for the wind resource at Lichteiland Goeree (LEG), Europlatform (EPL) and Wintershall platform K13a.

1.3 Open-access and public datasets

Since 2020 TNO has published annually reports on the wind conditions for each measurement campaign location: reports [7] and [8] provide wind conditions analysis for the K13a platform for the periods 2016-2019 and 2016-2020; [9], [10] , and [11] for the LEG platform for the periods 2014-2019, 2014-2020, and 2014-2021; [12], [13] and [14] for the EPL for the periods 2016-2019, 2016-2020, and 2016-2021. This report includes the wind conditions for the period 2016-2021 at the K13a platform. These reports are available at https://www.windopzee.net/en/.

The data measured in the "2022 Wind Conditions @ North Sea" 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 of "2022 Wind Conditions @ North Sea" 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. (2020) K13-a LiDAR measurement campaign; Instrumentation Report, TNO 2020 R10868
2. Citation of this report:
   Pian A., Vitulli J.A., Verhoef J.P., Bergman G., van der Werff P.A., Gonzalez-Aparicio I., (2022) Offshore wind energy deployment in the North Sea by 2030: long-term measurement campaign. K13a, 2016-2021. TNO 2022 R11001.

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: 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.**

2 Measurement campaign at K13a

2.1 Location and instrumentation

The K13a offshore platform is located northwest of Den Helder, 101 kilometers from the coast. The platform serves as a production platform for natural gas, but since November 2016 also makes wind measurements using a platform-mounted (~35 m above MSL) ZX 300M wind LiDAR (Figure 3 left). The platform is part of the North Sea Monitoring Network consisting of several permanent monitoring locations over the North Sea.

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. KNMI locations are shown in Figure 3 right.

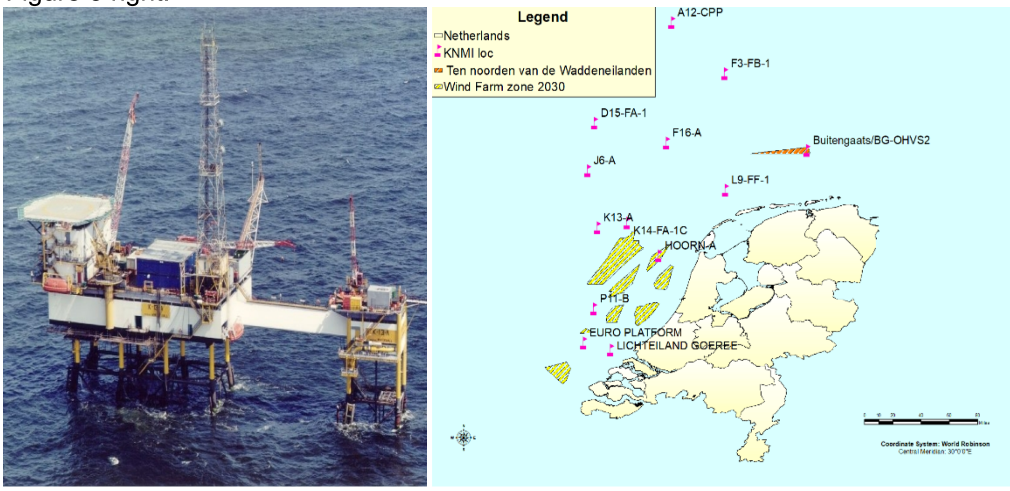


Figure 3 Aerial capture of the K13a platform in November 2016 (left), and KNMI measurement locations in the North Sea (right).

TNO performs 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. The LiDAR is scheduled for replacement, which is set to occur later in 2022.

2.2 Installation plan of instrumentation

The initial phase of a measurement campaign is formed by 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 EPL platform has been recently updated and described in the installation report [15]. At K13a, the suitable place was found just aside the helipad of the platform (Figure 4c, d).

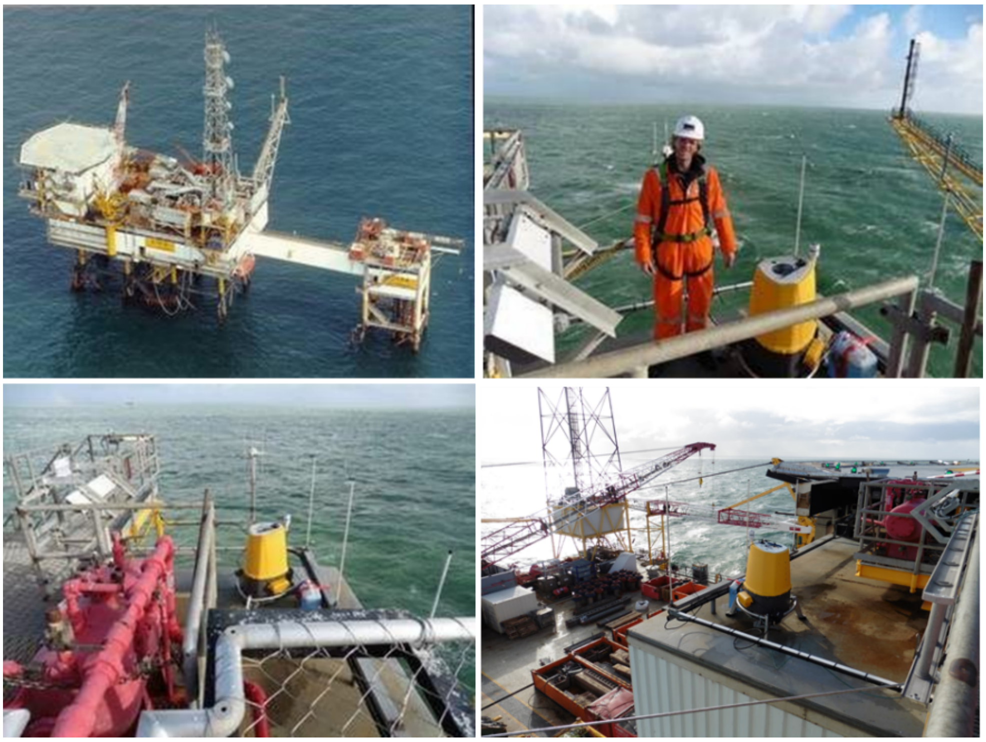


Figure 4 a) Front of K13a platform (geographical coordinates 53° 13'N, 3° 13'E); b) c) and d) location of the LiDAR installation.

2.3 Onsite installation and operational status

The LiDAR selected is the ZX Lidars ZX 300M LiDAR. The instrument measures wind profiles across 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, the LiDAR was first verified at the TNO RSD Verification Facility [16]. 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 4c, d) [15].

The LiDAR was installed to provide measurements at 10 different heights between 63 m and 300 m above mean sea level. The data is timestamped at the start of 10 minute time frame. This is the same configuration as for the LiDAR at the LEG and EPL platforms. Manufacturers guarantee data quality up to 200 m above the LiDAR although the ZX 300M can measure beyond that height too. The analysis of the data at highest levels shows the same quality patterns as at the guaranteed heights (see section 3 and 4). Two different electrical connections are required in order to have the LiDAR fully operational. Firstly, 230V AC power supply connection, provided at the computer room of the platform where the AC-DC power converter of the LiDAR is placed. Secondly, a network connection. The LiDAR is connected by ethernet cable to a TNO laptop located in the computer room. The laptop is connected to the internet by local wireless network and a satellite connection.

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 issue. 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, oil and gas company working at the platform, supports monitoring and control of the LiDAR.

During 2021, there were no observable events that would suggest downtime and reduce data availability.

Table 1 Replacements of LiDAR at the K13aplatform.

Id LiDAR	LiDAR in operation	Planned replacement
U563	1 - 11 – 2016 to Present	Q3-Q4 2022

2.4 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.

3 LiDAR performance assessment

Remote sensing devices bring many advantages with them, such as ease of transportation, measurement capabilities beyond meteorological mast configurations, etc. However, these devices are exposed to the 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 malfunctioning of the system, 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 2021at 23:50 hr. UTC and the campaign is still ongoing, with future yearly analytical updates envisioned.

Table 2 List of variables measured in the LiDAR during the experimental campaign. Where K13a is the platform; HXXX are the different heights measured above mean seas level (MSL): 63, 91,116,141,166,191,216,241,266 and 291 m.

Acronym	Signal name	Units
K13a_batvoltage	Battery Voltage	V
K13a_tempmax	Maximum temperature inside the LiDAR	deg C
K13a_tempmin	Minimum temperature inside the LiDAR	deg C
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_tair	Air temperature at LiDAR position	Deg
K13a_pair	Air Pressure at LiDAR position	hPa
K13a_rh	Relative humidity at LiDAR position	%
K13a_wsmet	Wind speed measured by LiDAR meteo station	m/s
K13a_wdmet	Wind direction measured by LiDAR meteo station	Deg
K13a_rain	Precipitation measured by the LiDAR meteo station	%
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_sd	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_Ws_ver	Vertical wind speed average	m/s
K13a_HXXX_cs	CS	
K13a_HXXX_bs	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 2) 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 [17], based on the Offshore Wind Accelerator roadmap [18].

As indicated in Figure 5 and Table 3 (and Annex A); in contrast with the LEG measurements, the data availability with the ZX 300M at the K13a and the ZX 300 at EPL platforms is independent of the height. The LiDAR provides data at all heights for the full period analysed. The estimation of the measured availability follows the approach by [17].

Table 3 Data measured availability (in %) by height and by year. Data >90% available are considered as available (green), <90% (in yellow) and in red not available data.

Year	H 63 (%)	H 91 (%)	H 116 (%)	H 141 (%)	H 166 (%)	H 191 (%)	H 216 (%)	H 241 (%)	H 266 (%)	H 291 (%)
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

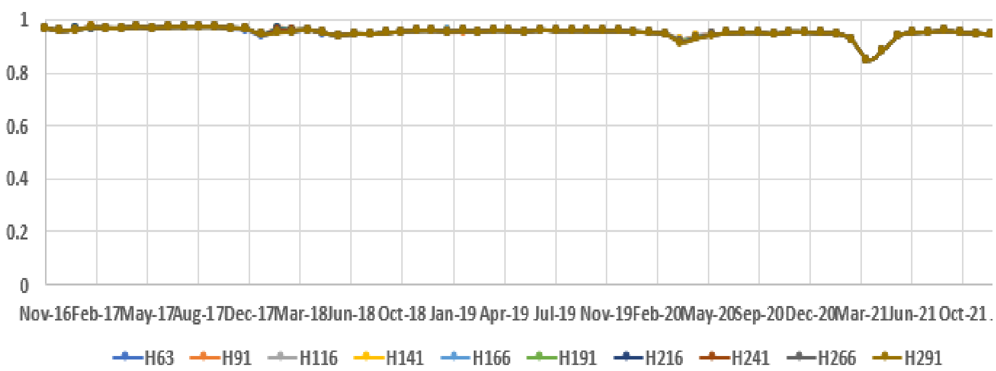


Figure 5 Monthly averages of the data available (fraction based) measured by the ZX 300M LiDAR by height at the K13a platform for the period 2016-2021.

During the measurement campaign, data verification is performed at different levels: quality checks are 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 from over the entire measurement period.

There are complementary reports with data verification comparing with other measurements. In particular, [19] examines the wind speed and direction measurements campaigns at eight offshore measurement locations distributed throughout the North Sea, including the K13a 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.

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 based on the of number of packets shown in Figure 7 and in Table 3 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.

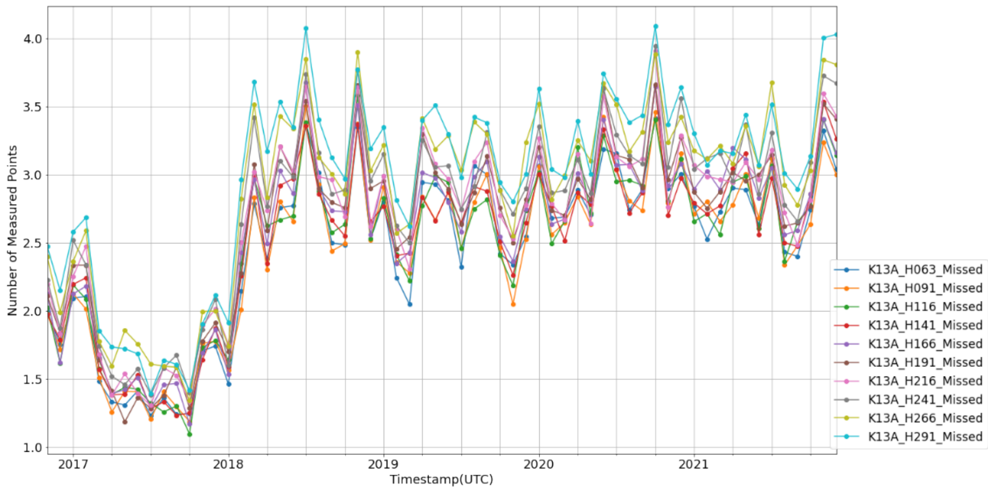


Figure 6 Monthly number of missed points measured over one LiDAR system measurement period

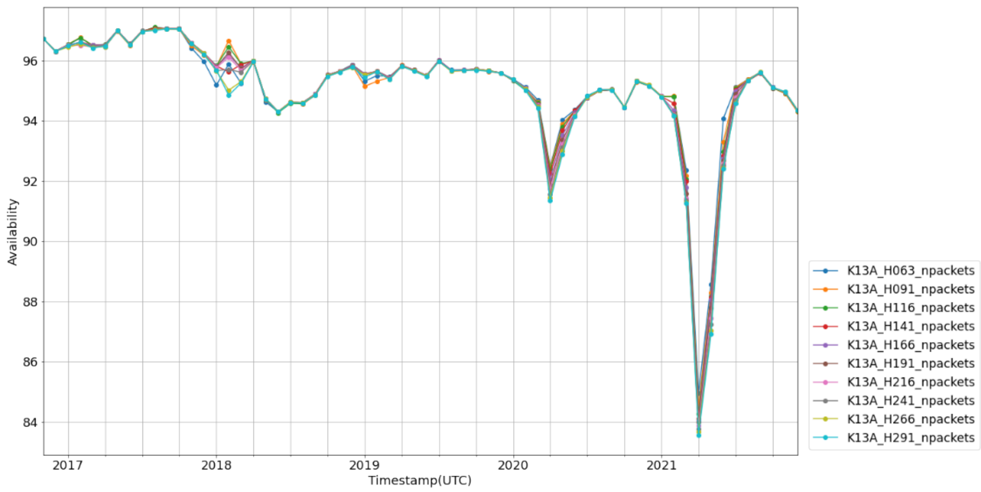


Figure 7 Monthly availability (5) over one LiDAR system measurement period

4 Wind conditions at K13a

The following section is a presentation of results following an assessment of the weather conditions and important wind resource metrics during the measurement campaign at the K13a platform for the entire period of 2016-2021. The main meteorological characteristics are presented in the form of dominant wind directions and distribution of wind speeds at different heights; temporal variation and the descriptive statistics. Complementary analysis on the annual and monthly weather conditions at K13a is included in the Annex B and C. Past weather events are presented with the aim to show that the behaviour of such events is also captured and measured by the LiDAR (section 4.4).

Further, this makes the data useful for purposes beyond the wind resource assessments such as power system analysis; congestion management, impact of climate extremes on the grid, etc. A detailed description of other applications can be found in the chapter *Application for system integration and cross-sectional synergies*.

4.1 Weather conditions during the period 2016-2021

The North Sea is influenced by a wide range of oceanic effects including the large-scale atmospheric circulation North Atlantic Oscillation (NAO), North Atlantic low pressure systems and tides and continental effects (freshwater discharge, heat flow, input of pollutants).

The atmosphere mainly controls the general circulation of the North sea via the heat fluxes and their variability. The dominant effect is the positive phase of NAO, associated with higher air temperatures and stronger westerly winds over the North Sea, inducing higher water temperatures and sea levels. A thermal stratification is generated in the northern and central parts during early summer and remains up to early autumn, when stronger winds mix the water again [20] [21].

At the K13a platform, the weather analysis for 2016-2021 shows that the wind profiles are dominated by the effects of the positive NAO.

Wind speed average varies from 9.33 m/s at the lowest measured height of 63 m up to 10.44 m/s at 291 m, increasing gradually. The dominant direction is South West, measuring between 201° to 206° degrees with a lower and upper quartiles range from 132° to 275° (Table 4). Wind roses in Figure 8, clearly show the dominant wind direction for all the heights and how the wind speeds with higher intensities (mean wind speeds above 22 m/s) increases with the height of the measurements.

Table 4 Descriptive statistics for the wind speed (Ws) and direction (Wd) at different heights for the 2016-2021 period at the K13aplatform.

H (m)	63	91	116	141	166	191	216	241	266	291
Ws – Min	0,30	0,25	0,22	0,66	0,22	0,25	0,54	0,12	0,21	0,19
Ws – 1st quartile	6.14	6.32	6.38	6.39	6.40	6.40	6.40	6.39	6.39	6.40
Ws - Median	8.95	9.31	9.49	9.59	9.65	9.67	9.69	9.69	9.69	9.69
Ws - Mean	9.33	9.70	9.93	10.09	10.20	10.28	10.34	10.39	10.42	10.44
Ws -3rd quartile	12.12	12.70	13.06	13.30	13.47	13.57	13.65	13.70	13.73	13.75
Ws -98 p	19.34	20.11	20.79	21.37	21.86	22.34	22.75	23.11	23.42	23.66
Ws - Max	32.41	34.02	34.88	35.77	36.43	36.84	37.27	37.67	38.00	38.09
Wd - 1st quartile	132.2	133.9	135.6	137.2	137.8	138.1	138.2	138.6	140.3	140.7
Wd - Median	217.3	218	219.2	220.3	221.1	221.9	222.5	223	223.8	224.2
Wd - Mean	201.2	202.1	202.9	203.8	204.3	204.6	204.9	205.2	205.9	206.2
Wd - 3rd quartile	270.1	271.5	272	272.7	273.2	273.6	274	274.3	275	275.3

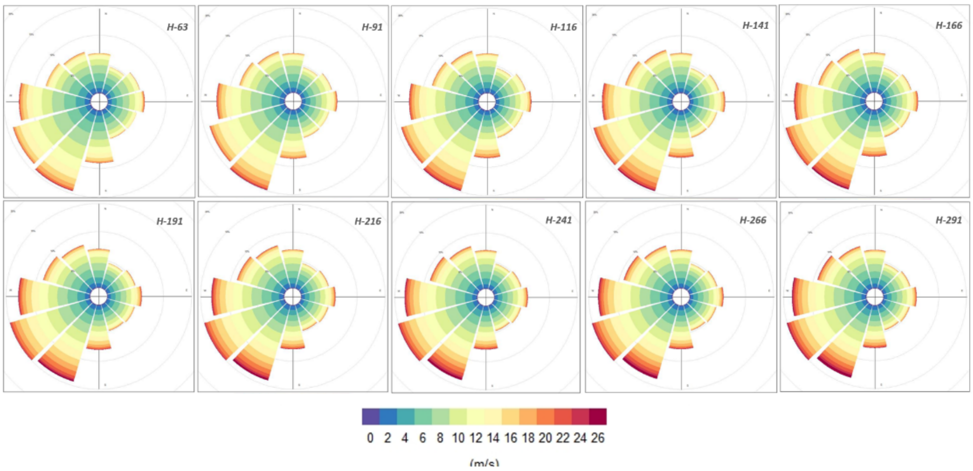


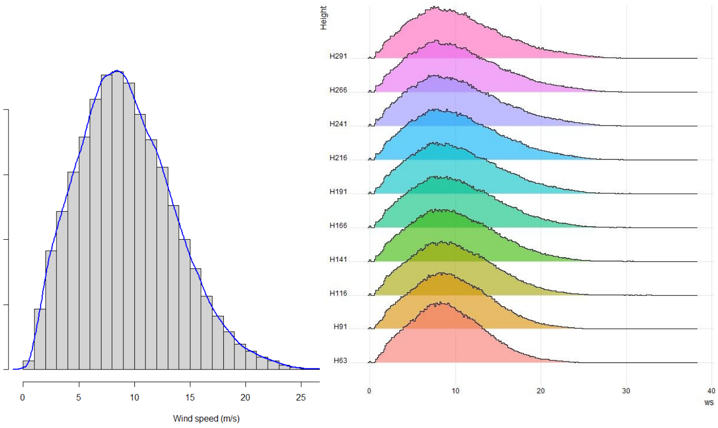
Figure 8 Wind roses at different heights showing the wind prevailing direction for the 2016 -2021 period.

Wind regimes and intra-annual variability are defined by the conventional (two-parameter) Weibull probability density function. The 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:

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

The shape parameter describes the wind behaviour according to its value, it provides information on the shape of the distribution is inversely proportional to wind variability, that is, large k values indicate less wind variability. The parameter scale c is proportional to the average of the wind speed of the distribution and thus, also increases with height. At K13a, during the period 2016-2021, the Weibull distribution at 141 m height shows that k = 2.168 and c = 11.540 m/s (see table in Figure 9). Figure 9 (left) shows the wind speed frequency probability density for each wind speed bin, and the Weibull probability density function fitted.

The Figure 9 (centre) indicates the distribution of the wind speed for each measurement height and it shows how the distribution is flattered and skewed right increasing the heights, as reflected by the shape and scale parameters presented in Figure 9 (table) where the former decreases meaning a less variability and the latter increases meaning higher wind speeds. For the 2016-2021 period at 141 m height, the k parameter is similar to the k at LEG and EPL platforms.



Height (m)	Shape (k)	Scale (c)
63	2.278	10.702
91	2.250	11.109
116	2.207	11.357
141	2.168	11.540
166	2.135	11.676
191	2.105	11.782
216	2.080	11.865
241	2.058	11.928
266	2.042	11.986
291	2.031	12.031

Figure 9 (top) Weibull distribution and curve fitting at 141 m height and (bottom) Weibull distributions at different heights for the measurement campaign with k and c parameters (table) at K13afor 2016-2021 period.

The Figure 10 presents the seasonal variation, monthly and diurnal cycle at different heights. A clear seasonal and monthly pattern can be observed both for wind speed and direction at different heights. There is a drop in the wind speed (5 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 and it is also explained by the cycle derived from vertical mixing occurred by the lower-atmosphere and land energy balance.

However, the variability each hour is less pronounced than at monthly scales. At the K13aplatform, the offshore wind speeds vary within margins of about 0.5 m/s on hourly averages and of 12 degrees in wind direction.

The wind conditions analysed in this report are in line with the assessment presented in [19], [22] and [13]. Such studies present additional description over the temporal variability of horizontal and vertical wind profiles at different offshore locations over the Dutch North Sea.

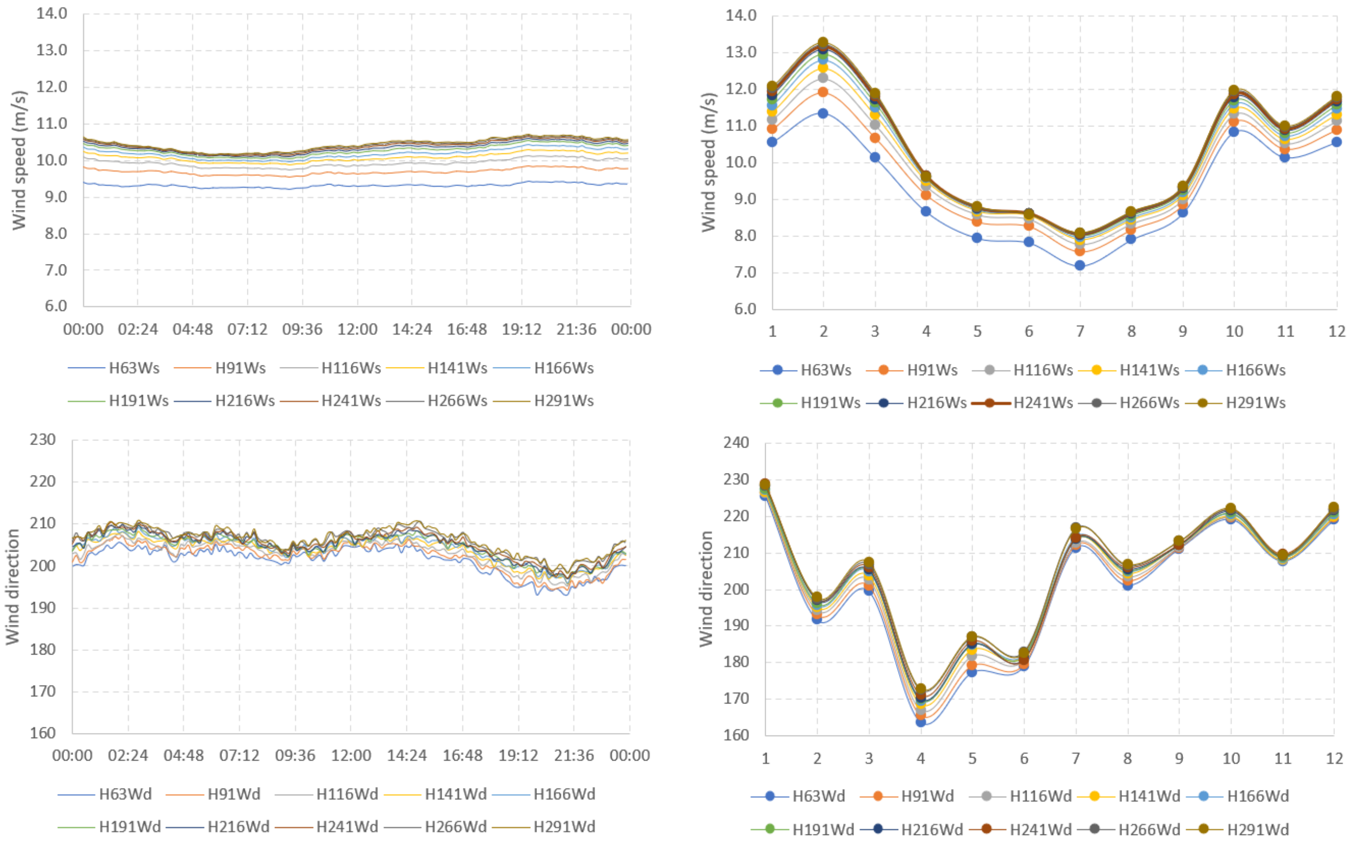


Figure 10 a) Monthly wind speed and direction averages and b) average daily cycles at different heights for the 2016-2021period.

4.2 Annual wind statistics

As regards the wind regimes and intra-annual variability; Figure 13 presents the annual Weibull distribution parameters at all heights for each year. 2021 measurements show lower values compared to the windiest years of 2020, this is also reflected in the c parameter which shows lower values compared with the other years, in particular with the windiest year of 2020. For the shape parameter, which is inversely proportional to wind variability, 2021 shows again lower values, meaning higher wind availability, in particular compared to 2016, 2017 and 2018. These years, 2018 and 2019, show very high values due to low data availability. In specific the annual Weibull distributions at different heights are shown for each year in Figure 14, and the annual statistics are provided in Table 5.

On the temporal evolution, Figure 13 shows the monthly averaged wind speed per year. There is no particular trend at monthly or at seasonal level: the months with highest wind speeds occurred in winter, 2021 is characterized as mentioned above by lower wind speed in the winter months compared to the previous years between November and February, and with exceptionally higher wind speed in October. This is also reflected in Table 5, where the mean wind speed in this year is the only one below 10 m/s. The lowest wind speeds were registered in summer in June. The trend of the annual and seasonal statistics is similar as at LEG and K13a platform, indicating that the main influence comes from the regional patterns. The annex B includes additional annual wind analysis and statistics for the K13a platform.

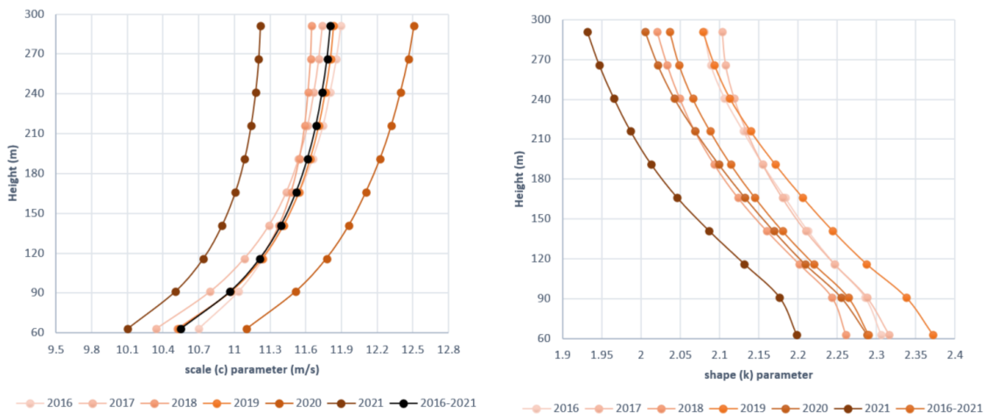


Figure 11 Annual Weibull (left) scale and (right) shape parameters at different heights at the K13aplatform from 2016 to 2021.

Table 5 Descriptive annual statistics of the wind speed (Ws) and direction (Wd) at 141m height at the K13aplatform.

H141 (m)	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**
Ws (m/s) - Min	0	0	0	0	0	0
Ws (m/s) – 1st q	6.62	6.39	6.35	6.699	6.573	5.947
Ws (m/s) - Median	9.75	9.66	9.52	9.721	10.016	9.094
Ws (m/s) - Mean	**10.17**	**10.00**	**10.08**	**10.305**	**10.575**	**9.655**
Ws -(m/s) 3rd q	13.21	13.30	13.42	13.457	13.765	12.607
Ws (m/s) – Max	26.74	31.72	32.34	29.492	35.765	27.693
Wd (°)- 1st q	141.13	173.66	112.46	157.7	137.8	108.0
Wd (°)- Median	222.25	234.38	204.75	224.6	218.4	219.4
Wd (°)- Mean	**198.56**	**219.14**	**191.94**	**212.0**	**198.7**	**199.1**
Wd (°)- 3rd q	258.82	282.52	265.68	275.0	263.4	280.7

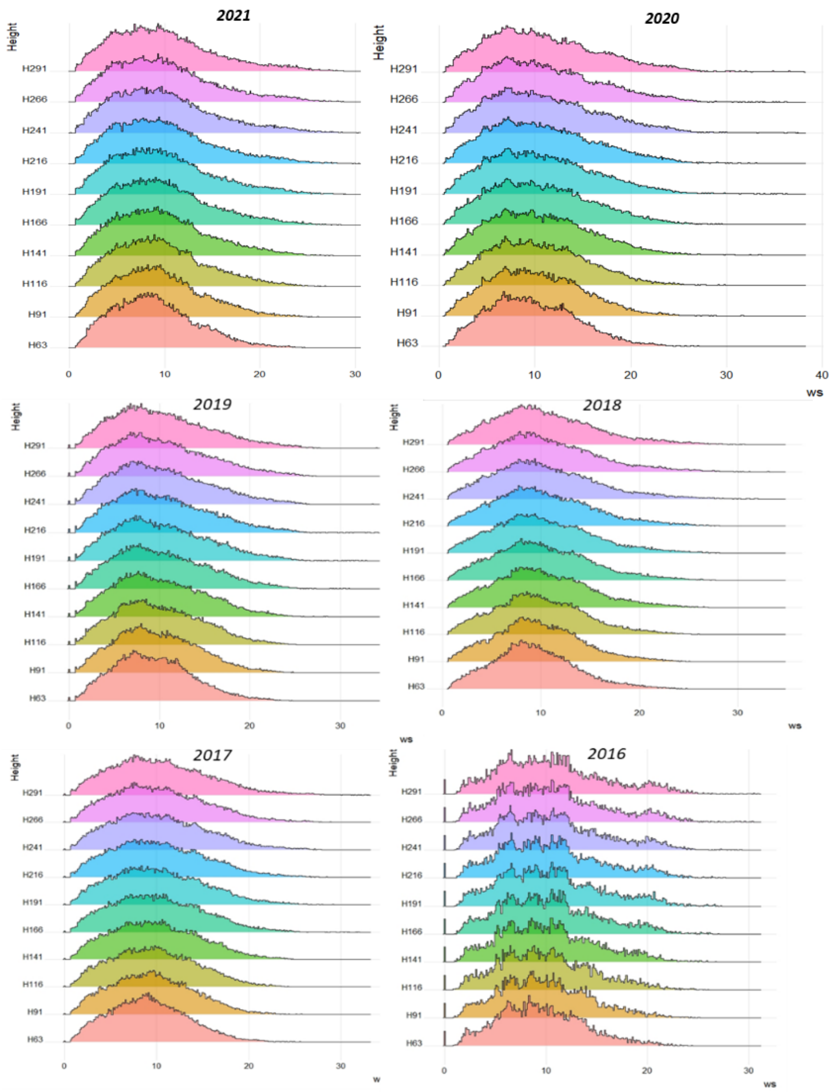


Figure 12 Annual Weibull distributions at different heights for the 2016-2021 period.

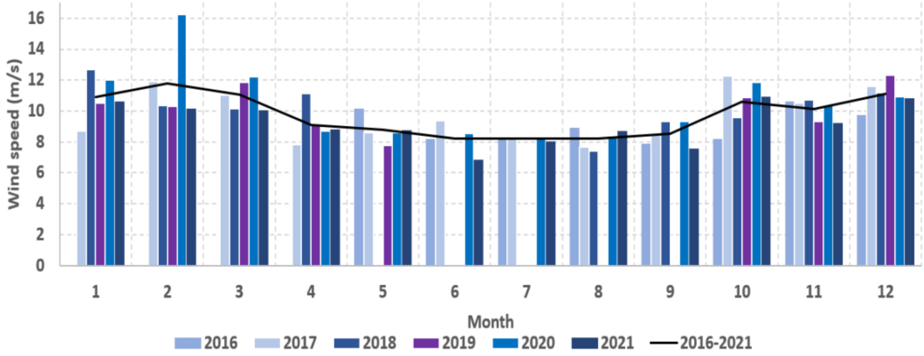


Figure 13 Annual wind speed (m/s) monthly averages bars at 141 m height and 2016-2021 monthly average (black line). Note: low availability in 2018 and 2019 between May and August.

4.3 Analysis of wind shear and veer

The variations of wind speed with respect to height, the **wind shear**, is an important characteristic of the wind resource that impacts the assessment of wind speeds from measurement heights to the hub height of propose 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 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:

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

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 assessed. Figure 14 shows the directional shear profile for different sensor height pairings for the entire data period of 2016 to 2021. The data was left unfiltered and thus lower height pairings tend to have higher availability values between them overall compared to higher height parings. The variation of shear exponent by direction is noticeable, ranging from 0.18 from south west direction to negative shear in the eastern sectors. 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.

Table 6 shows the sensor pairs and the resulting annualized shear value over the entire data period. Here the annualized shear exponent regardless, ranging from 0.02 to 0.093, is decreasing with increasing sensor pair heights. This would indicate the present of shear relaxation, which would result in a slowing down of wind speeds with an increase in height.

Much like wind speed measurements, variations in shear can be observed on an monthly and hourly basis. Figure 16 presents these variations for each sensor level pairing. It can be seen that shear is highest in the evening and nighttime hours of the day, and lowest in the early mornings. Shear exponents show higher values 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 2021, distinguishing between daytime and nighttime hours. Wind speed profile does not follow a consistent shear exponent. Much like the values reported in Table 6, shear relaxation is observed, with larger changes in wind speeds at lower heights compared to higher heights. This was found to be the case within all individual years as well.

Table 6 Annualized shear exponent for different sensor height pairings at K13a

Shear Pairing	Shear exponent
63 m to 91 m	0.093
91 m to 116 m	0.072
116 m to 141 m	0.057
141 m to 166 m	0.046
161 m to 191 m	0.038
191 m to 216 m	0.029
216 m to 241 m	0.020

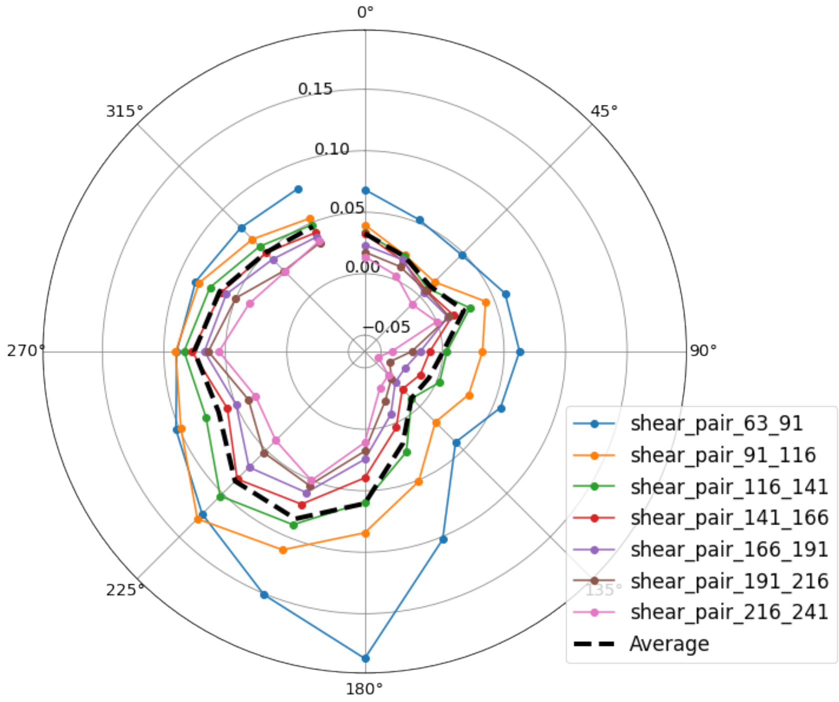


Figure 14 Directional shear profile trends for LiDAR sensor pairings

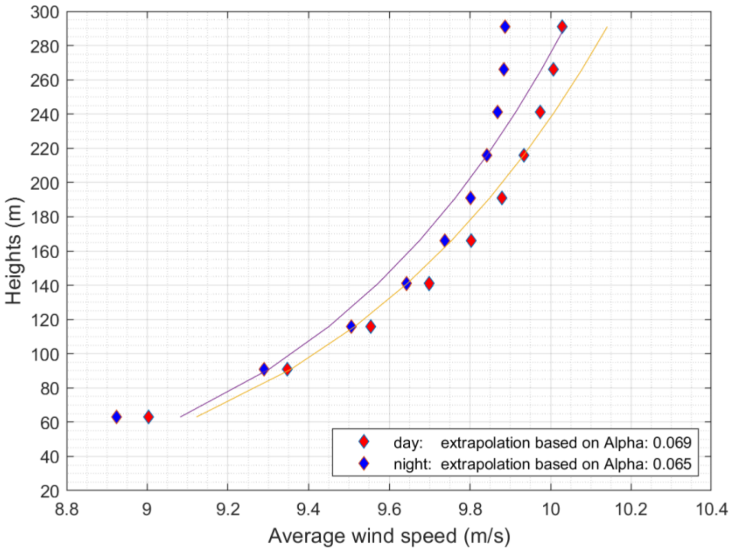


Figure 15 Day and night shear profile for the year 2021 at K13a

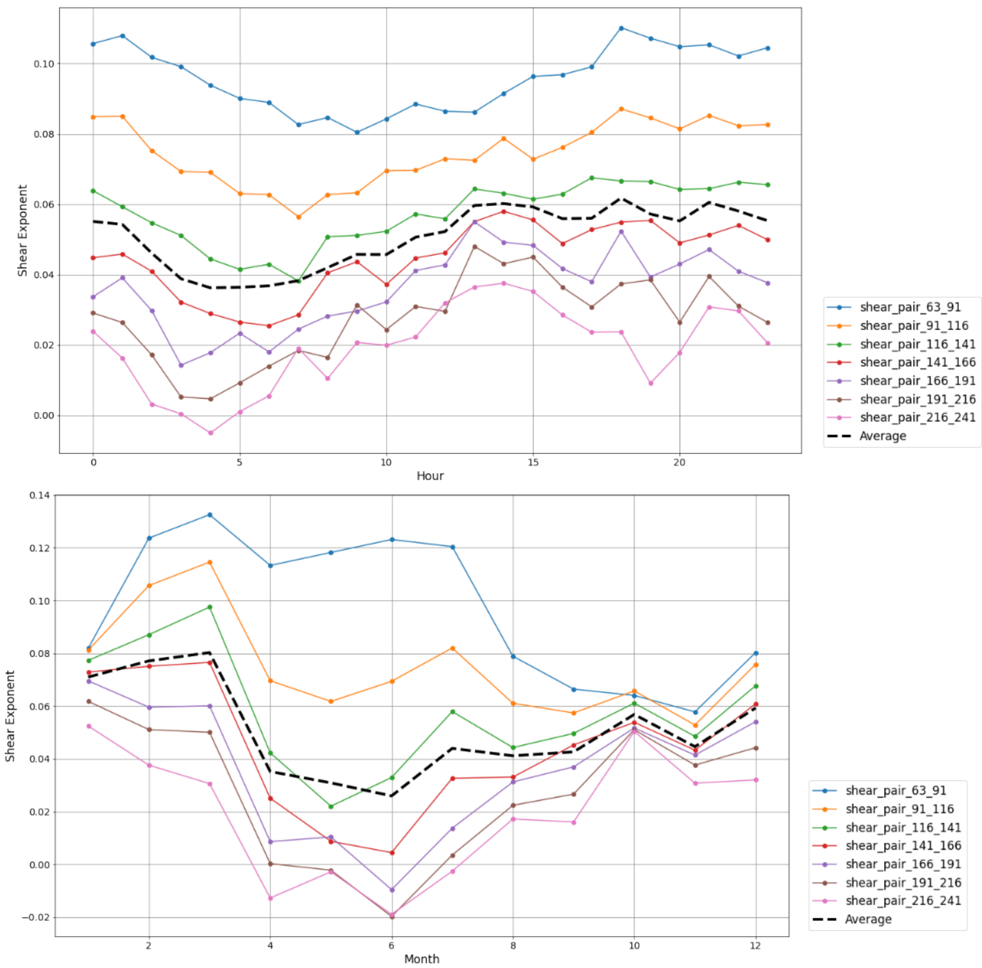


Figure 16 Shear profiles for LiDAR sensor pairs showing hourly (top) and monthly (bottom), trends for the data period of 2016 to 2021

Variations in wind direction with height, known as **wind veer**, are also an important atmospheric input and phenomena that can impact the overall production and loading for 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. An analysis on the wing veer pattern has been conducted, and is summarized in the following figures.

Figure 18 presents the annualized veer for the entire data period between each sensor pair. 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". It can be seen that the direction offsets are consistent and vary by not more than 1 degree. The figure also demonstrates a clockwise increase in wind direction (veering) with height. Figure 19 presents the monthly and diurnal variations in veer averaged over the entire data period considered. Here, it can be seen that the wind direction changes (with) slightly throughout the hours of the day of the year, and summer months varying more than winter months.

Figure 17 shows the average wind direction for all sensor heights at K13a considered only over the year 2021. At the lowest measured height of 63 m, the average wind direction was calculated to be approximately 197 degrees, while at the highest sensor height of 291 m the average wind direction was found to be approximately 200 degrees. That results in a difference of approximately 3 degrees between these levels. The observance of "backing" is found between 141 m and 241 m heights.

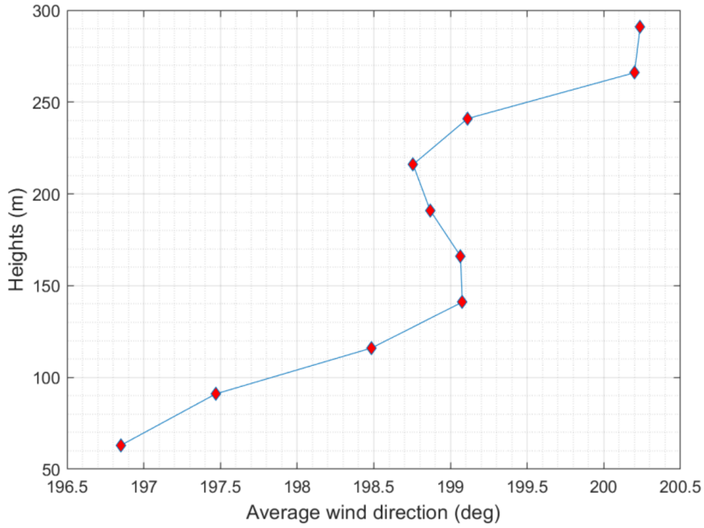


Figure 17 Variations in average wind direction for different sensor heights over the year 2021

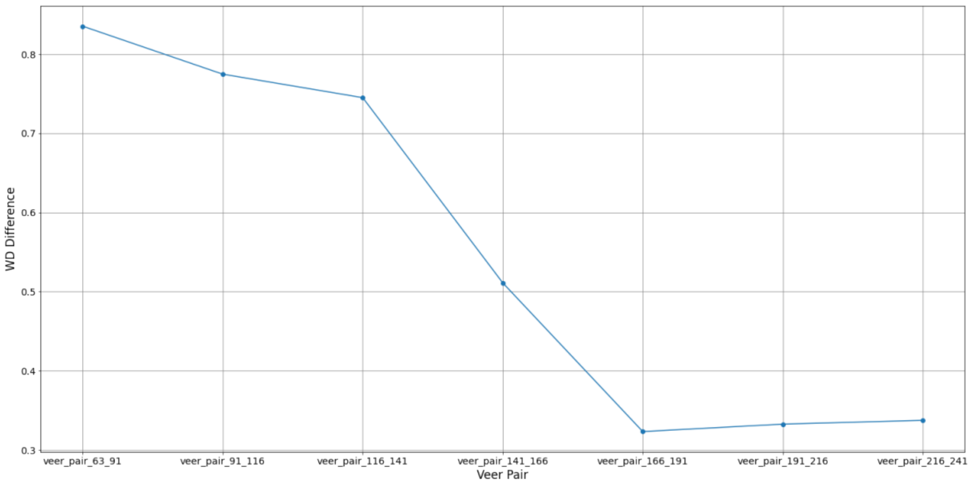


Figure 18 Annualized veer by LiDAR sensor pairing heights

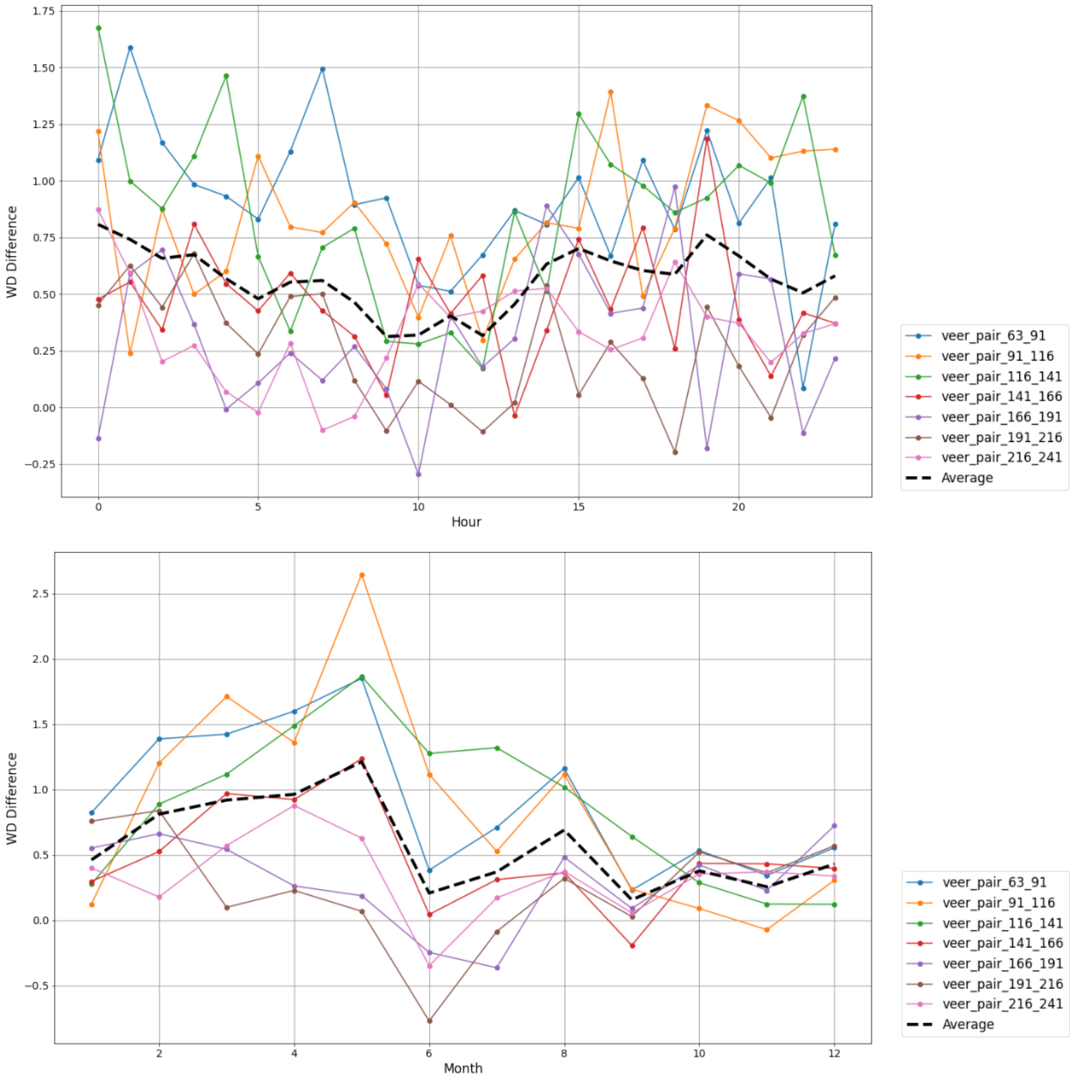


Figure 19 Veer profiles for LiDAR sensor pairs showing hourly (top) and monthly (bottom), trends for the data period of 2016 to 2021

4.4 Past extreme weather events

Building on the analysis of the wind measurements from 2021, presented in this report, it is noticeable that 2021 was characterized by lower wind speed along the entire year. Differently from the year 2020 where several strong storms hit the Netherlands, fewer storms occurs in 2021 and were mainly characterized by heavy rain or snow storm and not by extreme wind speeds.

One event occurs during March, where the Netherlands were hit by the storm Evert, being the first of the year [23]. This storm occurs between the 10 and 11th of March, for which a Yellow code was issued. From the LiDAR measurements, the higher wind speed are captured and shown in the following figures. Figure 20 shows the time series for the wind speed at 10 heights for the entire month of March. The wind speed reached higher values, between 25 and 32 m/s. A detail for the time series in the days during the storm is presented in Figure 21, where the measurements shows accurately the increasing of wind speed during the storm. Overall, this period is characterized by a fairly consistent and high wind speeds. The effects on the power system and electricity prices fluctuations during the storm in March 2021 are shown in Section 6.

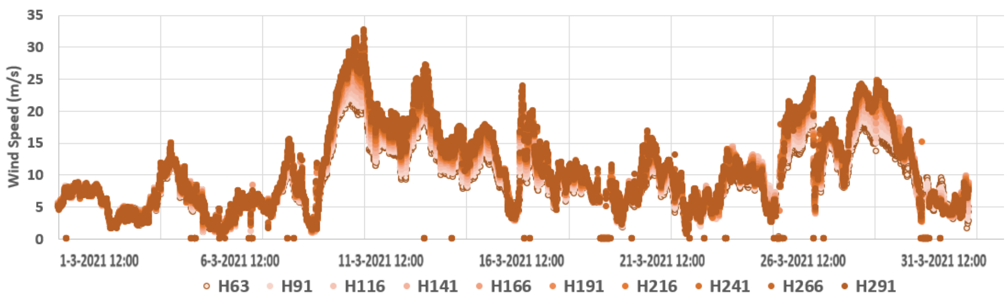


Figure 20 Time series of wind speed measured by the LiDAR at K13a platform during March 2021

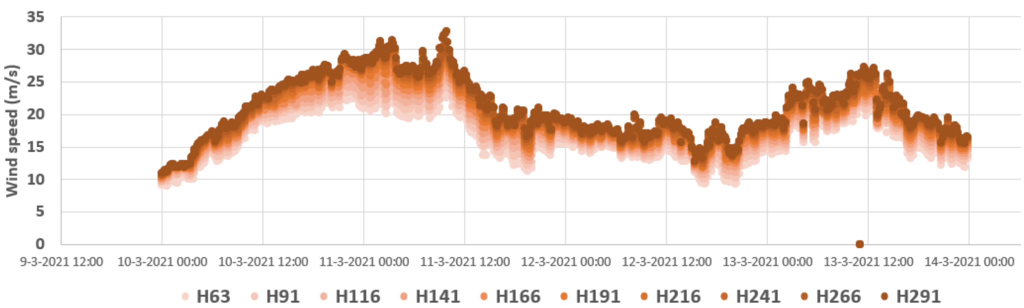


Figure 21 Focus on wind speeds measurements during Evert storm between 11th and 13th March

5 Comparison to other measurement locations

Furthermore, Section 5.1 and Section 5.2 present a cross comparison between the measurement campaigns at the LEG, EPL and K13a platform as well as a benchmarking with the observations coming from KNMI met masts. Conclusions based on similarities and differences are noted and built on from regional expectations.

5.1 Comparison of LiDAR and KNMI measurements

Wind resource campaigns can be further strengthened by comparing multiple measurement locations together. Here, the comparison of the two data measurements of the LiDAR and KNMI met mast at K13a platform is carried out by statistical analysis. The goal of this cross comparison is to assess the LiDAR measurements with that of nearby source, and to address eventual difference observed. As well, this source is there for meteorological purposes, but it does not meet the wind energy sector's standard guidelines, i.e. it is not IEC compliant (no yearly calibration of sensor, disturbances from structures on the wind measurements, etc.).

Therefore for this analysis the available measurement height from the KNMI met mast is 38m and the lowest measurements height from the LiDAR is 63m. These two heights are compared observing statistical analysis, time series, wind roses and distributions histograms. Table 7shows the measured wind speeds at both KNMI and the LiDAR oat K13a. The mean wind speeds differs by approximately 0.5 m/s, and average wind directions by approximately 4 degrees among the entire period. Differences are due to shear effects at these different height and different locations.

From the time series presented in Figure 22 and Figure 23. The wind duration curve is presented in Figure 24, and are in agreement with one another. From the wind roses based on the year 2021 in Figure 25, the overall shape and general distribution of the wind roses are aligned. Figure 26 presents the distribution histograms for both wind speed and wind direction, also showing general consistency in shape and trends between the two locations.

Table 7 Summary descriptive statistics for LiDAR measurements (by TNO) and met mast (by KNMI) at the LEG platform, for 2014-2021.

Ws (m/s)	**KNMI (38 m)**	**LiDAR (63 m)**
Mean	9.45	8.92
Max.	27.03	25.96
Std dev.	5.15	4.34
Wd (°)	**KNMI (38 m)**	**LiDAR (63 m)**
Mean	192	196
Min./ Max	0 / 360	0 / 360
Std dev.	94	93

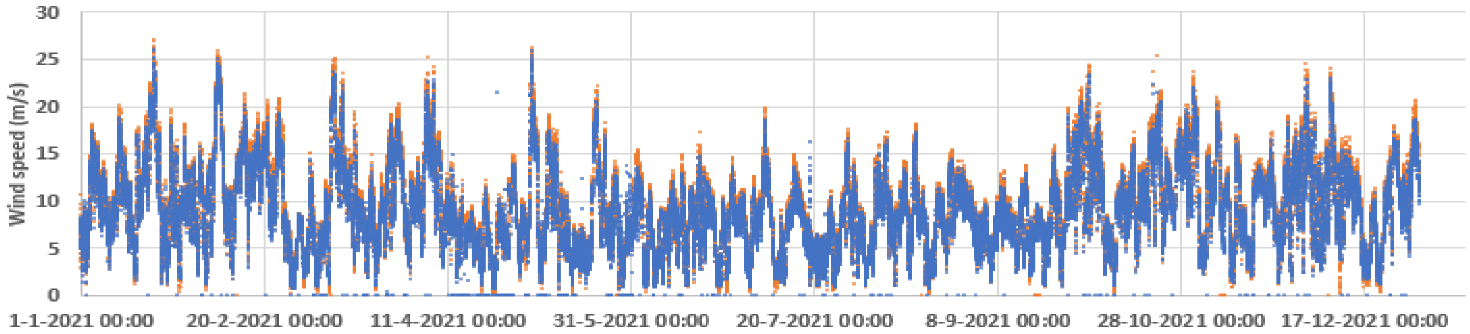


Figure 22 Time series wind speed for the year 2021 between LiDAR (blue) and KNMI (orange) measurements at the K13a platform

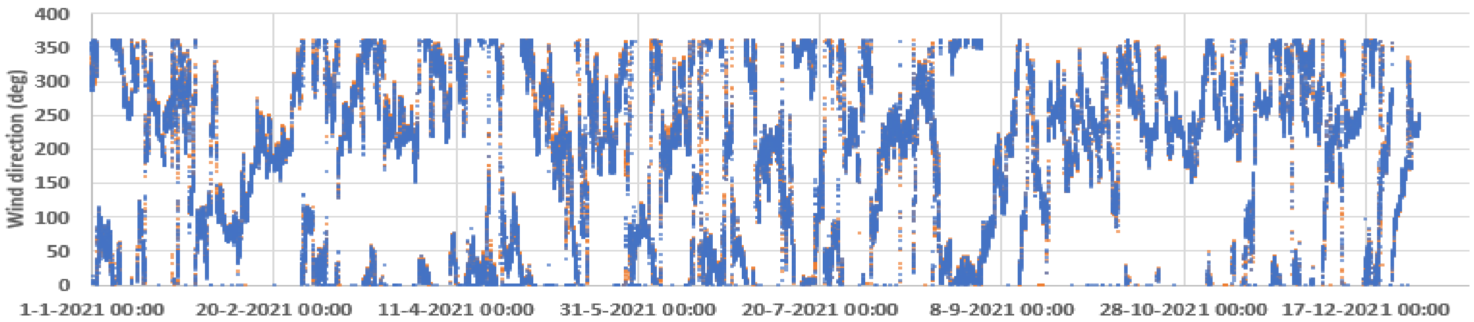


Figure 23 Time series wind direction for the year 2021 between LiDAR (blue) and KNMI (orange) measurements at the K13a platform

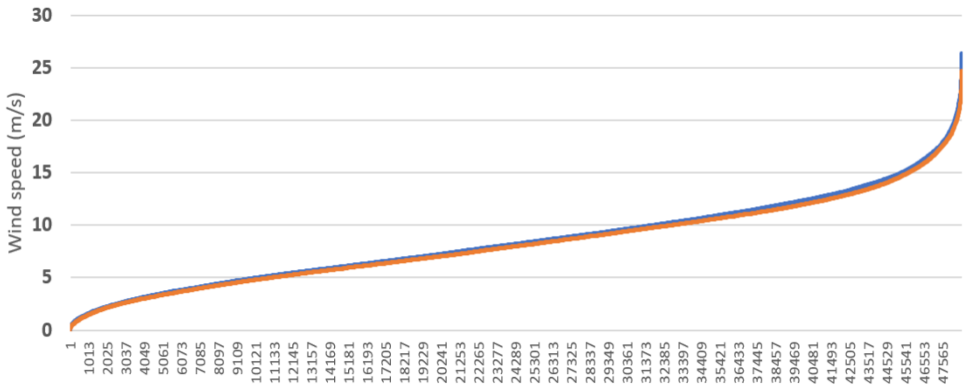


Figure 24 Wind speed duration curves for the period 2021, KNMI (orange) and LiDAR (blue)

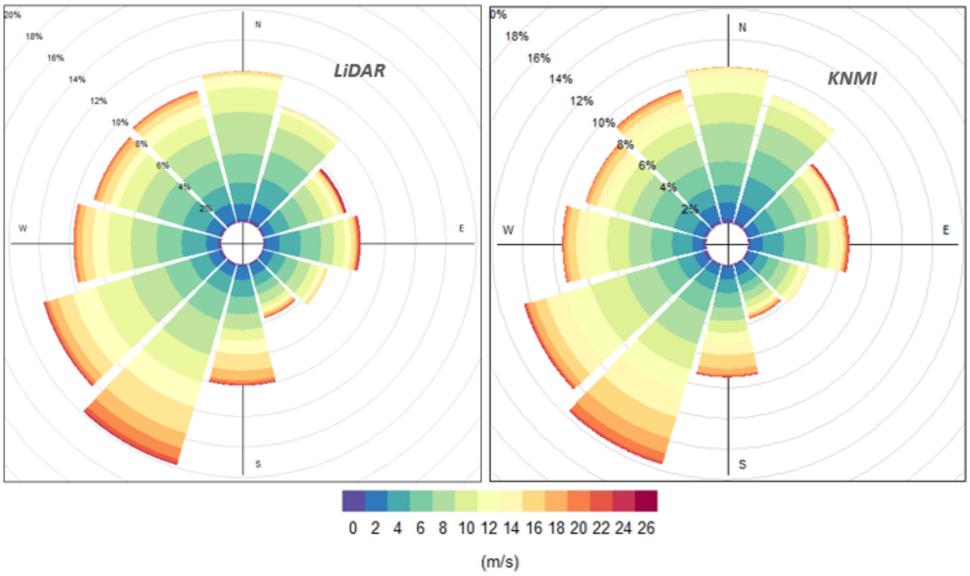


Figure 25 Wind roses for LiDAR at 63m (left) and KNMI at 38m (right) measurements at the K13a platform for the year 2021.

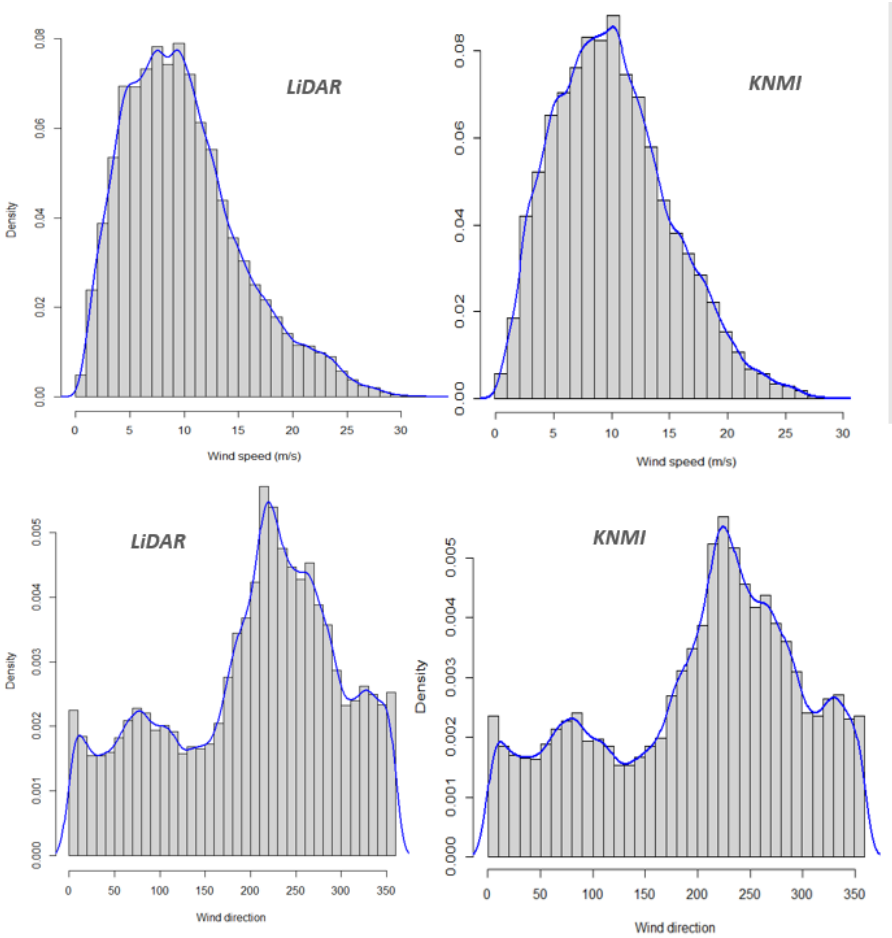


Figure 26 Distribution histograms the wind speed (m/s) (top) and wind direction (°) (bottom) between the LiDAR at 63 m height (left) and KNMI at 38 m height (right) measurements at the K13aplatform for the year 2021.

5.2 Comparison of LiDAR measurements at the K13a, EPL and LEG platform

A comparison between the measurements at the LEG, EPL and K13a platform are presented in this section. Figure 27 illustrates the locations in the North Sea of the three platforms, the wind rose illustrating the wind direction at each site and the location of existing wind farms in operation. The wind direction can be influenced by nearby obstacles, which can be defined as wind farms. From the illustration, K13a is clearly further North in the North Sea far from existing wind farms, whereas LEG and EPL are 15km and 45 km from the land, respectively, and to existing operating wind farms along the coast that might have an influence in the wind speed and direction. This is an important factor to consider when selecting locations for wind measurements. The three wind roses shows the main direction as South-West, whereas at LEG and EPL the wind speed and directions are more concentrated in the main direction, at K13a it seems to be more distributed around the other directions.

The Weibull c and k parameters per height averaged over 2016-2021 period is also calculated (Figure 28). The results are aligned with the offshore wind patterns. The lowest wind speed intensities, expressed as the scale c parameters is found at LEG, increasing while further distance to shore; i.e. EPL and then K13a with the highest intensity. This effect is also proportional with heights. The variability profile of the wind, given by the k parameter, also indicates that at lowest altitudes LEG is characterized with higher variability than the others, may be explained by higher turbulences nearby the shore. This effect is smoothed at higher altitudes with similar wind variability at the three platforms.

While vertical profiles of c and k parameters are very similar between EPL and K13a, the profiles at LEG differ, most likely due to the different local situations as distance to shore (Figure 28).

It is also important to mention that the LiDAR used at LEG (*LEOSPHERE WINDCUBE V2*) has a different technology than the used at EPL (*ZX 300 LiDAR*) and K13a (*ZX 300M LiDAR*), implying different ranges of uncertainties. Manufacturers of the LiDAR at LEG guarantee data quality up to 200 m although some WINDCUBE V2 LiDAR's can measure beyond that height. For this analysis, heights up to 241 m were considered.

Furthermore, annualized shear profiles can be assessed between the different platforms. The comparison is made based on the concurrent data available to all three platforms over the entire data period.

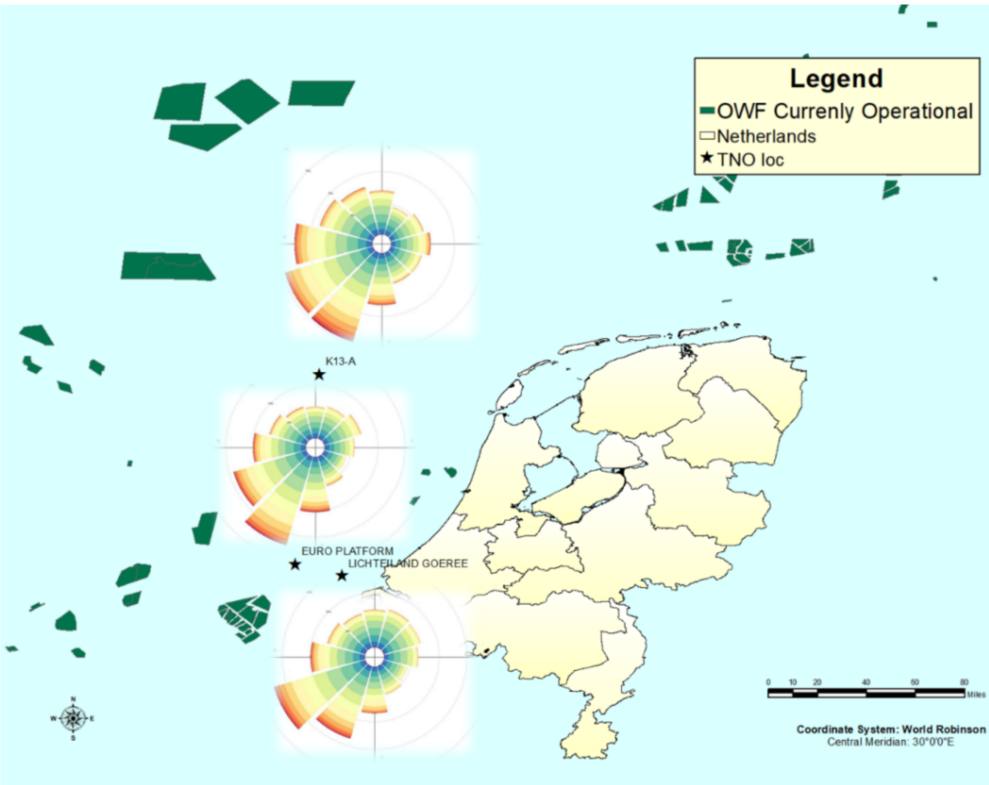
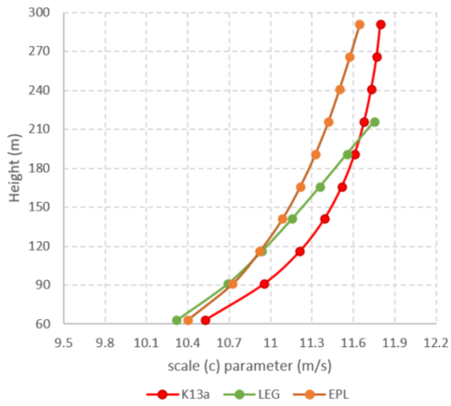


Figure 27 International and Dutch offshore wind farms currently operational and TNO measurement locations with wind roses at 141m for the 2016-2021 period

Table 8 shows that the shear exponent for the concurrent data period and for similar height pairings are consistent to one another. Similarly the veer over the concurrent period is presented in Table 9, with positive values indicating a clockwise direction difference. From these tables, it can be seen that the annualized shear is quite constant at LEG, whereas we see a decrease in shear with higher sensor heights at EPL and K13a. This could indicate shear relaxation at those locations, which implies that wind speeds slow down at higher elevations. This can have impacts on the load conditions along the blades. Veer is consistent across all sensor height pairings, with LEG showing the largest veer at around 1 degree offset clockwise between consecutive heights, compared to EPL and K13a that are closer to 0.5 degrees.



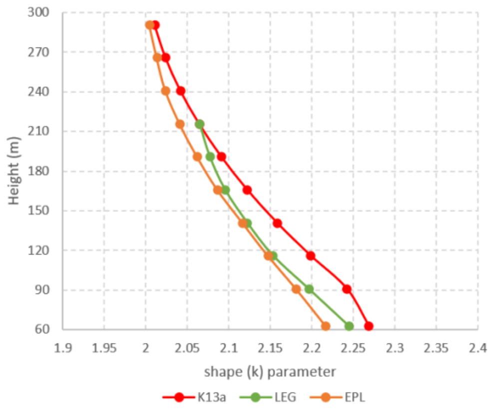


Figure 28 (left) Weibull distribution c and (right) k parameters for all heights at K13a, EPL and LEG over averaged 2016-2021 period.

Table 8 Shear exponent comparison of common sensor pairs at K13a, EPL, and LEG platforms

Height Pairing	K13a	EPL	LEG
63 m to 91 m	0.090	0.066	0.077
91 m to 116 m	0.075	0.058	0.072
116 m to 141 m	0.064	0.058	0.073
141 m to 166 m	0.054	0.055	0.073
161 m to 191 m	0.046	0.053	0.071
191 m to 216 m	0.039	0.049	0.075
216 m to 241 m	0.028	0.041	0.077

Table 9 Veer (degrees, positive implies clockwise) comparison of common sensor pairs at K13a, EPL, and LEG platforms

Height Pairing	K13a	EPL	LEG
63 m to 91 m	0.82	0.71	1.21
91 m to 116 m	0.75	0.72	1.08
116 m to 141 m	0.58	0.55	0.97
141 m to 166 m	0.48	0.63	0.97
161 m to 191 m	0.37	0.49	1.01
191 m to 216 m	0.42	0.57	0.92
216 m to 241 m	0.42	0.51	0.87

6 Application for system integration and cross-sectional synergies

Wind conditions measurements are a valuable source of data for different application. Nowadays more data and conditions are monitored in the North Sea, not only in regards of the wind resource, but also on other weather conditions and ecological parameters. Hereafter, a list of measurement campaign applications.

- A part from the estimation of the AEP, accurate wind resource assessment provide a better insight in the wind condition allowing a better layout and design of the wind farm. Wake effect are measured in function of wind speeds and wind directions.
- Large and sharp fluctuations in wind speeds due to storms can influence the generation of wind energy that is transmitted, bid and provided to the electrical grid, and therefore has an impact on electricity markets and prices. If periods of high winds coincide with high demand, and curtailment of power, then market prices may surge to bring more costly resources online to provide the supply of energy to consumers. An example during the March 2021 storm event is presented in the following Section 6.1.

- One challenge for the current wind energy industry is the life time extension of the wind turbines, which allows to reduce the costs and increase the profitability of a project over the years. In this regards there have been several studies that correlate rains conditions to leading-edge-erosion, LEE. Studies have shown a correlation between the rain drops information, the wind speed and the operational condition of the blades. Therefore, long term high quality measurement of wind conditions provide an insight on the LEE parametrization in function of rain and wind conditions around the North Sea. An ongoing project, that TNO is taking part in has been described in Section 1.3.2

- On the ecological side, there have been several studies in which birds and bats behaviour around wind farm have been monitored. In specific, studies have proved that birds and bats activity tends to occur during certain weather conditions. The correlation of these activities with the wind condition can provide insight in the ecological impact of wind turbine and provide data and information for the development of intelligent stand still facilities and optimized curtailment strategies. This will allow a better and tailored operation of wind farm to minimize the impact on the ecology by decreasing the risk of collisions and maximize the revenue.

6.1 Effects on the power system and electricity prices fluctuations during March 2021

During the occurrence of storm Evert over the days of March 9th to March 11th, 2021 the Netherlands, wind speeds from the LiDAR fluctuated significantly from less than 5 m/s to almost 35 m/s, see Section 4.4. These wind speed events are captured also in Figure 29, which presents the impact of wind energy generation due these changes in available resource on the electricity market production of leading to and during the storm (source – ENTSO-E).

Starting on the 9th of March, Figure 29 (left) shows that the offshore wind generation is non-existent over the afternoon, coinciding with the decreased in wind speeds over that same time period, the electricity prices peak to 93 €/MWh in the evening due to this, as fossil fuel generation having a larger share in the production and enter the market, Figure 30 (top).

On March 10th, Figure 29 (center) shows a stable amount of wind power is generated throughout the day, coinciding with strong wind speeds that are still within productional limits of most turbines. Prices are in line with the two peaks throughout the day, reducing to 25 €/MWh by 22:00, Figure 30 (center).

Prices continue to drop to nearly 0 €/MWh during the early morning hours on March 11th as shown on Figure 29 (right), with higher amounts of wind energy being produced, due to wind speeds reaching their highest operational limits (between 25 and 30 m/s). Gas and fossil fuel generation are also at their lowest generation levels, as it is not profitable to operate at such low prices in the market. Interestingly, at approximately 08:00, the electricity price drastically increases to 120 €/MWh, and an increase in fossil fuel generation production, and increased demand during these morning hours, and slight reduction in wind power generated can be observed. This period coincides with wind speeds that are above operational limits (greater than 30 m/s usually), which would lead to either curtailment or shut down of turbines altogether. Following this event, wind speeds decrease back to within operational limits, and offshore wind production enter the market consistently over the remainder of the day. Prices over this period stabilize between 40 and 60 €/MWh.

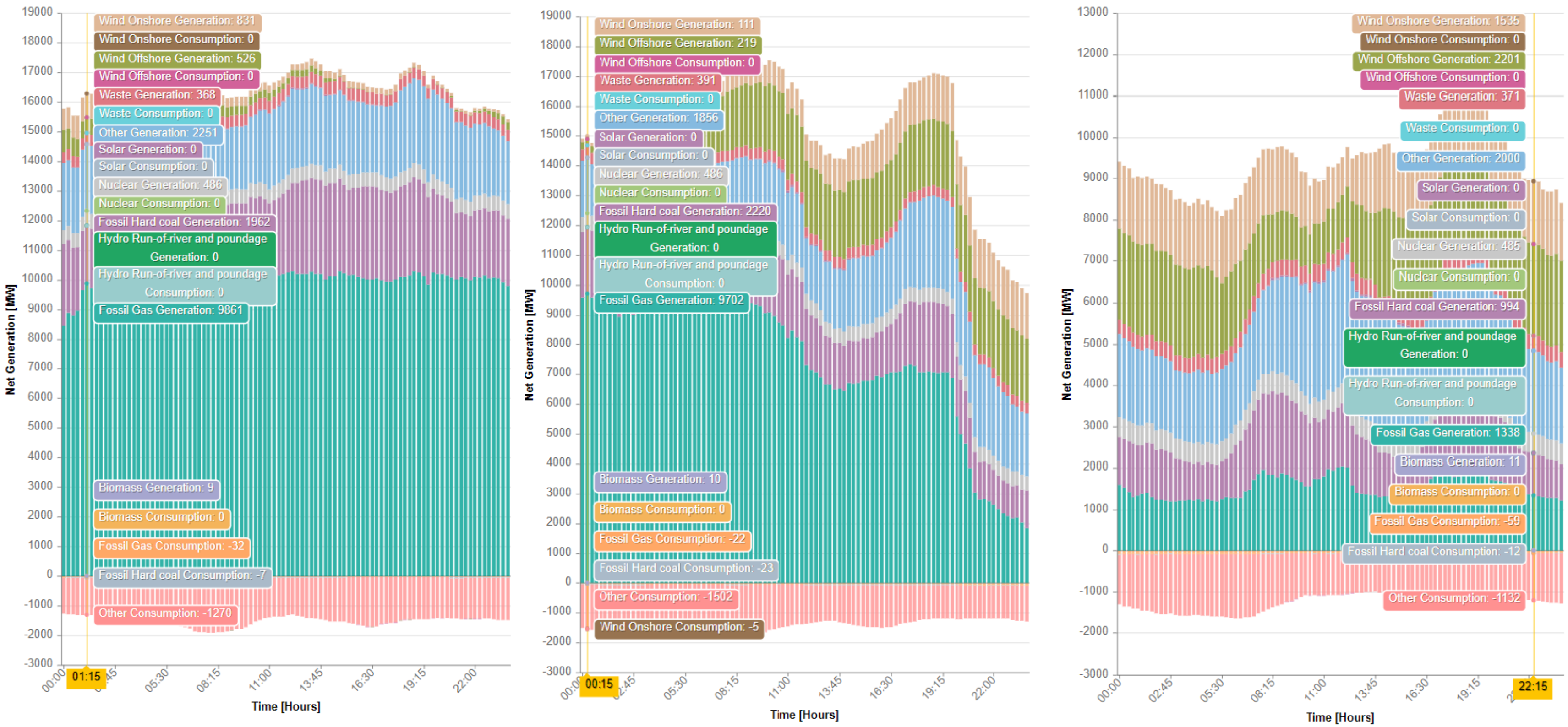


Figure 29 Energy mix for March 9th (left), 10th (centre) and 11th (right) 2021 (source – ENTSO-E).

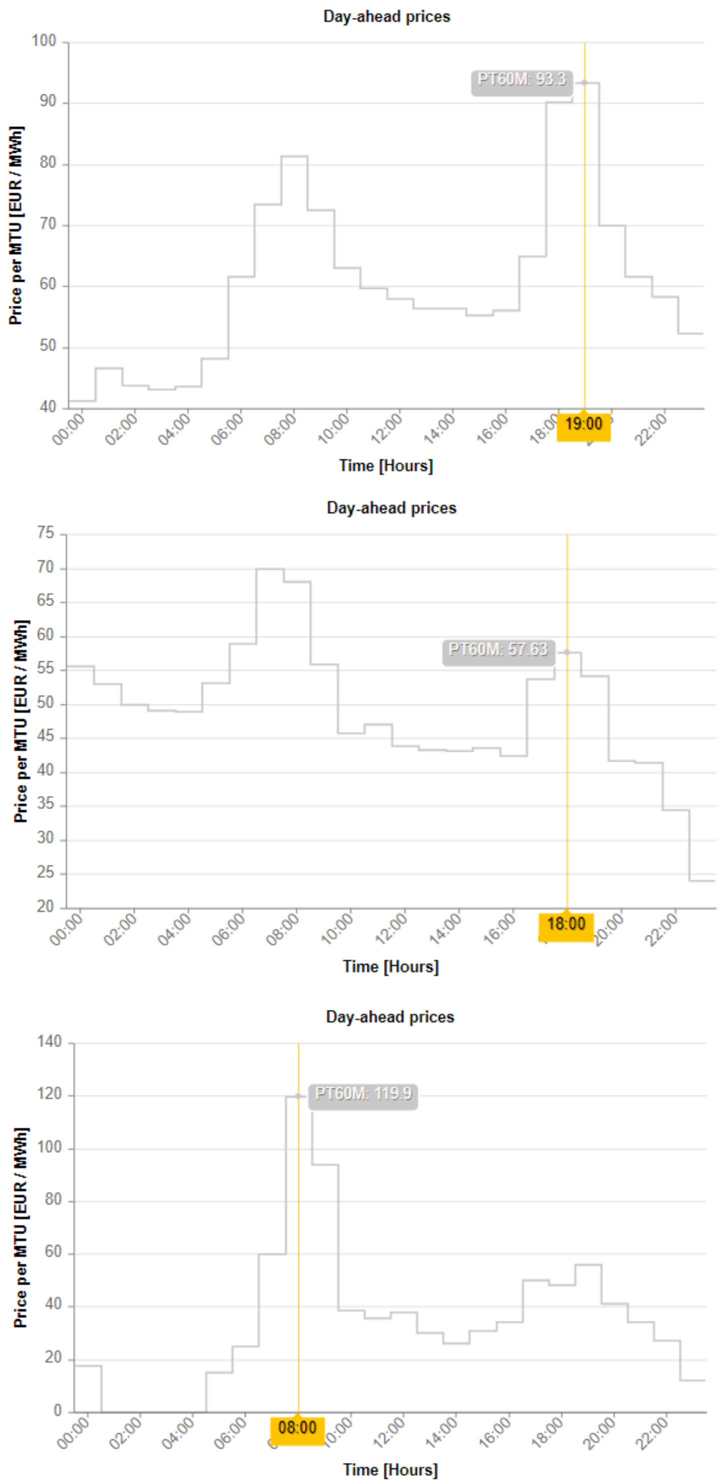


Figure 30 Day-ahead prices for March 9th (top), 10th (centre) and 11th (bottom) 2021 (source – ENTSO-E).

7 Conclusions and recommendations

Within the Dutch project “2022 Wind Conditions @ North Sea”, the Dutch Ministry of Economic Affairs and Climate Policy has agreed that TNO performs measurement campaigns in the North Sea from 2014 until 2030 at different locations, reviewed on annual basis. Currently, the locations of the measurements are Lichteiland Goeree (LEG), Europlatform (LEG) and Wintershall Noordzee B.V. platform K13a.

TNO has a leading role on accredited measuring campaigns for the offshore wind sector in the Dutch North Sea, with more than 10 years of experience. It is responsible for the entire life cycle during the measurements: from the installation plan at the platform; purchase and selection of the instrumentation, analysing, reporting and dissemination of the data. TNO has produced a series of reports on the measurement campaigns carried out at those locations.

This report refers to the measurement campaign at the K13a platform where a ZX 300M LiDAR has been deployed, 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 2016-2021 period shows that the wind profiles are dominated by the regional climate, mainly by positive NAO. Prevailing wind direction is South-West: mean of the distribution bell ranges 201° to 206° and the lower and upper quartiles range from 132° to 275° at all heights.

The Weibull distribution, indicating wind regimes and inter-annual variability, shows wind speed distributions with typical offshore wind k, and c parameters (k = 2.168 and c = 11.540 m/s at 141 m height).

The wind speed bell distribution is flattener and moderately skewed right with higher heights, with more frequent wind speeds >26 m/s.

The analysis of shear shows an annualized range of 0.02 to 0.09 considering the entire data period between sequential sensor heights of the LiDAR. Shear relaxation is observed, with larger changes in wind speeds at lower heights compared to higher heights. This was found to be the case within all individual years as well.

Veer in 2021 shows a “backing” trend between the 141 and 241 m height. However considering the whole data period, the trend is still considered “veering”.

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 and stationary measurement campaigns at specific sites, which can be the reference point for offshore wind atlases.
- Serving as a basis for the development and validation of high fidelity models: it is necessary to improve the accuracy over a wide range of site conditions, with sufficient resolution in both time and space, relevant for wind turbines.
- Improving and reducing uncertainties of the stochasticity of the planning and scheduling tools for the power sector with high RES penetration. 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 which 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, providing useful datasets for other type of assessments such as congestion management and impact of climate extremes on the grid.

The Dutch government have revised their targets and have established ambitious development plans to ensure more offshore wind in the North Sea by 2030. In recent announcements they have added new locations to the existing zones for the deployment of wind farms in the North Sea. It is clear that wind farms will be installed far from the coast, in more northernly locations. In these areas farther from the coast. there are no meteorological masts and no long term wind conditions present to accurately describe the wind resource potential which may lead to higher uncertainties at these locations. Only few locations in the North Sea measure the meteorological conditions, on behalf of KNMI. Nevertheless these measurements are performed at lower heights, and therefore are not suitable for the wind resource assessments of the present day and future hub heights of large wind turbines. TNO therefore recommends the installation and deployment of additional locations in preparation of the future installations and developments for 2030 and beyond.

8 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.

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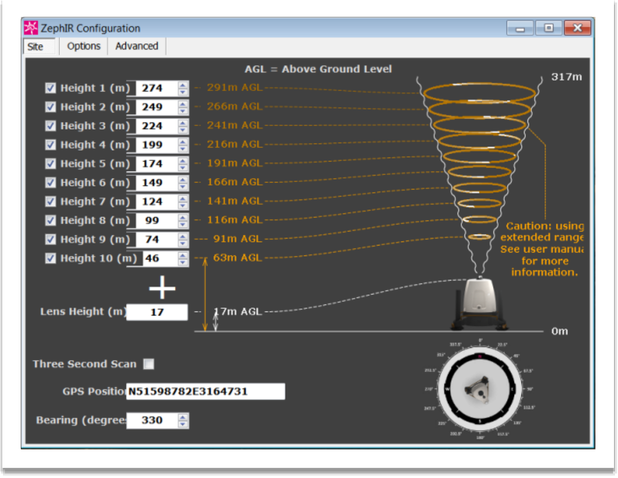
A LiDAR specifications ZX 300M

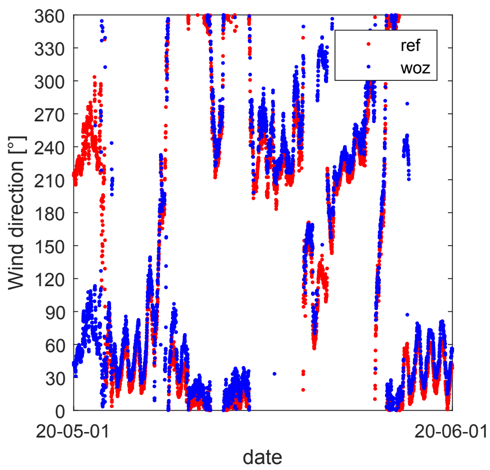
Setting and configuration

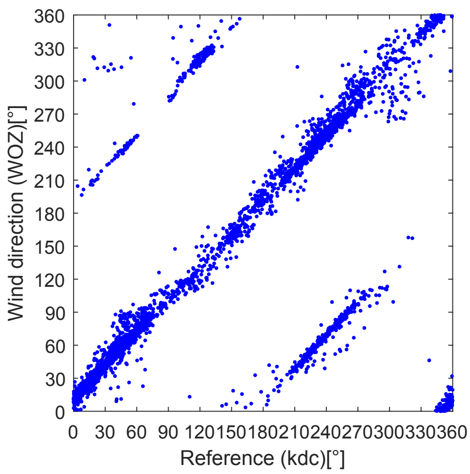
TNO is accredited for remote sensing device calibration (ISO 17025). The LiDAR is upfront verified against Meteorological Mast 4, in accordance with IEC 61400-12-1:2017. The validation is performed by checking Key Performance Indicators (KPIs) [16]. The figure below shows an example of screen setting of the LiDAR configuration and adjustments.

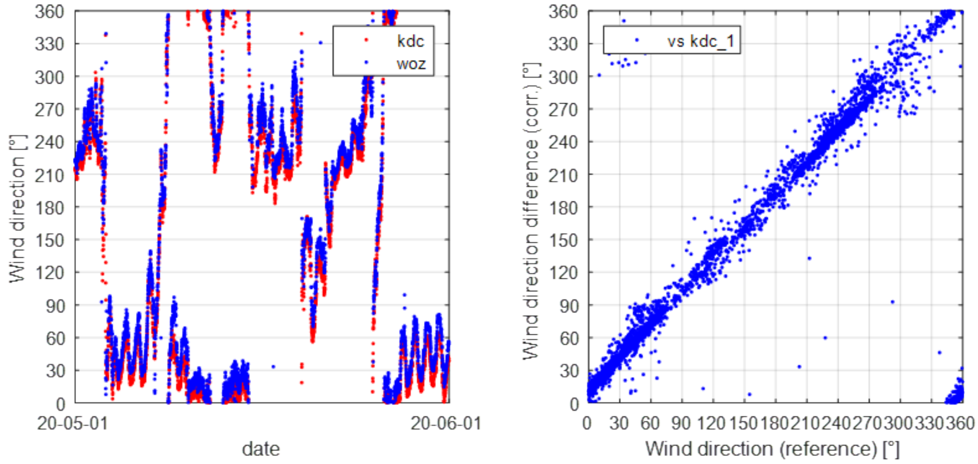


Data correction – 180 degrees offset

As abovementioned, 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 2) 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.







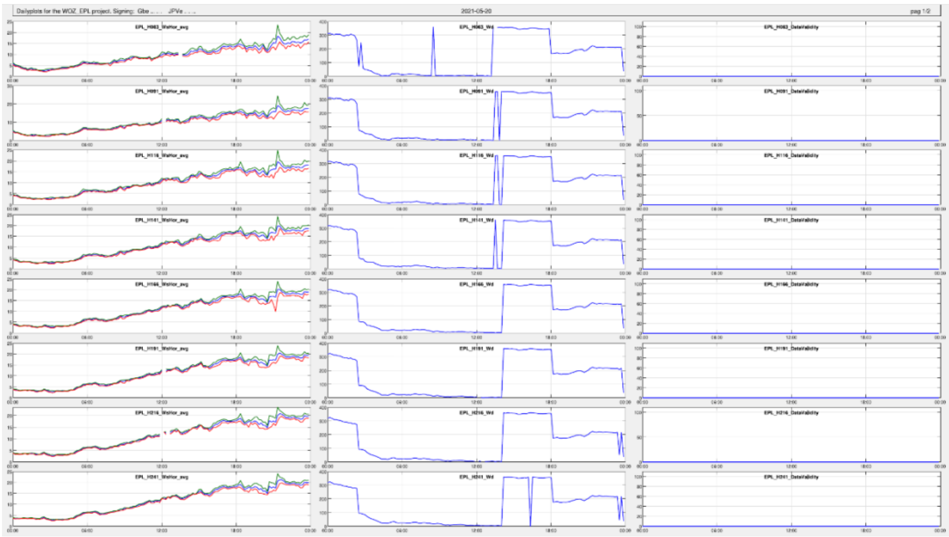
Data availability

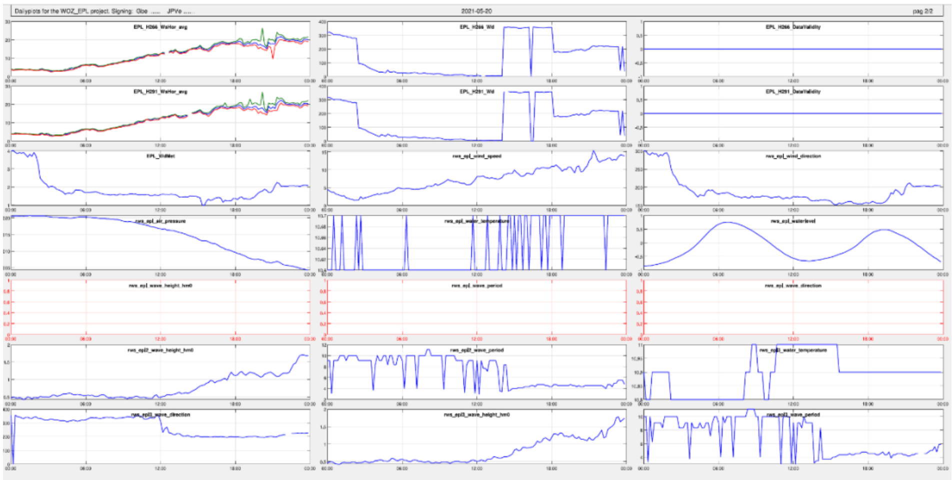
For the ZX 300M LiDAR, the quantification of the overall availability in a 10-minute interval (for a certain height), it is considered the number of packets by definition [24]. Due to different technology, the methodology to calculate data availability of the ZX 300M LiDAR is not comparable with the data availability of the LEOSPHERE LiDAR. Here, the number of packets in a 10-minute interval to 100% are normalized by:

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

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

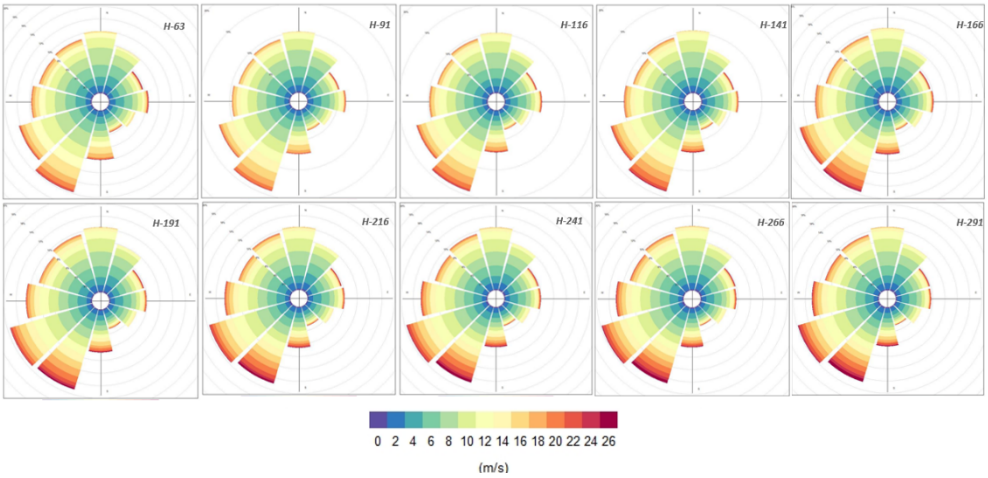


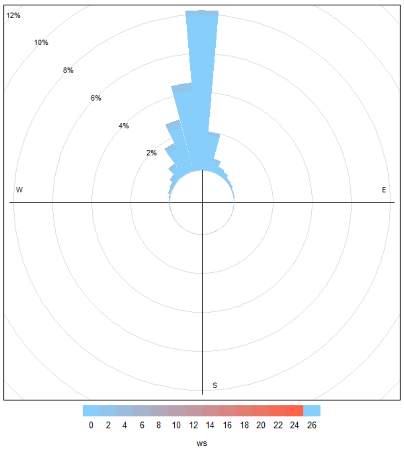


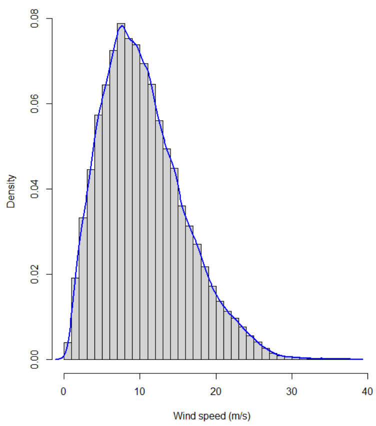
B Annual weather conditions during the campaign at K13a

This section contains visual and statistical descriptive summary about the annual weather conditions per year at the K13a from 2021 backwards in time to 2015. The annual prevailing wind direction recorded was South-West, at different heights, as indicated by the wind roses (top). Although the predominant wind direction is South-West, with lower heights, the North component is stronger. The wind rose chart (bottom left) shows the difference on wind speed and direction between heights of 241m and 63 m above LLWS level indicating the mean difference of wind direction between lowest and highest height measured._The main wind speed distributions (m/s vs. frequency) at different heights (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 2021

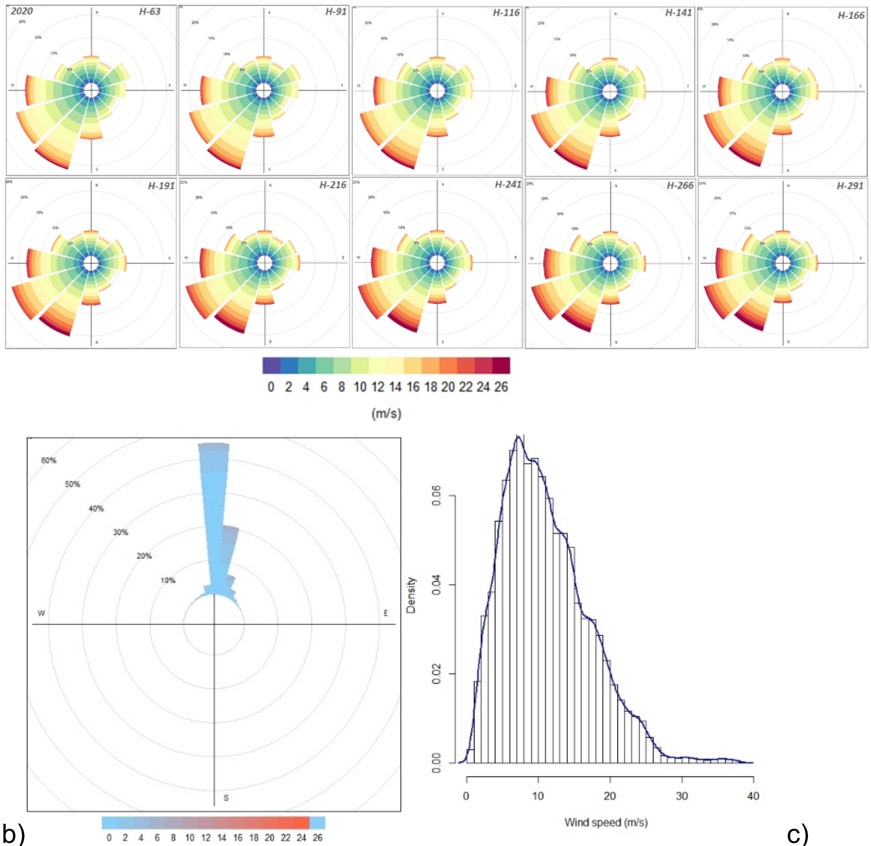






H (m)	63	91	116	141	166	191	216	241	266	291
Ws - Min	0.295	0.247	0.217	0.658	0.220	0.249	0.540	0.115	0.205	0.189
Ws – 1st q	5.718	5.891	5.933	5.947	5.938	5.919	5.904	5.886	5.874	5.866
Ws - Median	8.517	8.858	9.005	9.094	9.130	9.151	9.171	9.182	9.187	9.190
Ws - Mean	8.945	9.302	9.514	9.655	9.756	9.826	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 - 1st q	106.03	106.01	107.27	107.95	107.61	107.31	106.38	106.27	107.91	107.62
Wd - Median	216.00	216.68	218.10	219.36	220.23	220.68	221.11	221.83	222.84	223.19
Wd - Mean	196.85	197.47	198.49	199.08	199.07	198.87	198.76	199.11	200.20	200.24
Wd - 3rd q	278.40	279.58	280.44	280.69	280.49	280.25	280.16	280.56	281.53	281.78

B.2 2020

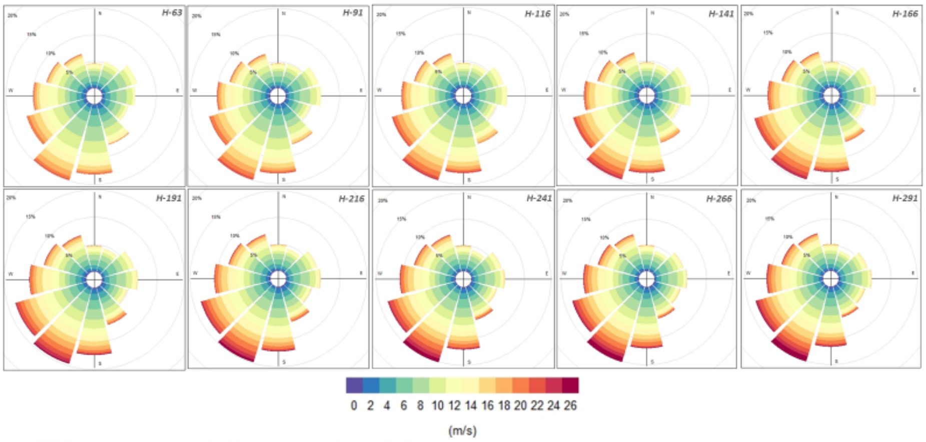


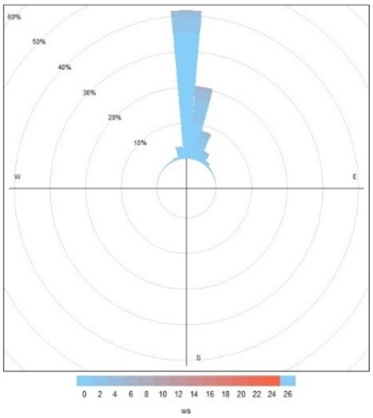
a)

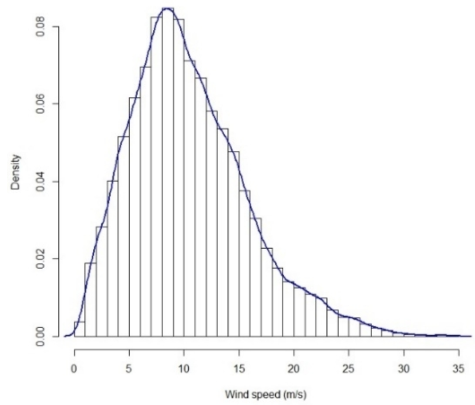
b) c)

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	14.133	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 - 1st q	133.14	135.60	136.23	137.83	138.49	139.19	139.54	140.18	141.79	142.00
Wd - Median	215.95	216.63	217.33	218.32	219.32	220.01	220.61	221.19	221.73	222.22
Wd - Mean	196.24	197.35	197.78	198.69	199.28	199.88	200.24	200.72	201.33	201.17
Wd - 3rd q	261.48	262.61	262.76	359.99	263.85	264.38	264.84	265.40	265.86	266.29

B.3 2019

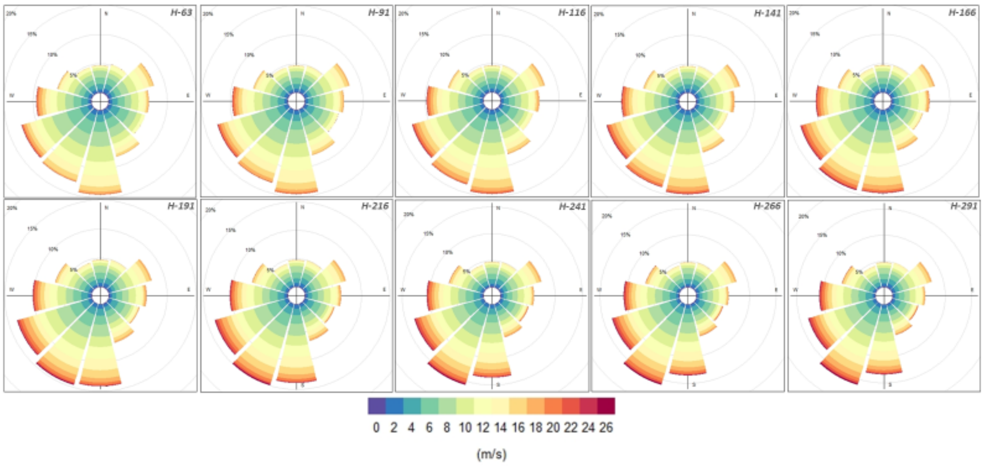


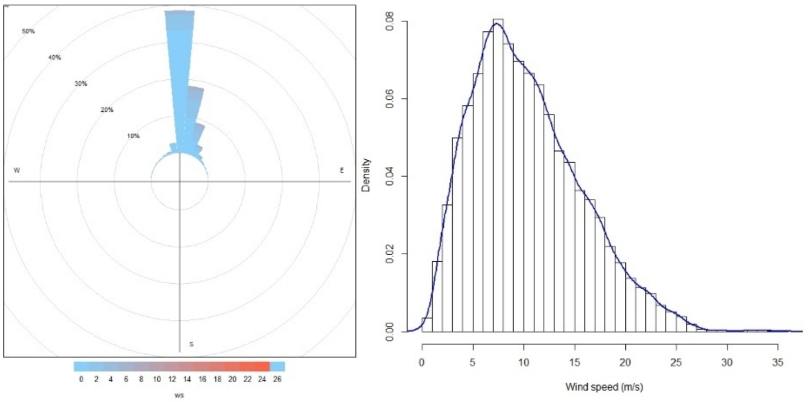




H (m)	63	91	116	141	166	191	216	241	266	291
Ws - Min	0	0	0	0	0	0	0	0	0	0
Ws – 1st q	6.44	6.64	6.685	6.68	6.69	6.69	6.70	6.68	6.68	6.68
Ws - Median	9.01	9.38	9.57	9.67	9.71	9.72	9.72	9.73	9.72	9.72
Ws - Mean	9.33	9.72	9.95	10.11	10.22	10.30	10.36	10.41	10.45	10.47
Ws - 3rd q	11.92	12.52	12.92	13.17	13.33	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 - 1st q	140.27	150.23	153.85	155.42	156.12	157.89	158.52	159.45	161.25	161.12
Wd - Median	220.56	221.23	222.35	223.11	223.90	224.78	225.69	226.85	226.52	226.85
Wd - Mean	207.85	209.63	210.12	210.78	211.23	212.53	212.12	212.23	213.85	213.34
Wd - 3rd q	271.14	272.85	273.34	274.23	274.87	275.23	275.87	276.56	276.96	277.67

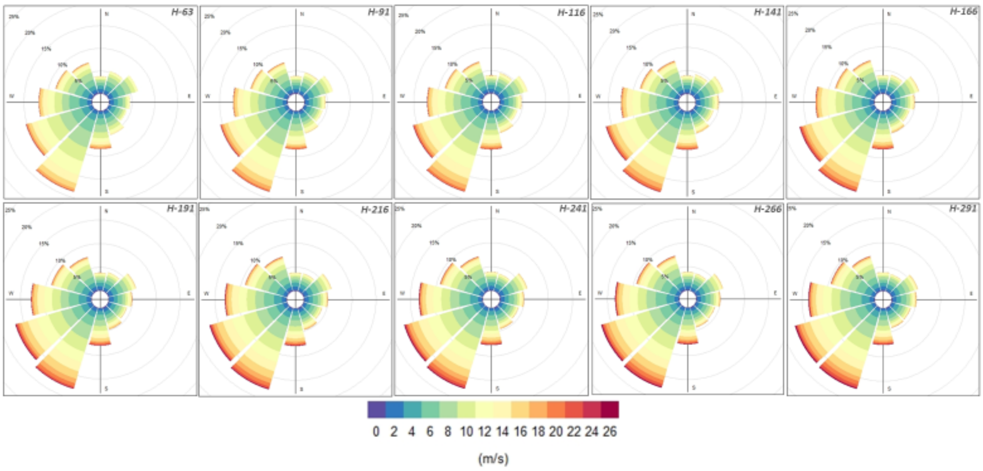
B.4 2018

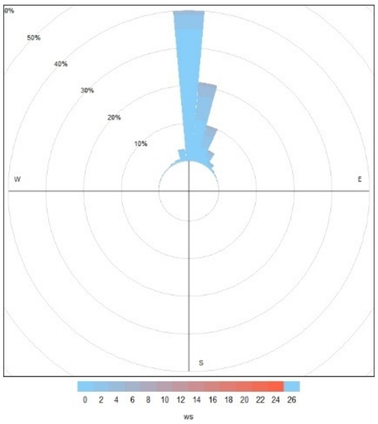


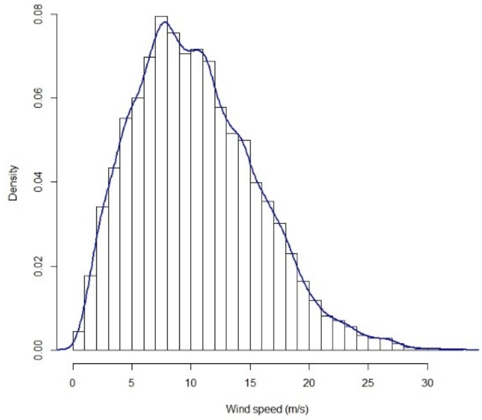


H (m)	63	91	116	141	166	191	216	241	266	291
Ws - Min	0	0	0	0	0	0	0	0	0	0
Ws – 1st q	6.10	6.30	6.34	6.35	6.35	6.32	6.13	6.30	6.29	6.28
Ws - Median	8.97	9.29	9.44	9.52	9.56	9.58	9.59	9.58	9.57	9.56
Ws - Mean	9.33	9.72	9.94	10.08	10.17	10.23	10.27	10.29	10.31	10.32
Ws - 3rd q	12.11	12.81	13.19	13.42	13.55	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 - 1st q	109.44	109.33	110.52	112.46	113.2	113.15	113.24	112.71	113.52	113.40
Wd - Median	201.61	201.92	203.32	204.75	205.83	206.37	206.64	206.92	208.28	208.73
Wd - Mean	190.14	190.07	190.73	191.94	192.57	192.43	192.38	192.24	193.38	193.32
Wd - 3rd q	264.23	264.21	264.83	265.68	266.02	266.24	266.37	266.47	267.43	267.42

B.5 2017

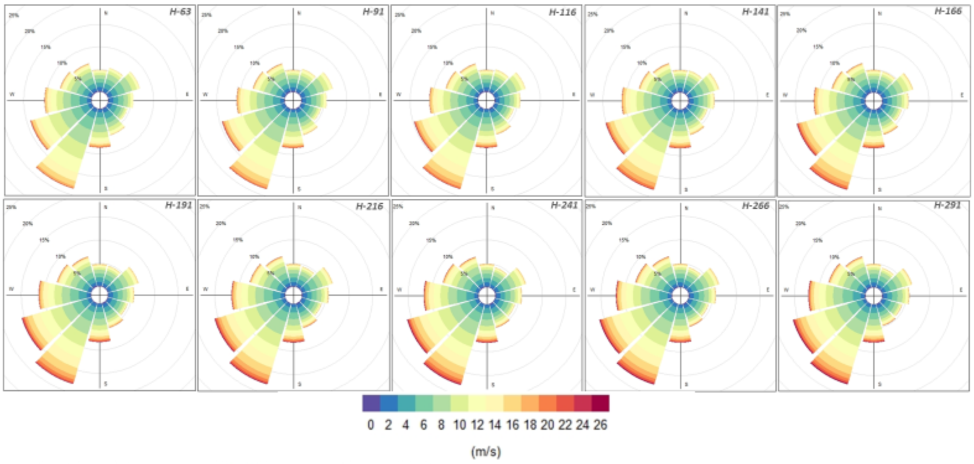


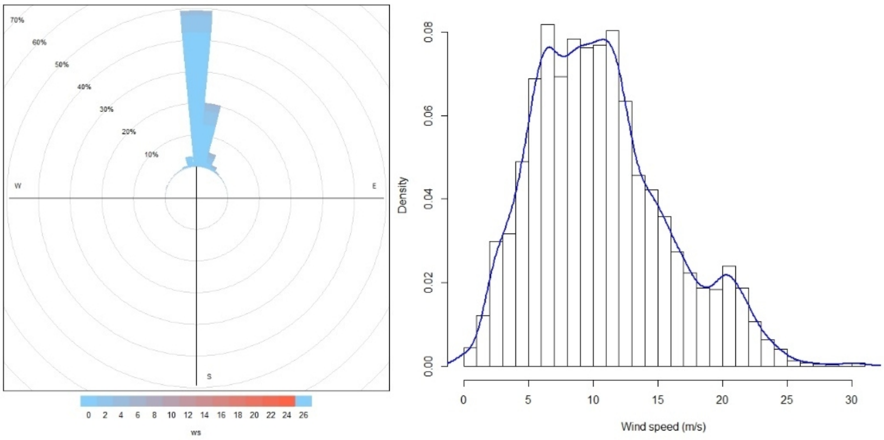




H (m)	63	91	116	141	166	191	216	241	266	291
Ws - Min	0	0	0	0	0	0	0	0	0	0
Ws – 1st q	6.07	6.26	6.34	6.39	6.42	6.43	6.46	6.46	6.49	6.51
Ws - Median	8.91	9.33	9.54	9.66	9.74	9.76	9.80	9.82	9.83	9.85
Ws - Mean	9.16	9.56	9.82	10.00	10.13	10.22	10.28	10.33	10.36	10.39
Ws - 3rd q	11.95	12.59	13.00	13.30	13.51	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 - 1st q	168.23	170.62	172.01	173.66	174.63	175.82	176.56	177.59	178.35	179.21
Wd - Median	230.42	231.92	233.12	234.38	235.22	236.12	237.42	238.52	239.23	239.24
Wd - Mean	215.33	217.18	218.27	219.14	219.88	220.57	221.17	221.77	222.17	222.68
Wd - 3rd q	278.77	281.12	281.92	282.52	283.02	283.52	284.12	284.62	284.97	285.42

B.6 2016

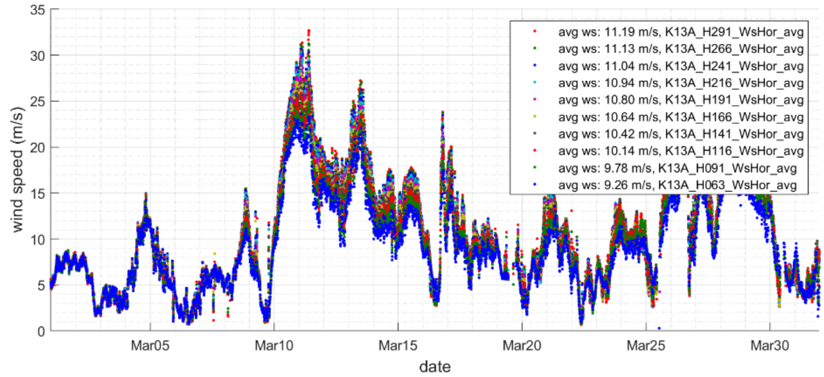


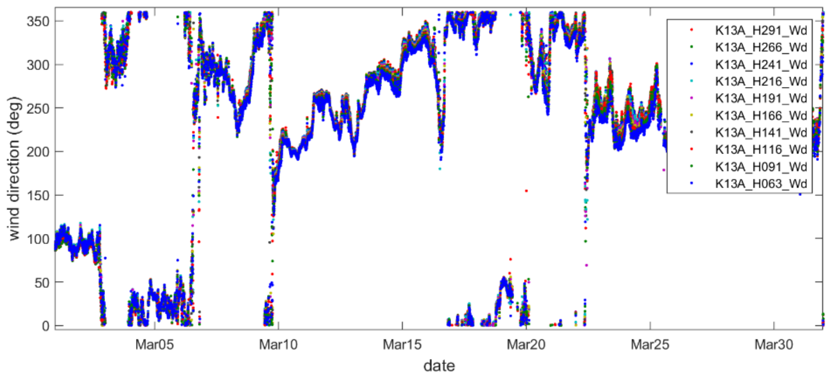


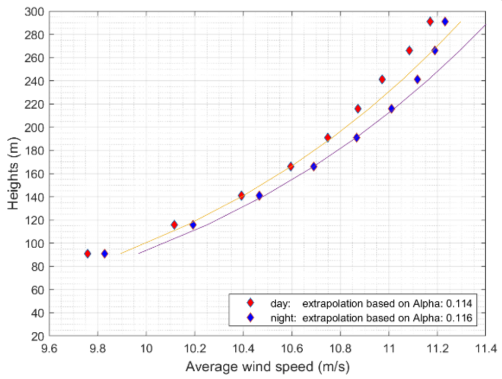
H (m)	63	91	116	141	166	191	216	241	266	291
Ws - Min	0	0	0	0	0	0	0	0	0	0
Ws – 1st q	6.40	6.58	6.60	6.62	6.654	6.651	6.643	6.613	6.62	6.629
Ws - Median	9.18	9.46	9.60	9.75	9.829	9.884	9.939	9.95	9.953	9.978
Ws - Mean	9.54	9.84	10.02	10.17	10.293	10.388	10.464	10.515	10.562	10.595
Ws - 3rd q	12.38	12.77	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 - 1st q	140.72	140.90	141.23	141.13	141.42	142.12	143.52	143.21	142.58	142.47
Wd - Median	221.01	221.30	222.01	222.25	222.97	223.72	224.46	225.04	223.95	224.43
Wd - Mean	197.63	198.04	198.42	198.56	199.23	199.73	200.53	200.82	200.52	200.78
Wd - 3rd q	256.42	257.04	257.73	258.82	259.87	260.73	262.09	262.92	263.33	263.92

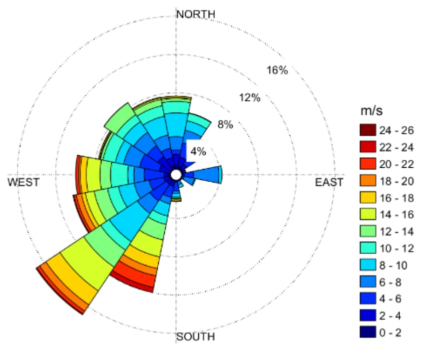
C Weather conditions analyses during the monthly reporting

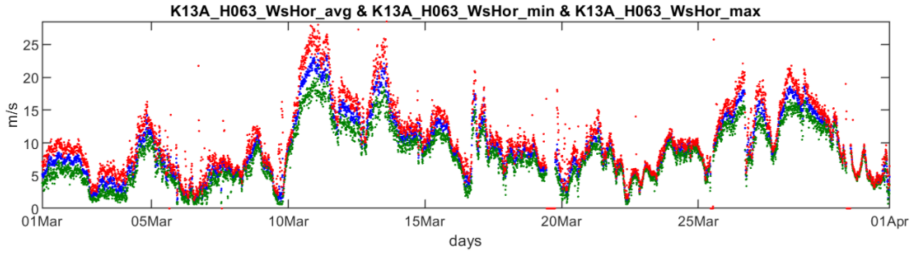
Weather conditions were analysed through different signalling figures including wind speed and direction signals, wind shears and dominant winds. Maximum, minimum and mean wind speed and directions time series are also analysed each month. The figures below show visual examples of the monthly reporting in March 2021 as an example, wind speed (a) and direction (b) signals; (c) wind shear and (d) wind rose at the K13a platform. Similar plots for the rest of months in the reporting period are available as well.

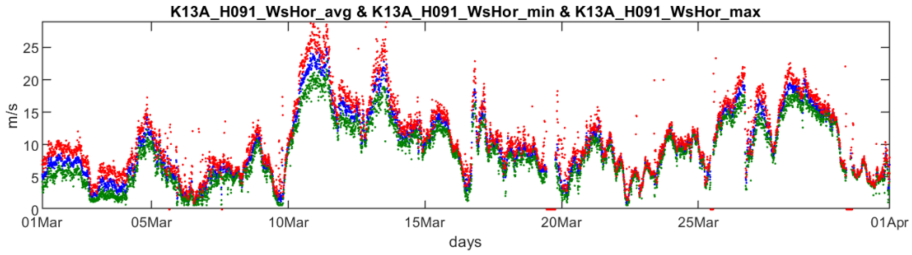


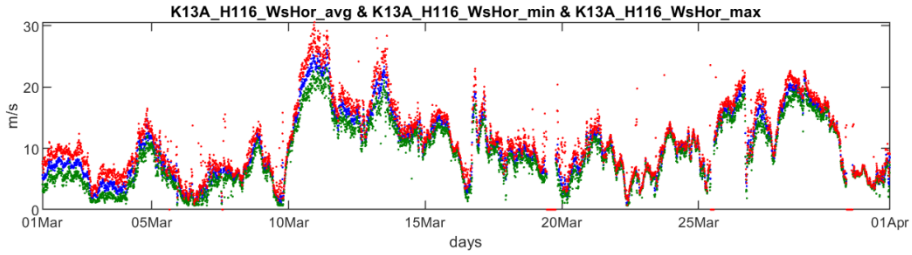


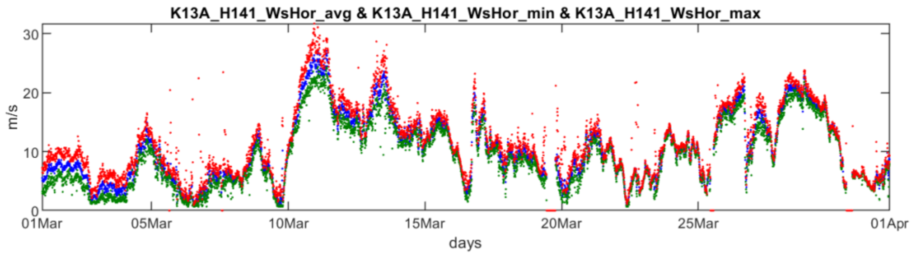


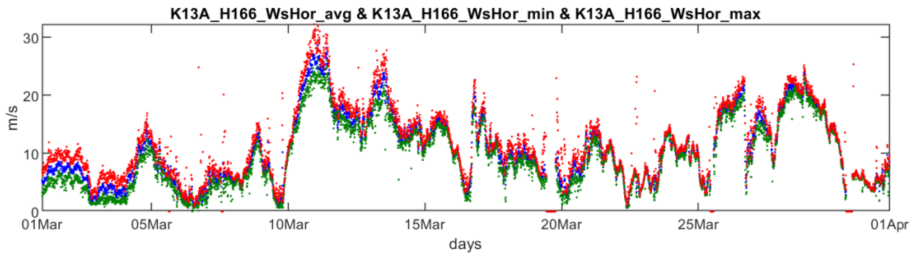




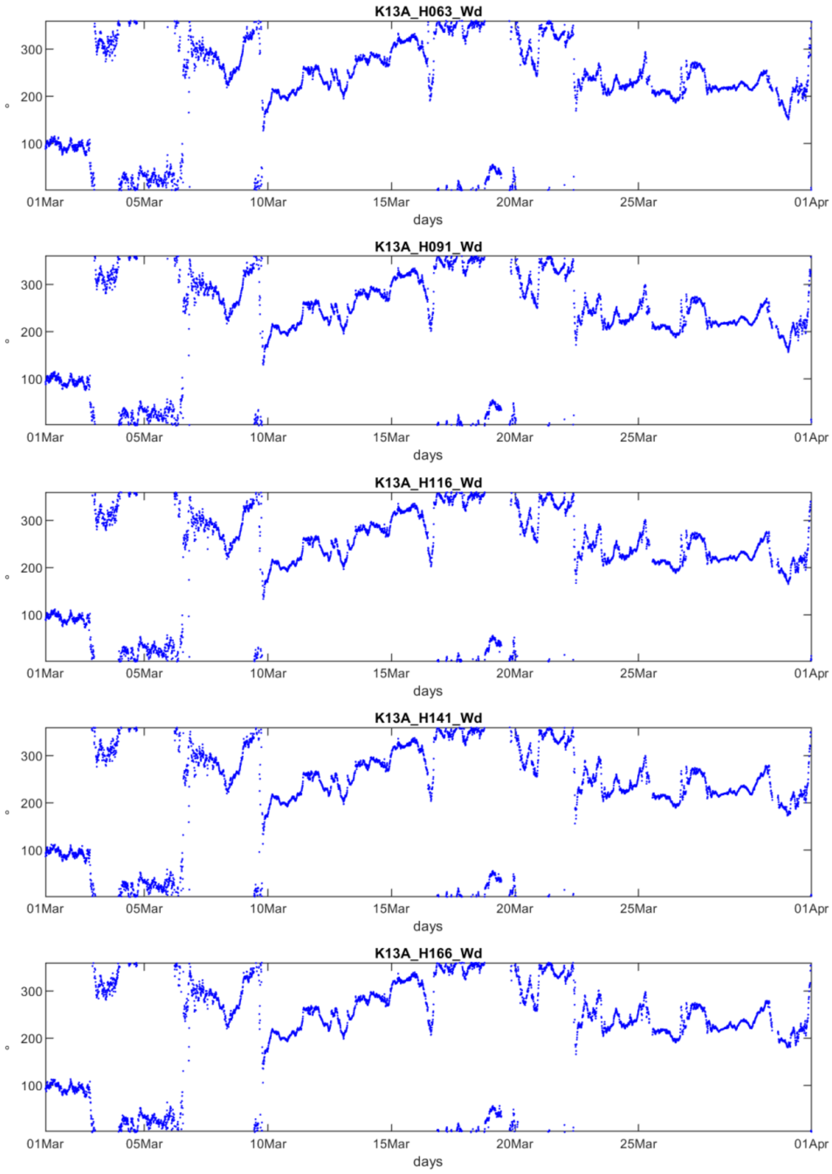








legend: [blue]: signal 1, [green]: signal 2, [red]: signal 3



legend: [blue]: signal 1, [green]: signal 2, [red]: signal 3