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TNO report

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Offshore wind energy deployment in the North Sea by 2030: long-term measurement campaign. Lichteiland Goeree, 2014-2021.

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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 at the 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 LEG platform for the period 2014-2021 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 measurements at LEG platform and with the wind measurements at both EPL and K13a shows a good alignment and quality of the data along the entire period.

The average data availability over the 8 year of the measurement campaign was found to be approximately 90% 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 LEG platform, the wind analysis for the 2014-2021 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 189° to 198° and the lower and upper quartiles range from 101° to 263° at all heights.

The analysis of shear shows an annualized range of 0.07 to 0.08 considering the entire data period between sequential sensor heights of the LiDAR. For 2021, the calculated day and night time shear was found to be approximately 0.06, slightly lower than the annualized range of the whole period.

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]). Furthermore, 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 offshore wind energy technology, and is key for the 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 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 targets 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 parameters to evaluate the financing of a project is the wind resource assessment (WRAs) of a specific site selected. Therefore, accurate long-term offshore wind measurements allow for improved estimations of WRAs, reducing uncertainties and increasing the financial success of a project. This increases the trust between interested stakeholders, from developers, consultants, the financial community, the government and policymakers. At the same time it allows for 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 farms. Floating remote sensing devices can be equipped with these suggested instrumentation to help characterize weather condition in deeper waters.

Figure 1 Locations of existing wind farms and designated zones for offshore wind farms 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).

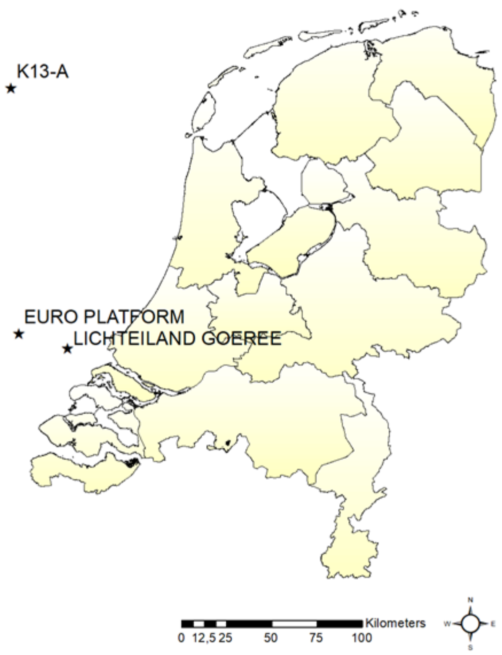


Figure 2 TNO locations of long term measurement campaigns for the wind resource at Lichteiland Goeree (LEG), Europlatform (EPL) and Wintershall platform K13a.

1.2.1 Complementary TNO activities in the North Sea

Besides the current LiDAR wind measurement campaign TNO is also performing additional measurement campaigns in the North Sea such as:

- A characterization of the precipitation levels over the entire Dutch North Sea based on wind climatology at different locations is carried out by TNO within the PROWESS project. This information is applied to develop a long term, and high resolution predictive model with the aim of assessing future levels of wind turbine degradation due to leading edge erosion. The measurement campaign couples different sources such as radar, weather stations and disdrometers and is ongoing at several strategic location in the North Sea (Figure 3). The measurements and their characteristics will be correlated to levels of blade erosion assessed by inspection reports, and later implemented to maintenance and operational planning, strategies and decisions for the development of future wind farms. This could help further reduce the levelized cost of energy and extend the operational lifetime of turbines [7].

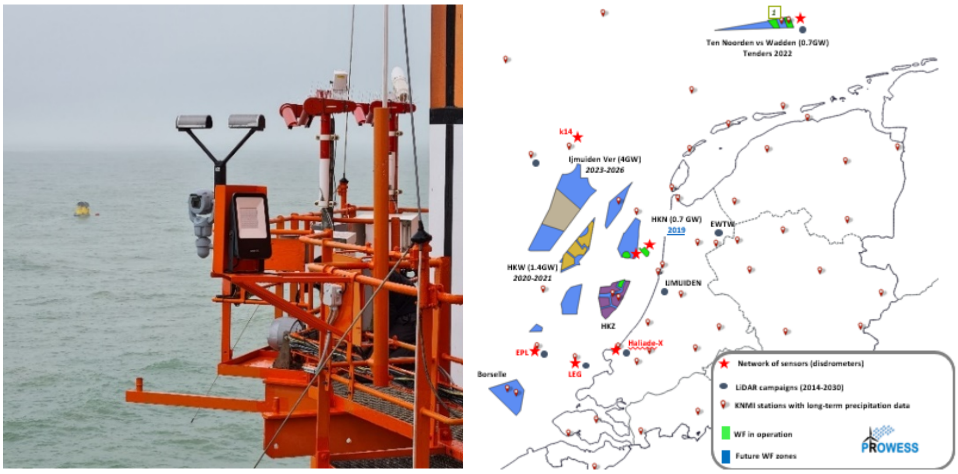


Figure 3 Disdrometer instrument installed at LEG platform (left) for the PROWESS project with a floating LiDAR in the background and the measurement campaign layout (right) for PROWESS project running form 2021 until 2023.

- Since 2018, TNO has carried out numerous floating LiDAR system (FLS) validations for multiple interested companies, see Figure 4 and Figure 5. Within

Figure 4 Aerial capture of the LEG platform and 4 floating lidar systems during a validation campaign, photo taken by Flying Focus.

these validations, the availability and the accuracy of the FLS's are investigated prior to use in wind resource assessments. These campaigns were performed at the Lichteiland Goeree (LEG) platform in the Dutch sector of the North Sea, where the pre-verified platform-mounted vertical profiling WindCube V2 LiDAR is installed, for direct comparison of the FLS outputs. The Carbon Trust's Offshore Wind Accelerator (OWA) Roadmap is used in order to calculate and evaluate the key performance indicators (KPI's) for multiple different heights above mean sea level (MSL). Through these campaigns, the maturity level is evaluated for each system, allowing for accurate FLS systems to be used in the field and ensure further understanding of the state of the technology.

Figure 5 Aerial captures of three floating LiDAR systems during a validation campaign at LEG platform photo taken by Flying Focus.

- Additionally, other parameters can be monitored offshore. There are several met ocean conditions which are useful and fundamental for the successful design and assessment of a project. These parameters can range from wave, current and meteorological data. Wave information can be used to estimate spatial variation of the extreme wave conditions required for design calculations. Present day wave measurements provide low resolution both spatially and temporally, and are limited in the measurement period. Furthermore, TNO is establishing a campaign to monitor ocean current speeds and directions at different water depths, in an effort to further characterize met ocean conditions of the Dutch North Sea. Accurate high resolution wave, and current measurements will support the roll-out of the planned wind farms in the upcoming years. Therefore it is recommended that additional buoy installations be considered in analyses throughout the project development cycle.

1.3 Open-access and public datasets

Since 2020 TNO has published annually reports on the wind conditions for each measurement campaign location: reports [8], [9] and [10] provide wind conditions analysis for the K13a platform for the periods 2016-2019, 2016-2020, and 2016-2021; [11] and [12] for the LEG platform for the periods 2014-2019 and 2014-2020, [13], [14], and [15] for the EPL platform for the periods 2016-2019, 2016-2020, and 2016-2021. This report includes the wind conditions for the period 2014-2021 at the LEG 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 after free registration. To use “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:
   Verhoef, J.P., Bergman, G., van der Werff, P.A. (2020) Lichteiland Goeree LiDAR measurement campaign; Instrumentation Report, TNO 2020 R10866
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. Lichteiland Goeree, 2014-2021. TNO 2022 R10649.

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 LEG measurement campaign: https://www.windopzee.net/en/locations/LEG/data/

- For monthly files: **LEG-STAT-yyyy-mm.CSV**
- After a quarter of a year is completed the monthly files will be replaced by: **LEG-STAT-yyyy-Qx.CSV**
- After the year is completed the quarterly files will be replaced by a yearly file as: **LEG -STAT-yyyy-Y.CSV.**

2 Measurement campaign at LEG

2.1 Location and instrumentation

The platform Lichteiland Goeree (LEG) is located 30 km South-West from Hoek van Holland, serving as a beacon for ships on the North Sea. It includes a helicopter pad, accommodation deck and a lighthouse (Figure 6 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 6 (right).

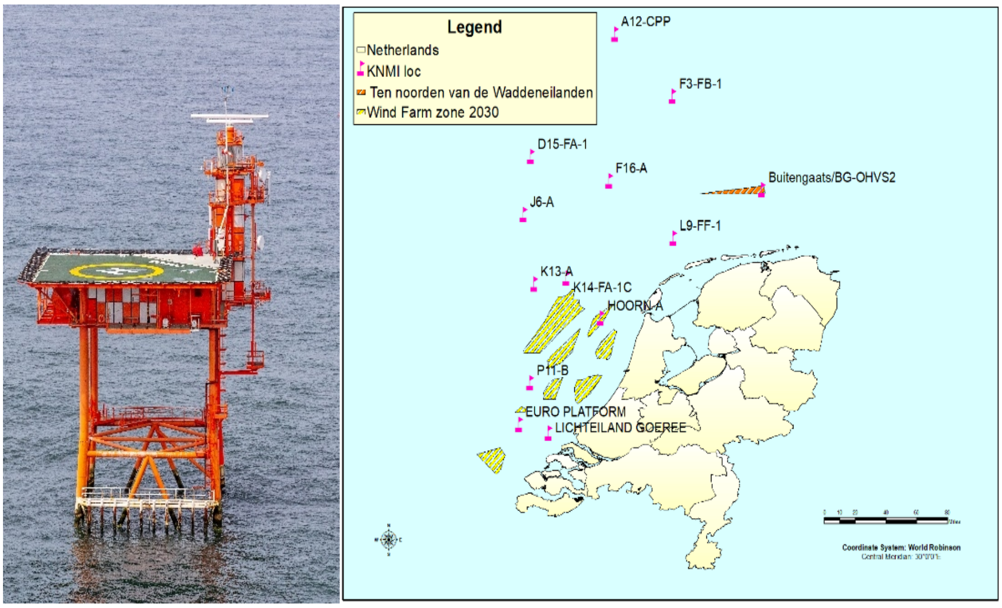


Figure 6 Aero capture of the Lichteiland Goeree (LEG) platform in May 2021 by Flying Focus (left), and KNMI measurement locations in the North Sea (right).

TNO performs an ongoing measurement campaign at LEG since 2014, 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 7 shows the replacement of the LiDAR on the LEG platform which occurred on September 6 2021.

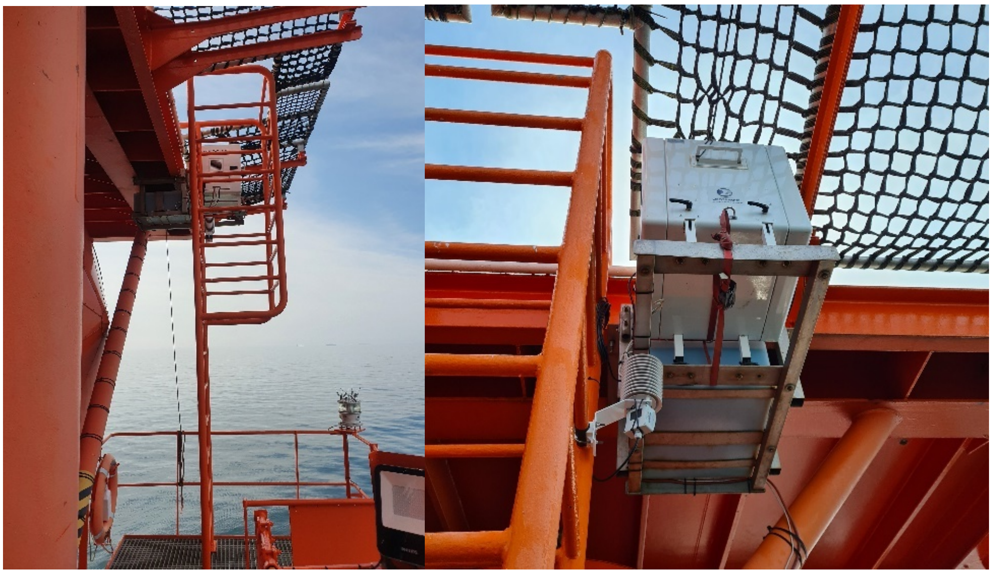


Figure 7 Views of newly installed LiDAR unit for the scheduled replacement period in 2021 onwards.

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 Rijkswaterstaat about the installation and safety measures [16] [17]. 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 [16]. At LEG, the suitable place was found beside the cage-ladder on the north-west side of the platform (Figure 8a, b). The LiDAR had to be installed in a new built mounting frame, oriented with the ‘North’ marker on the left side, pointing away from the lighthouse (Figure 8c, d).

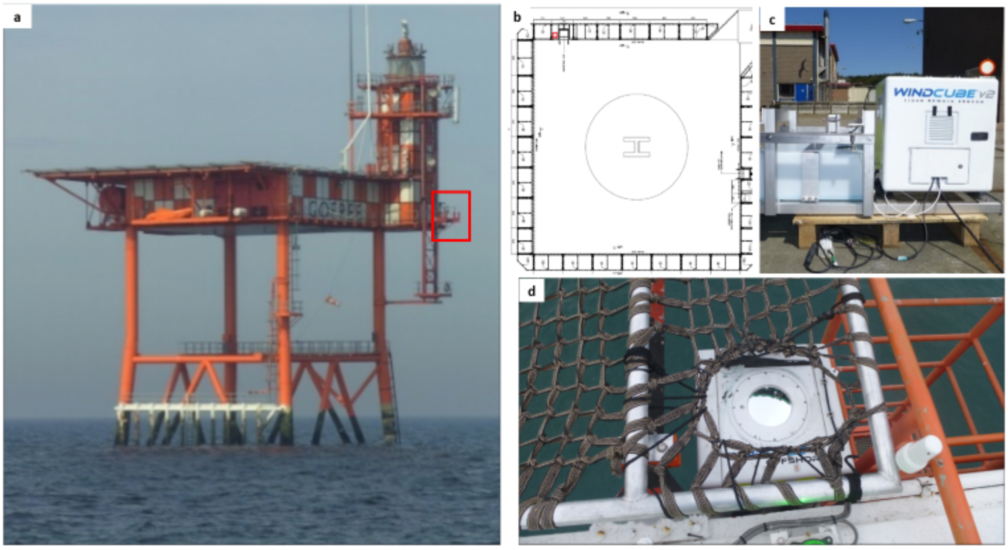


Figure 8 a) Front and b) top view of Lichteiland Goeree platform [LAT LON coordinates: 51.92503°N, 3.66844°E], helicopter deck at a height of 24.58m and the accommodation deck at 20.04m above mean sea level; c) mounting frame to place the LiDAR at the selected location in the platform; d) final installation of the LiDAR.

2.3 Onsite installation and operational status

The LiDAR selected is the LEOSPHERE WINDCUBE V2. The instrument measures wind profiles across up to 10 different heights by sending infrared pulses into the atmosphere. Before the LiDAR was installed at the LEG platform it was first calibrated [18] [19]. Manufacturers guarantee data quality up to 200 m although some V2 LiDAR's can measure beyond that height.

The LiDAR was mounted 22 m above Mean Sea Level (MSL) and provides both wind speed and direction measurements at 10 different heights between 62 m and 290 m above MSL. The reference heights for the measurements in this report refers to the Lowest Low Water Spring level (LLWS) 1.03 meter lower than the MLS [20], this to be aligned with the reference heights published in [11] and [12]. The measured data is timestamped at the start of each 10 minute time frame. Additional LiDAR specifications are included in Annex A.

Two different electrical connections are required in order to have the LiDAR fully operational. Firstly, a 24V DC power supply connection to the computer room of the platform where the AC-DC power converter of the LiDAR is placed. Secondly, an ethernet cable to the 3G/4G modem also placed in the computer room for the transfer of the data from the LiDAR.

As defined by TNO's ISO17025 quality system, the LiDAR should be serviced after one year of operation and should be replaced every two years (Table 1). All operational aspects with respect to installing and maintaining the LiDAR are recorded in a logbook of the team responsible for the measurement campaign.

During 2021 there were two down-time periods where the LiDAR was not operational due to technical issues with the newly installed system. These events affected the availability of data, but no issues on the quality were encountered, see

Table 2.

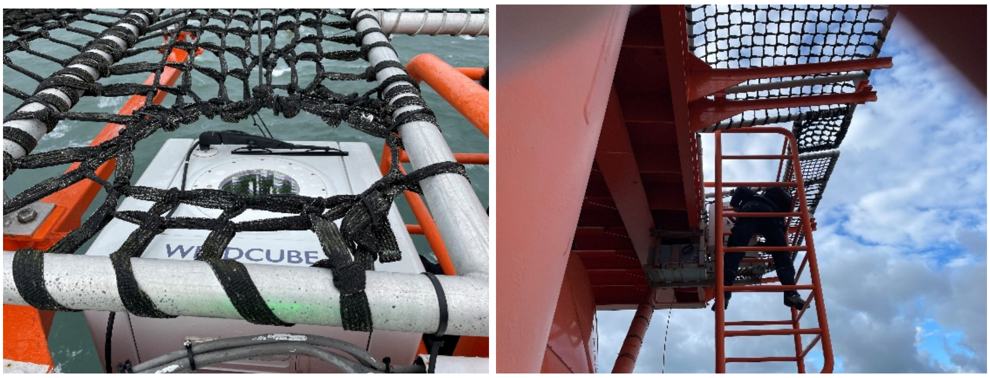


Figure 9 Photos from the repair visit on 21st of October 2021

Figure 10 View of rough waters and cloudy weather conditions on a site visit on 4th October 2021

Table 1 Replacements of LiDAR at the LEG platform.

Id LiDAR	LiDAR in operation	Planned replacement
127	06-10-2014 to 10-04-2015	3g communication switch
258	10-04-2015 to 28-09-2015	Good GSM communication
127	28-09-2015 to 05-10-2017	Periodically replacement
577	05-10-2017 to 24-10-2019	Periodically replacement
258	24-10-2019 to 06-09-2021	Periodically replacement
127	06-09-2021 to September 2023	Periodically replacement

Table 2 Down-time periods and motivations at LEG platform during the year 2021.

Date	Reason
08-10-2021 to 21-10-2021	The system suffers again from technical issue followed by a TNO personnel visit with a Leosphere technician. The problem was solved and the LiDAR worked properly after the repair (Figure 9).
25-09-2021 to 04-10-2021	Shortly after replacing the unit WLS7-258, there was a technical issue with the internal cabling of the LiDAR unit WLS7-127 followed by a TNO personnel visit on 4 October 2021 to solve the problem (Figure 10)

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 Rijkswaterstaat for the safe installation of the frame and the LiDAR were:

- A job-risk-assessment (AD-130, project RI&E) is made and signed by both parties involved. Minimize the number of employees working close to the edge of the platform, as the safety netting needs to be removed before the installation.
- Employees working close to the edge of the platform will be safe-guarded by a lifeline that prevents the people from falling over the platform edge.
- 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 on site 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 above the LLWS (Lowest Low Water Spring).

The data is measured on a 10-minute basis. The data collection period started from the 17th November 2014 at 13:00 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 updated envisioned.

The measurements heights reported in this report refers to the LLWS level. Despite the 1 meter difference with the MSL, due to the scale and scope of the comparison, the results and analysis are not affected.

Table 3 List of variables measured in the LiDAR during the experimental campaign. Where LEG is the platform; HXXX are the different heights measured above the lowest low water spring level(LLWS): 63, 91,116,141,166,191,216,241,266 and 291 m.

Acronym	Signal name	Units
LEG_Int_Temp	Internal temperature of the WINDCUBE	°C
LEG_Wiper_count	Wiper activation count	-
LEG_HXXX_CNR	Carrier to noise ratio	dB
LEG_HXXX_CNR_min	Minimum carrier To noise ratio	dB
LEG_HXXX_Data_Avail	Availability	%
LEG_HXXX_DSB	Doppler spectral broadening	Hz
LEG_HXXX_Wd	wind direction (average wind direction)	°
LEG_HXXX_Ws	average wind speed	m/s
LEG_HXXX_Ws_max	maximum wind speed	m/s
LEG_HXXX_Ws_min	minimum wind speed	m/s
LEG_HXXX_WsDisp	Wind speed dispersion (standard deviation wind speed)	m/s
LEG_HXXX_Z-Ws	Z-Wind (average of vertical wind speed)	m/s
LEG_HXXX_Z-WsDisp	Z-Wind dispersion (standard deviation of vertical wind speed)	m/s

As indicated in Figure 11 and Table 4 the data availability depends on the height of the measurements, and manufacturers will typically suggest usage of the LiDAR up to a certain height. For heights up to 200m, the data available is on average 95%, while up to 266 m the availability decreases to 64%. At 291 m the availability was about 56%. The decrease in data availability and coverage with increasing measurement height is mainly due to the lower concentration of aerosols in the air, which implies that there are less moving particles that the device can detect at those heights. During 2017/2018 the two highest levels showed invalid data. The analysis of the data availability are based on the available measurements periods, therefore, the percentage of data availability in Table 4 are biased by incomplete years and LiDAR system replacements or downtime periods. Please note that the measurements started in November 2014, and in 2015 data was not been available from May to August. That is why the variability in those years is higher.

In conclusion for this report, heights above 241 m are not considered for further analysis. Additionally to the data availability, there is degradation present as function of height. From Figure 11 it is noticeable that the signals have a tendency to reduce their data availability along the time of operation. Higher monthly data availability is shown by the system when it has been newly installed, as seen in the periods of October-March 2015, September 2017 and October 2019. Similar behaviour seems to be present over the period of October to December 2021. This leads to a conclusion that the signals suffer degradation over time, providing lower data availability in the end of its operational period. This effect is more prevalent at higher heights. This performance could be improved by a more regular maintenance, cleaning and by regularly replacing the wiper system. Nevertheless a little degradation in measured availability is inevitable.

Table 4 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 (%)
2014	99.9	99.9	99.9	99.4	97.9	95.9	92.4	85.9	76.3	64.6
2015	99.2	99.2	98.7	97.9	96.7	94.1	89.1	80.7	69.9	59.0
2016	96.4	97.1	97.3	96.0	93.2	88.2	80.7	71.0	59.2	47.5
2017	91.9	92.3	92.4	90.6	86.9	80.9	73.0	64.0	35.7	26.4
2018	97.4	96.4	96.1	94.7	91.8	86.7	79.6	70.7	NA	NA
2019	96.8	95.7	95.4	94.1	91.3	86.1	76.9	64.4	74.3	62.3
2020	99.9	99.9	99.9	99.7	96.8	93.6	87.0	76.6	63.8	71.7
2021	97.1	97.0	96.7	96.0	94.3	91.1	85.7	77.8	68.0	58.5

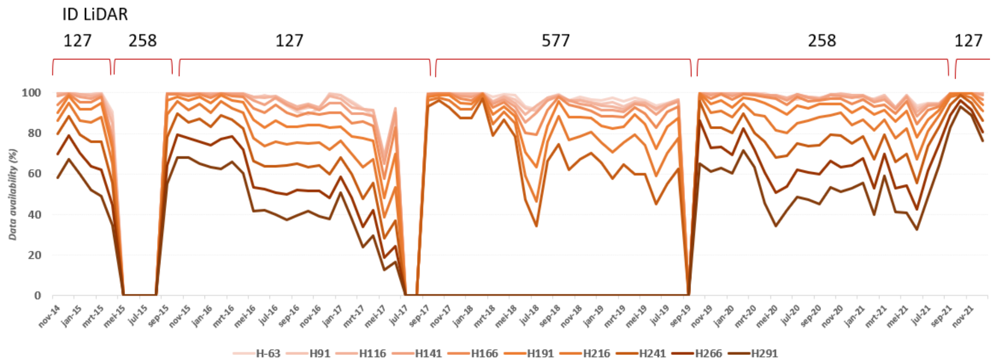


Figure 11 Monthly averages of the data available (%) measured by the LEOSPHERE WINDCUBE V2 LiDAR by height at the LEG platform for the period 2014-2021 and Id of the LiDAR during the operational period.

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 or failures to be able to react on a short notice. During these checks, no data filtering is applied on the data availability. As mentioned before, data availability refers to the number of valid data readings within an interval of 10 minutes.

There are complementary reports with data verification comparing with other measurements. In particular, [21] examines the wind speed and direction measurements campaigns at eight offshore measurement locations distributed throughout the North Sea, including the LEG 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.

Furthermore, Figure 12 presents the monthly sum of the wiper count signal, an indicator of reduced data availability and Figure 13 shows the monthly average Carrier to Noise Ratio (CNR), an indicator of the signal to noise ratio. When the CNR measures < -23, the signal to noise ratio is considered too low and the data point is flagged with a “NaN”.

The Figure 14 shows the displays the monthly average signal availability for the most recent previous LiDAR measurement period from October 2019 to September 2021, and most recent replacement. The wiper count increases as the LiDAR approaches its replacement date, then returning to zero once replaced. Increased wiper activity could lead to reduced data quality. This also coincides with a decrease in signal availability before replacement as shown in Figure 14 and in Table 5. Over the period, the CNR improves after replacement. Following the LiDAR replacement, values return to expected performance levels.

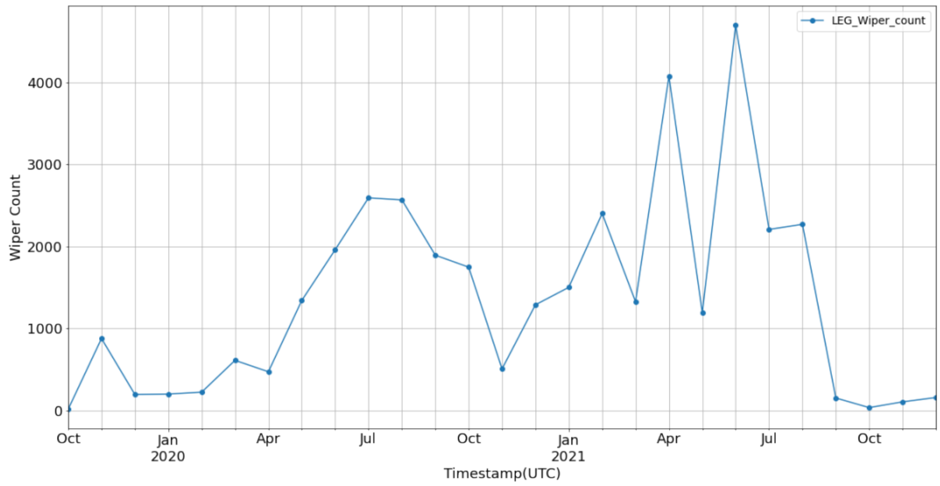


Figure 12 Monthly Wiper Count over one LIDAR system measurement period

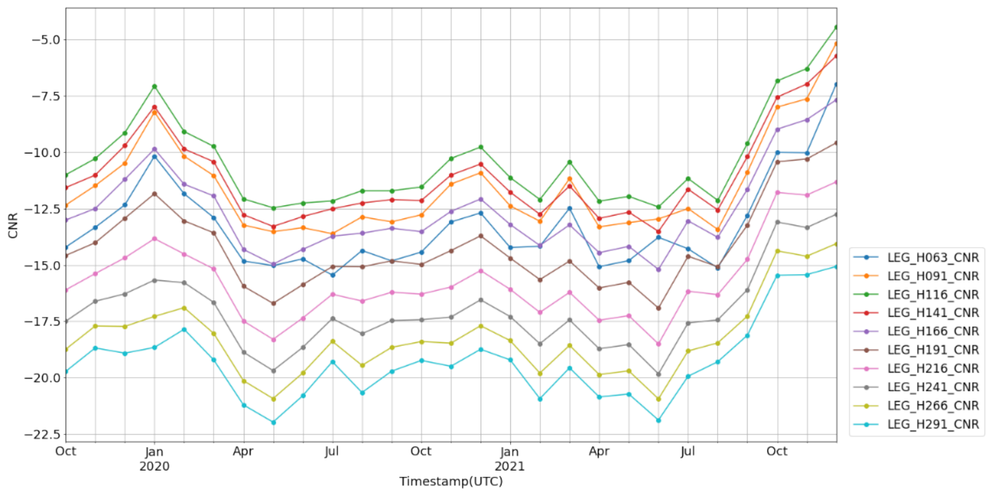


Figure 13 Monthly CNR over one LiDAR system measurement period

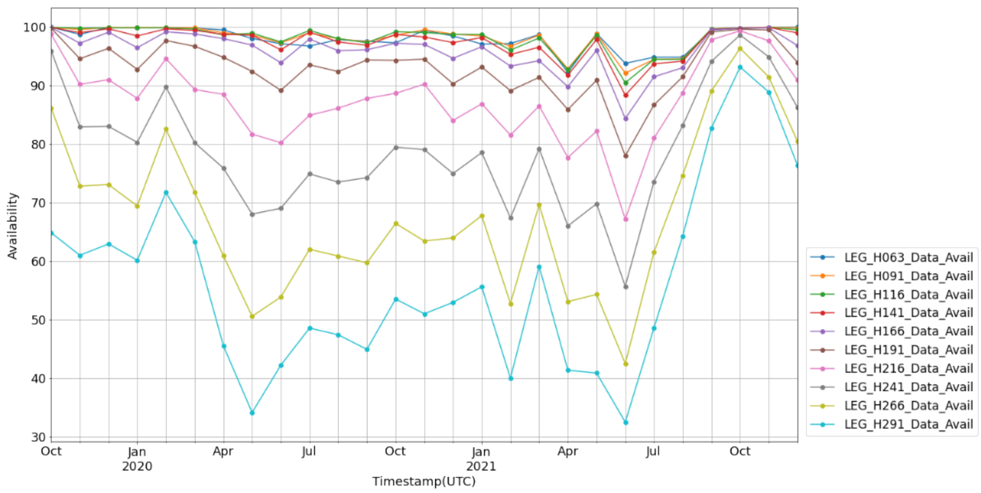


Figure 14 Monthly availability over one LiDAR system measurement period

Table 5 Data measured availability (in %) by height for 2021, for the period before the replacement (06/09/2021) and after the replacement. Data >90% available are considered as available (green), <90% (in yellow) and in red not available data.

Year 2021	H 63 (%)	H 91 (%)	H 116 (%)	H 141 (%)	H 166 (%)	H 191 (%)	H 216 (%)	H 241 (%)	H 266 (%)	H 291 (%)
01/01-05/09	96.0	95.9	95.6	94.6	92.5	88.6	81.8	72.1	60.1	48.3
06/09-31/12	100.0	99.9	99.8	99.6	98.9	97.8	96.0	93.0	88.8	85.3

4 Wind conditions at LEG

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 LEG platform for the entire period of 2014-2021. 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 LEG 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).

Furthermore, 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 2014-2021

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 wind speed average varies from 9.14 m/s at the lowest measured height of 63 m up to 10.58 m/s at 141 m, increasing gradually. In regards of wind directions, the dominant direction is South West, measuring between 189° to 198° degrees with a lower and upper quartiles range from 101° to 263° (Table 6). Wind roses in Figure 15 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) increase with the height of the measurements.

Table 6 Descriptive statistics for the wind speed (Ws) and direction (Wd) at different heights for the 2014-2021 period at the LEG platform.

H (m)	63	91	116	141	166	191	216	241
Ws – Min	0.06	0.10	0.07	0.09	0.04	0.13	0.04	0.06
Ws – 1st quartile	5.96	6.10	6.17	6.24	6.31	6.39	6.48	6.58
Ws - Median	8.76	9.03	9.20	9.34	9.47	9.60	9.72	9.86
Ws - Mean	9.14	9.47	9.69	9.88	10.06	10.23	10.41	10.58
Ws - 3rd quartile	11.9	12.41	12.73	12.99	13.24	13.46	13.67	13.87
Ws -98 p	18.98	19.9	20.67	21.39	22.02	22.63	23.19	23.69
Ws - Max	33.02	34.38	35.23	36.08	36.97	37.5	37.91	38.27
Wd - 1st quartile	109.60	110.70	112.40	113.88	115.60	118.10	120.65	123.90
Wd - Median	208.10	209.30	210.60	211.90	213.40	214.90	216.70	219.00
Wd - Mean	189.20	190.18	191.22	192.09	193.12	194.35	195.77	197.55
Wd - 3rd quartile	256.80	257.40	258.00	258.60	259.30	260.10	261.30	262.90

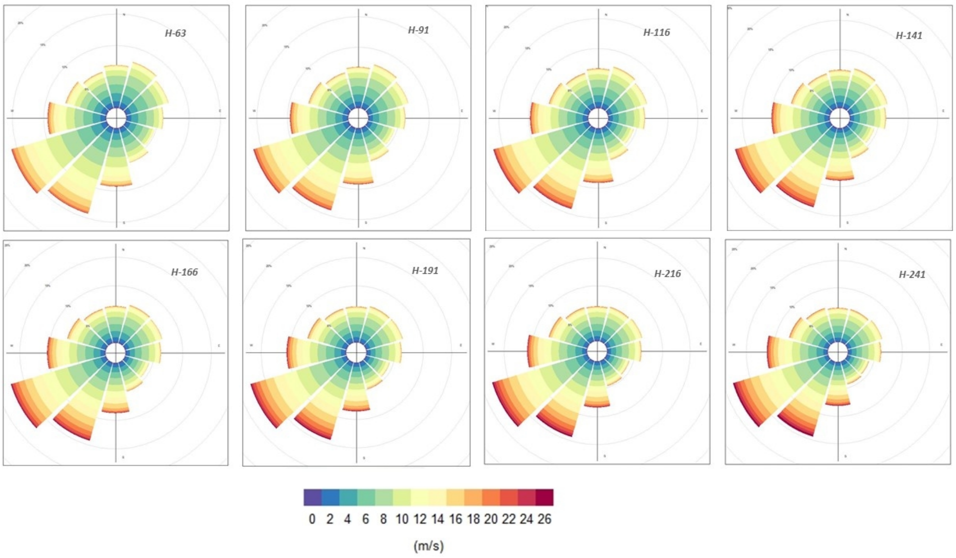


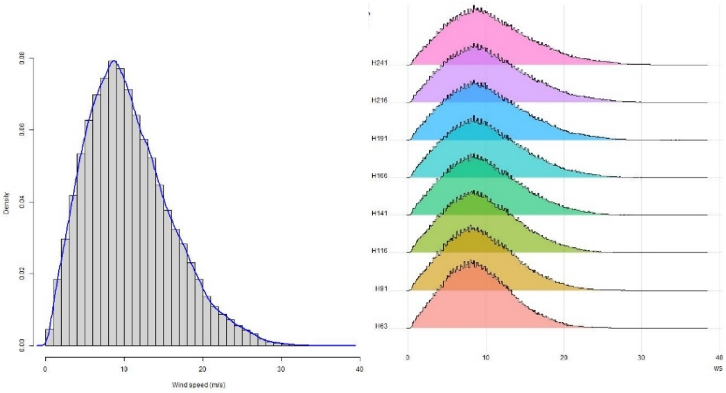
Figure 15 Wind roses at different heights showing the wind prevailing direction for the 2014 -2021 period.

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 and 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 LEG, during the period 2014-2021, the Weibull distribution at 141 m height shows that k = 2.122 and c = 11.156 m/s (see table in Figure 16). Figure 16 (left) shows the wind speed frequency probability density for each wind speed bin, and the Weibull probability density function fitted.

The Figure 16 (centre) indicates the distribution of the wind speed for each measurement height and clearly shows how the distribution is flattered and skewed right increasing the heights, as reflected by the shape and scale parameters presented in Figure 16 (table) where the former decreases meaning a less variability and the latter increases meaning higher wind speeds. For the 2014-2021 period at 141 m height, the k parameter is similar to the k at EPL and K13a platforms.



Height (m)	Shape (k)	Scale (c)
63	2.244	10.320
91	2.196	10.690
116	2.153	10.937
141	2.122	11.156
166	2.095	11.360
191	2.077	11.555
216	2.064	11.753
241	2.060	11.950

Figure 16 (left) Weibull distribution and curve fitting at 141 m height and (right) Weibull distributions at different heights for the measurement campaign with k and c parameters (table) at LEG for 2014-2021.

The Figure 17 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 (4 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 LEG platform, the offshore wind speeds vary within margins of about 1 m/s on hourly averages and of 10 degrees in wind direction.

The wind conditions analysed in this report are in line with the assessment presented in [21], [22] and [11]. Such studies present additional description over the temporal variability of horizontal and vertical wind profiles at different offshore locations over the Dutch North Sea.

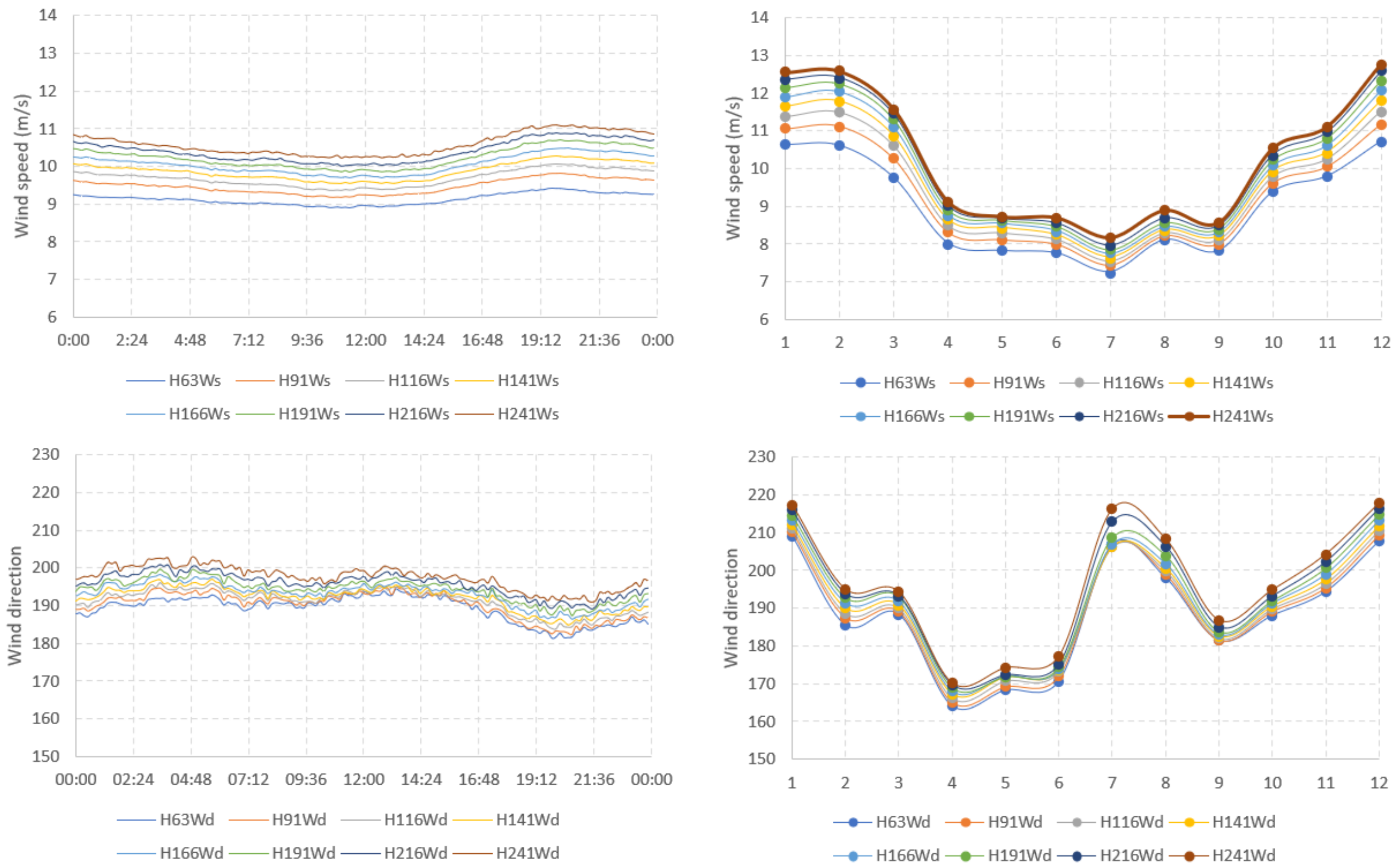


Figure 17 a) Monthly wind speed and direction averages and b) average daily cycles at different heights for the 2014-2021period.

4.2 Annual wind statistics

As regards the wind regimes and intra-annual variability; Figure 18 presents the annual Weibull distribution parameters at all heights for each year. The c parameter was very similar each year, with the exception of 2014 and 2015 where only few months of measurements were available. 2021 measurements show an average mean wind speeds between the years, with lower values compared to the windiest years of 2020 and 2017. The latter was limited in data availability in particular during the summer months where the wind speed tends to be lower. For the shape parameter, which is inversely proportional to wind variability, 2021 shows higher values, meaning lower wind availability, in particular compared to 2020, 2016 and 2019. Again, 2014, 2015 and 2017 shows very high values due to low data availability. In specific the annual Weibull distributions at different heights are shown for each year in Figure 19, and the annual statistics are provided in Table 7.

On the temporal evolution, Figure 20 shows the monthly averaged wind speed per year. Months with no data represents the period of LiDAR replacements (see Figure 11 for data availability). 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. The lowest wind speeds were registered in summer in July, August and winds are particularly low for September. The trend of the annual and seasonal statistics is similar as at EPL 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 LEG platform.

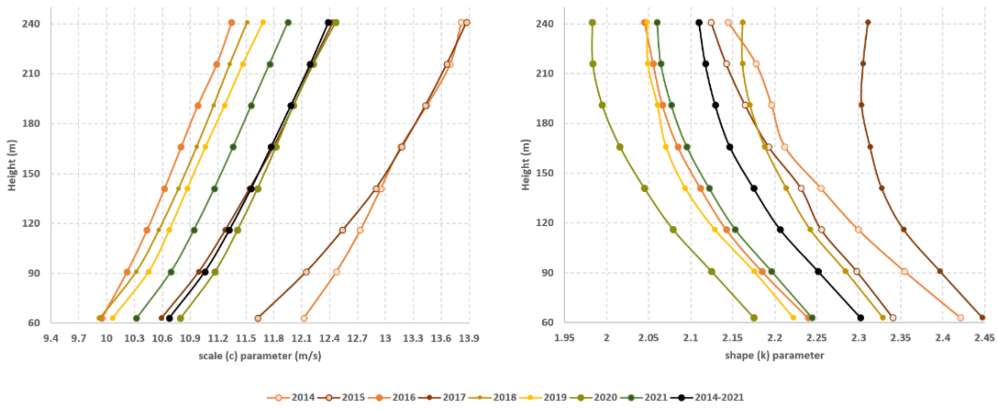


Figure 18 Annual Weibull (left) scale and (right) shape parameters at different heights at the LEG platform from 2014 to 2021.

Table 7 Descriptive annual statistics of the wind speed (Ws) and direction (Wd) at 141m height at the LEG platform.

H141 (m)	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**
Ws (m/s)- Min	0.26	0.30	0.14	0.18	0.20	020	0.09
Ws (m/s)– 1st q	7.23	5.93	6.75	6.22	6.19	6.21	5.73
Ws (m/s)-Median	10.87	8.88	9.88	9.16	9.01	9.79	8.65
Ws (m/s)- Mean	**11.42**	**9.404**	**10.23**	**9.547**	**9.62**	**10.30**	**9.13**
Ws (m/s)- 3rd q	15.28	12.35	13.36	12.52	12.51	13.74	11.95
Ws (m/s)– Max	29.48	34.74	30.9	36.08	28.89	30.37	29.74
Wd (🎹)- 1st q	149.5	119.7	164.2	87.5	126.1	125.8	78.9
Wd (🎹) Median	205.9	214.6	233.6	194.3	215.5	191.5	210.6
Wd (🎹)- Mean	**194.4**	**193.7**	**214**	**178.1**	**197.4**	**190.0**	**185.0**

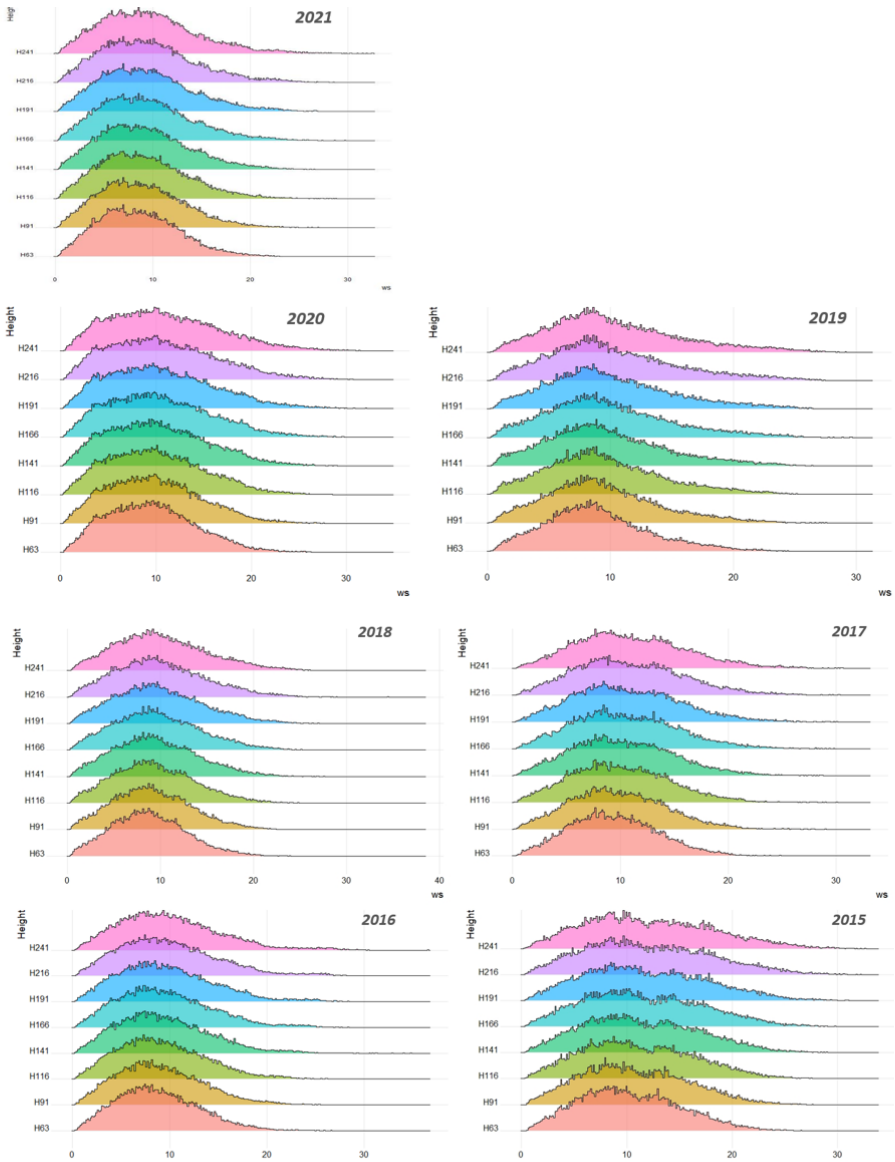


Figure 19 Annual Weibull distributions at different heights for the 2015-2021 period.

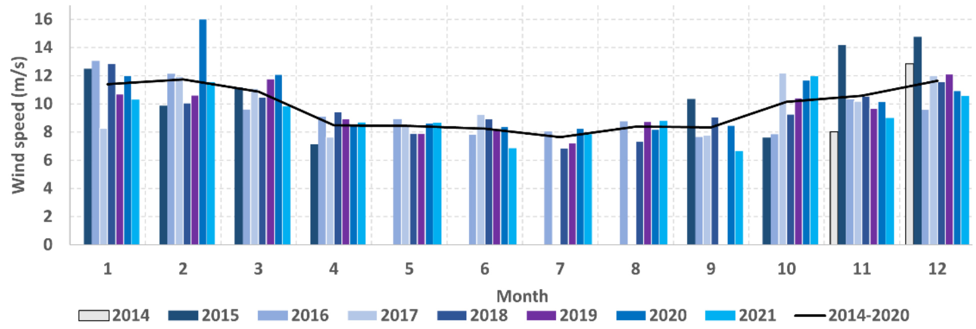


Figure 20 Annual wind speed (m/s) monthly averages bars at 141 m height and 2014-2021 monthly average (black line). Note: measurements started in November 2014; in 2015 date are not available from May to August (Figure 11).

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:

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

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 21 shows the directional shear profile for different sensor height pairings for the entire data period of 2014 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 0.125 from south west direction to negative shear in the northeast direction. Shear exponents are tightly bound and consistent from the south to north western directions, which are in line with the prevailing wind regime for the site. Larger variations in shear are seen from the north east to the south east, with higher sensor pairing demonstrating negative shear, hence a reduction of wind speed with height.

Table 8 shows the sensor pairs and the resulting annualized shear value over the entire data period. Here the annualized shear exponent regardless of direction, are quite consistent, ranging from 0.072 to 0.078.

Figure 22 presents the extrapolated shear exponent considering only the data for the year 2021, distinguishing between daytime and nighttime hours. During the night we can observe slightly higher shear exponents and wind speeds, which is in line with the trends observed in the results presented in Figure 23.

Much like wind speed measurements, variations in shear can be observed on an monthly and hourly basis. Figure 23 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.

Table 8 Annualized shear exponent for different sensor height pairings at LEG

Shear Pairing	Shear exponent
63 m to 91 m	0.079
91 m to 116 m	0.072
116 m to 141 m	0.075
141 m to 166 m	0.075
161 m to 191 m	0.077
191 m to 216 m	0.078
216 m to 241 m	0.077

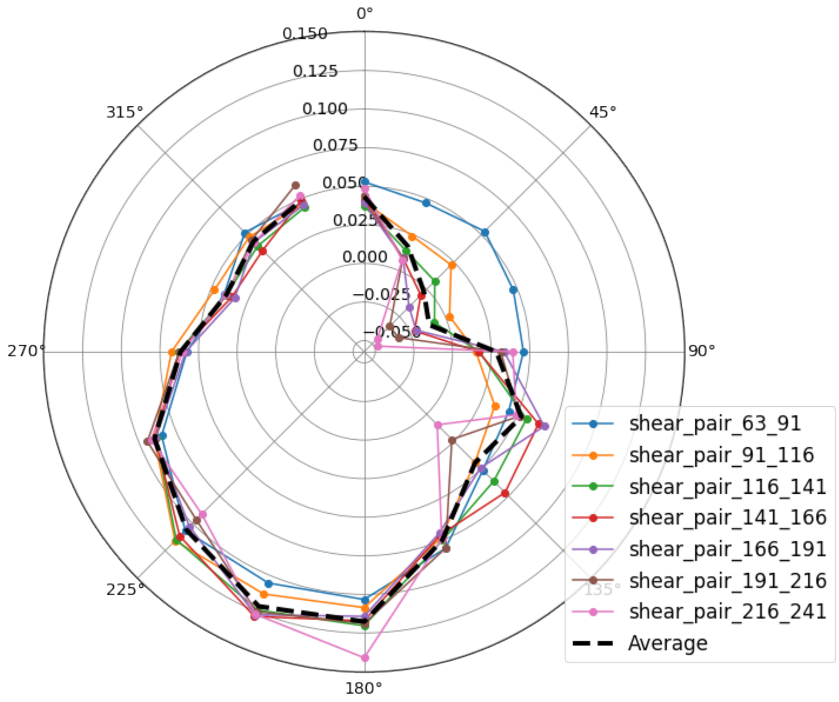


Figure 21 Directional shear profile trends for LiDAR sensor pairings

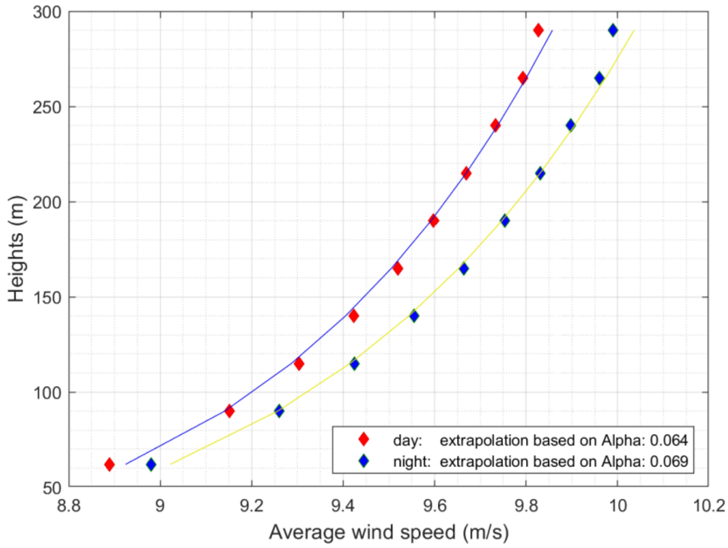
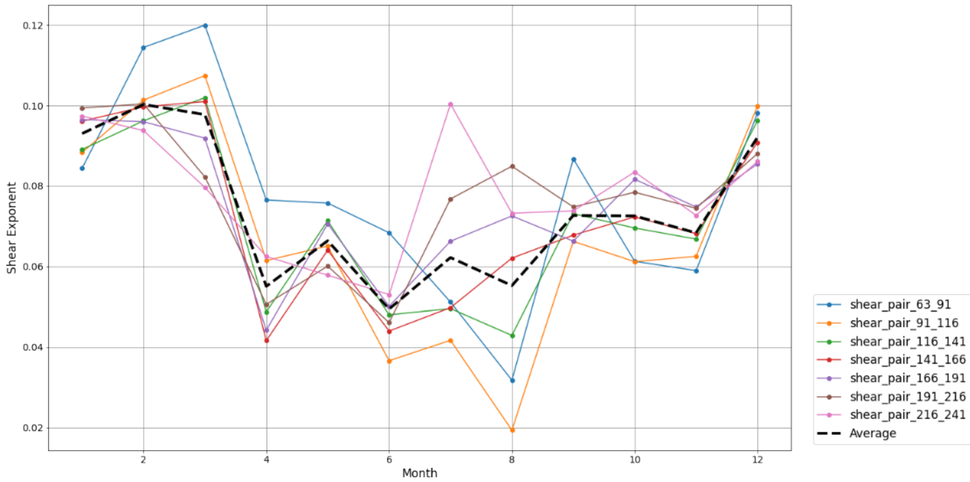


Figure 22 Day and night shear profile for the year 2021 at LEG



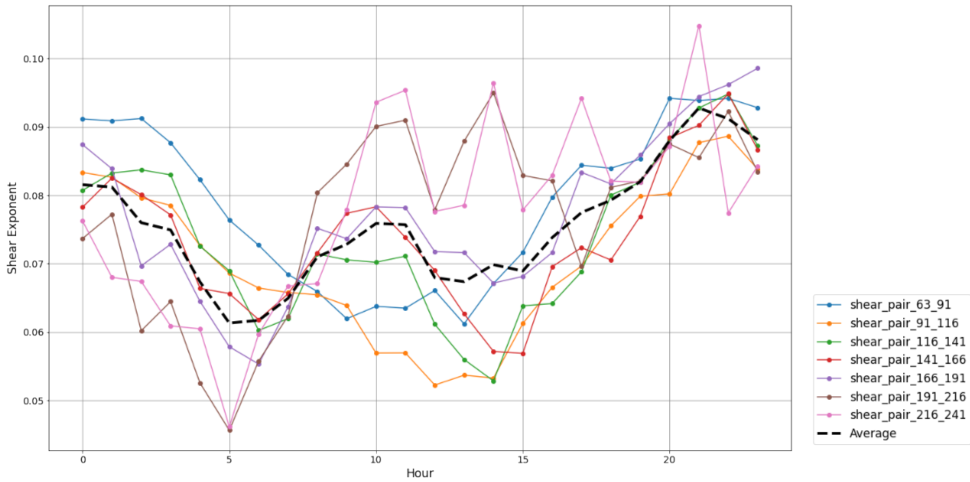


Figure 23 Shear profiles for LiDAR sensor pairs showing hourly (top) and monthly (bottom), trends for the data period of 2014 to 2021

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 24 shows the average wind direction for all sensor heights at LEG considered only the year 2021. At the lowest measured height of 63 m, the average wind direction was calculated to be approximately 184 degrees, while at the highest sensor height of 291 m the average wind direction was found to be approximately 195 degrees. That results in a difference of approximately 9 degrees between these levels.

Figure 25 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 as observed in Figure 24. Figure 26 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 and months of the year, and all sensor pairs are consistent in trend.

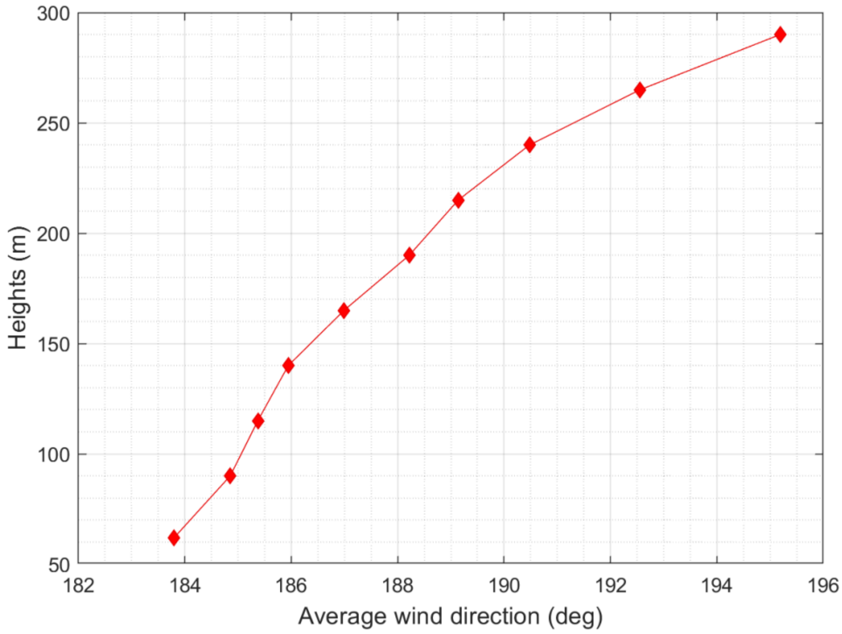


Figure 24 Variations in average wind direction for different sensor heights over the year 2021

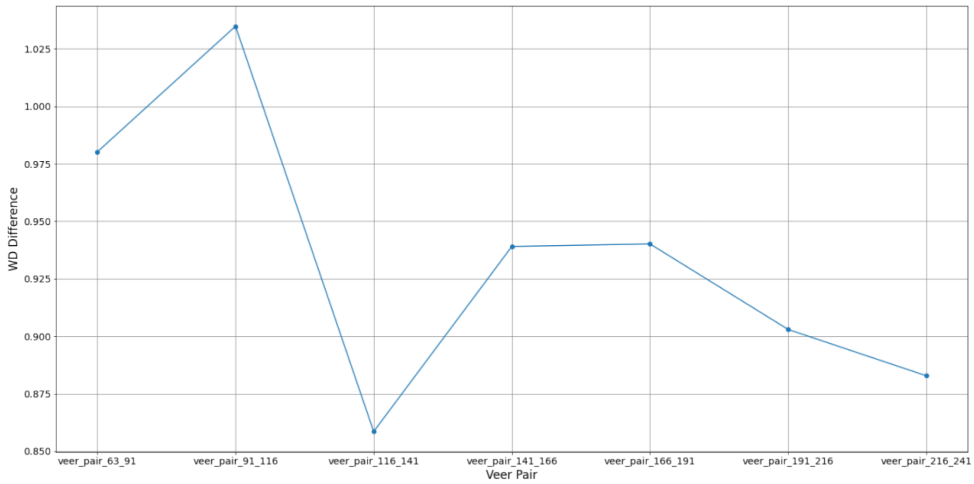


Figure 25 Annualized veer by LiDAR sensor pairing heights

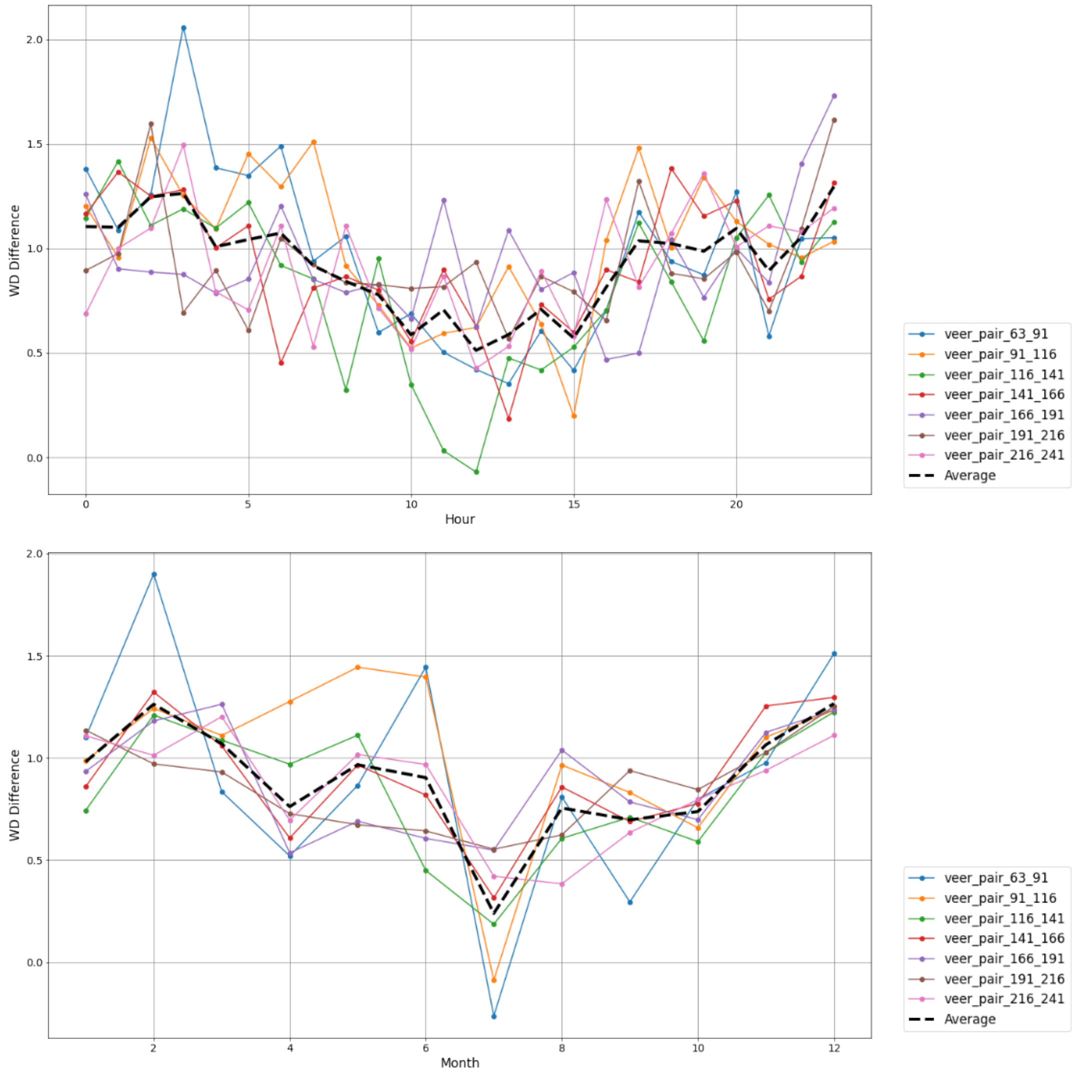


Figure 26 Veer profiles for LiDAR sensor pairs showing hourly (top) and monthly (bottom), trends for the data period of 2014 to 2021

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 occurred in 2021 and were mainly characterized by heavy rain or snow storms and not by extreme wind speeds.

One event occurred during March, where the Netherlands were hit by the storm Evert, being the first of the year [23]. This storm occurred between the 10 and 11th of March, for which a Yellow code was issued. From the LiDAR measurements, the higher wind speed were captured and are shown in the following figures. Figure 27 shows the time series for the wind speed at 8 heights for the entire month of March. The wind speed reached clearly higher values than usual, between 25 and 34 m/s. A detail for the time series in the days of the storm is offered in Figure 28 where the measurements show accurately the increased wind speed during the storm. Overall, this period is characterized by fairly consistent and high wind speeds. The effects on the power system and electricity prices fluctuations during the storm in March 2021 are discussed in Section 6.

Figure 27 Time series of wind speed measured by the LiDAR at LEG platform during March 2021

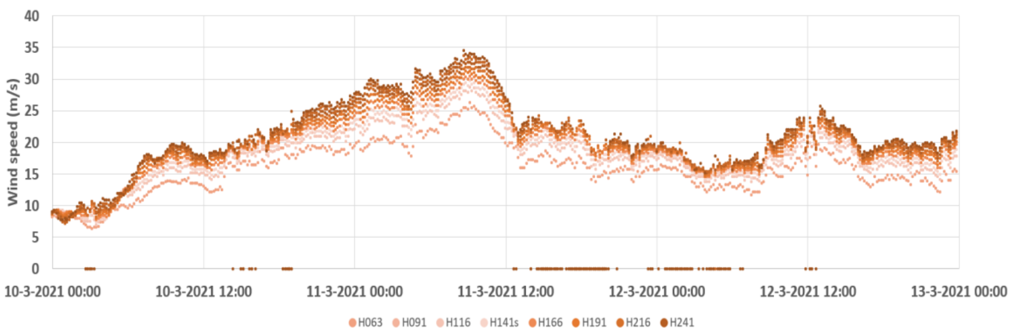


Figure 28 Focus on wind speed measurements during Evert storm between 11th and 13th March 2021

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 between the LiDAR and the KNMI met mast at LEG 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 differences 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 LLSW. These two heights are compared observing statistical analysis, time series, wind roses and distributions histograms. Table 9 shows the measured wind speeds at both KNMI and the LiDAR at LEG. The mean wind speeds differs by approximately 1 m/s, and average wind directions by approximately 4.5 degrees. Differences are due to shear effects at these different height and different locations.

From the time series presented in Figure 29 and Figure 30, the down-time periods from the LiDAR where no data are available is visible. The wind duration curves are presented in Figure 31, and are in agreement with one another.

From the wind roses of the 2021 wind directions in Figure 32, KNMI seems to have recorded more wind speed occurrences from 24 to 26 m/s from the South-West direction. Overall the shape and general distribution of the wind roses are aligned. Figure 33 presents the distribution histograms for both wind speed and wind direction, also showing general consistency in shape and trends between the two locations.

Table 9 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	8.07	9.14
Max.	27.80	33.02
Std dev.	3.98	4.30
Wd (°)	**KNMI (38 m)**	**LiDAR (63 m)**
Mean	194.69	189.19
Min./ Max	0 / 360	0 / 360
Std dev.	96.45	96.28

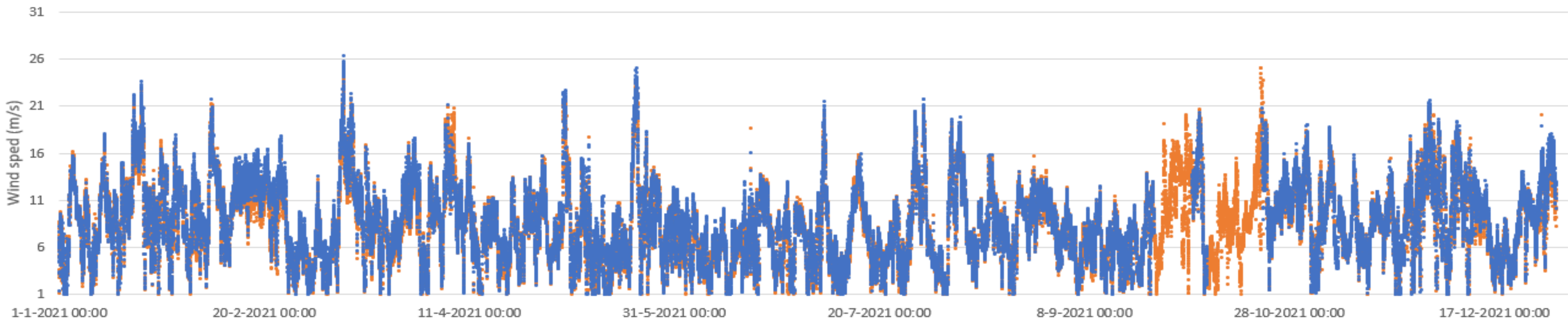


Figure 29 Time series wind speed for the year 2021 between LiDAR (blue) and KNMI (orange) measurements at the LEG platform

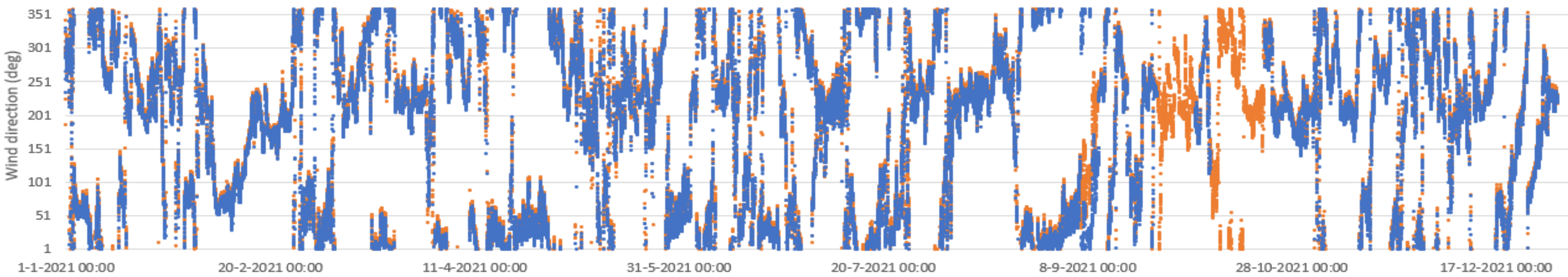


Figure 30 Time series wind direction for the year 2021 between LiDAR (blue) and KNMI (orange) measurements at the LEG platform

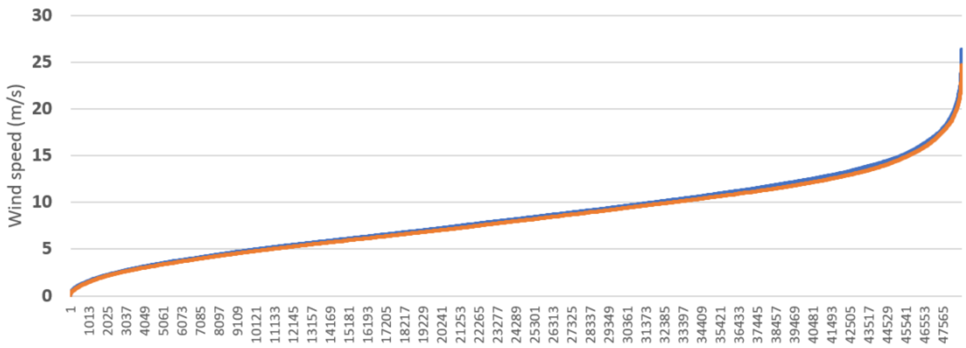


Figure 31 Wind speed duration curves for the 10-min time stamps (x-axis) for the period 2021, KNMI (orange) and LiDAR (blue)

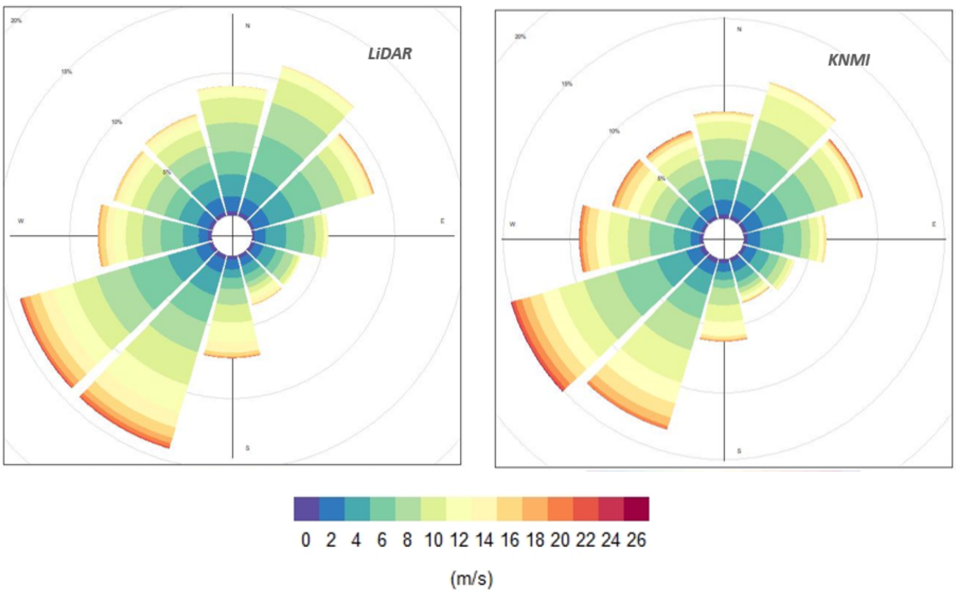


Figure 32 Wind roses for LiDAR at 63m (left) and KNMI at 38m (right) measurements at the LEG platform after filtering the outliers.

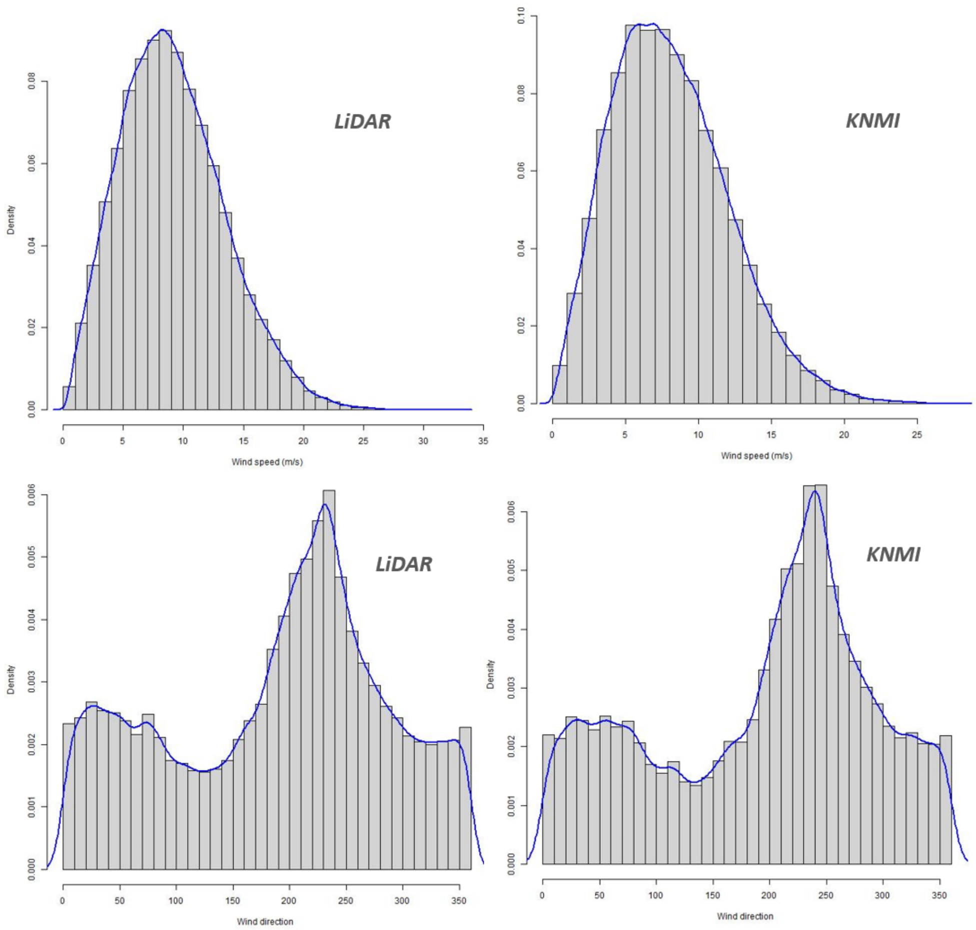


Figure 33 Distribution histograms the wind speed (m/s) (top) and wind direction (°) (bottom) between the LiDAR at 63 m height (left) and KNMI at 38 m height (right) measurements at the LEG platform, before the filtering of the outliers.

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 34 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, such 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 show the main direction as South-West, whereas at LEG and EPL the wind speed and directions are more concentrated along the main direction (South-West), at K13a it seems to be more distributed over a wider range of directions.

The Weibull c and k parameters per height averaged over 2016-2021 period are also calculated (Figure 35). 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 35). This difference in the wind profile at LEG was also observed in an previous report by TNO while studying the offshore wind resource at high altitudes [21].

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.

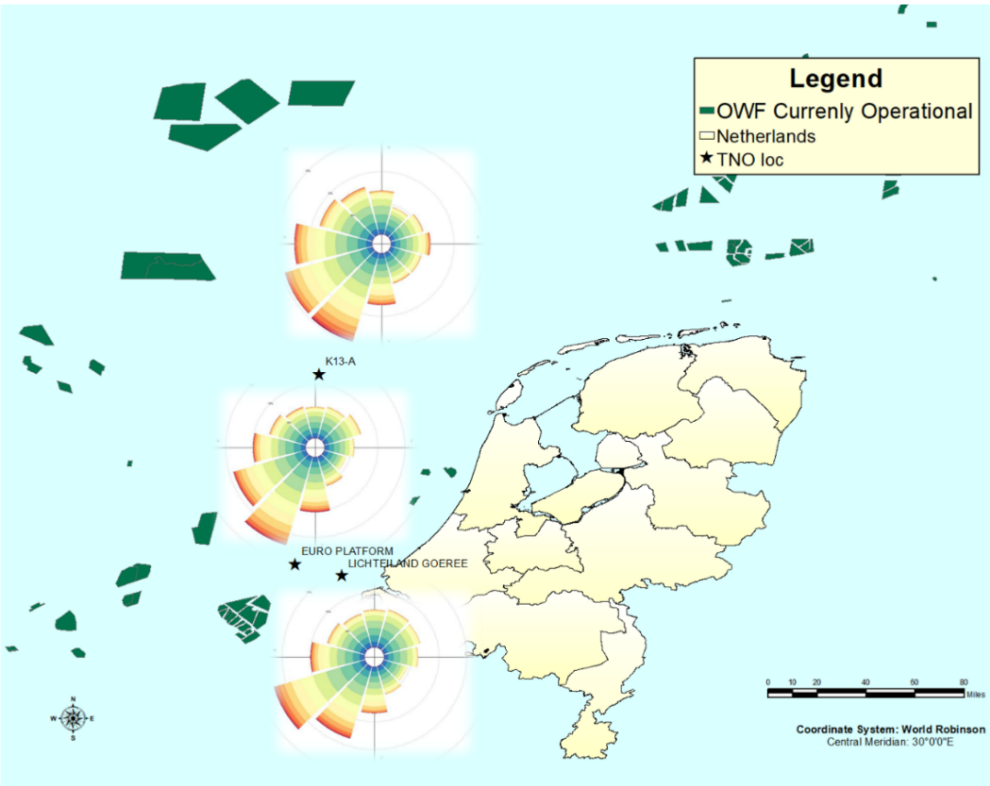
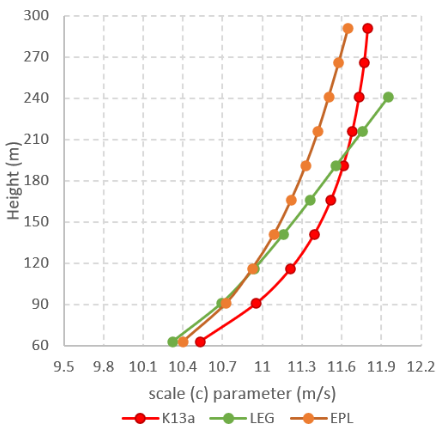


Figure 34 International and Dutch offshore wind farms currently operational and TNO measurement locations with wind roses at 141m for the 2016-2021 period

Table 10 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 11, 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 having the most calculated veer at around 1 degree offset clockwise between heights, compared to EPL and K13a that are closer to 0.5 degrees.



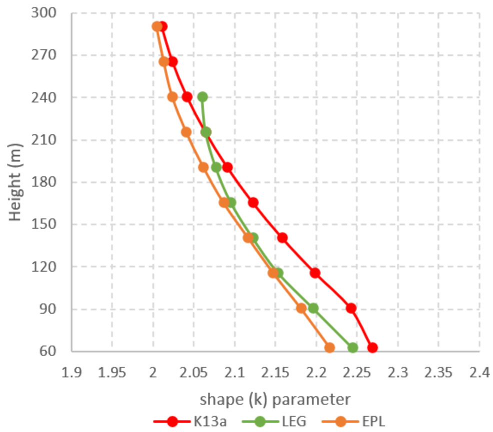


Figure 35 (left) Weibull distribution c and (right) k parameters for all heights at K13a, EPL and LEG over averaged 2016-2021 period.

Table 10 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 11 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 condition 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 as a 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 regard, there have been several studies that correlate rain 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 measurements of wind conditions provide an insight on the LEE parametrization as a 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 bird and bat behaviour around wind farms has been monitored. More specifically, studies have proved that bird and bat activities tend to occur during certain weather conditions. The correlation of these activities with the wind conditions can provide insight in the ecological impact of wind turbines and provide data and information for the development of intelligent stand still facilities and optimized curtailment strategies. This will allow for a better and tailored operation of wind farms 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 in 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 in Figure 36, which presents the impact of wind energy generation due these changes in available resource on the electricity market production leading to and during the storm (source – ENTSO-E).

Starting on the 9th of March, Figure 36 (left) shows that the offshore wind generation is non-existent over the afternoon, coinciding with a decrease in wind speeds over that same time period, and 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 37 (top).

On March 10th, Figure 36 (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 37 (center).

Prices continue to drop to nearly 0 €/MWh during the early morning hours on March 11th as shown on Figure 36 (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 increased 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.

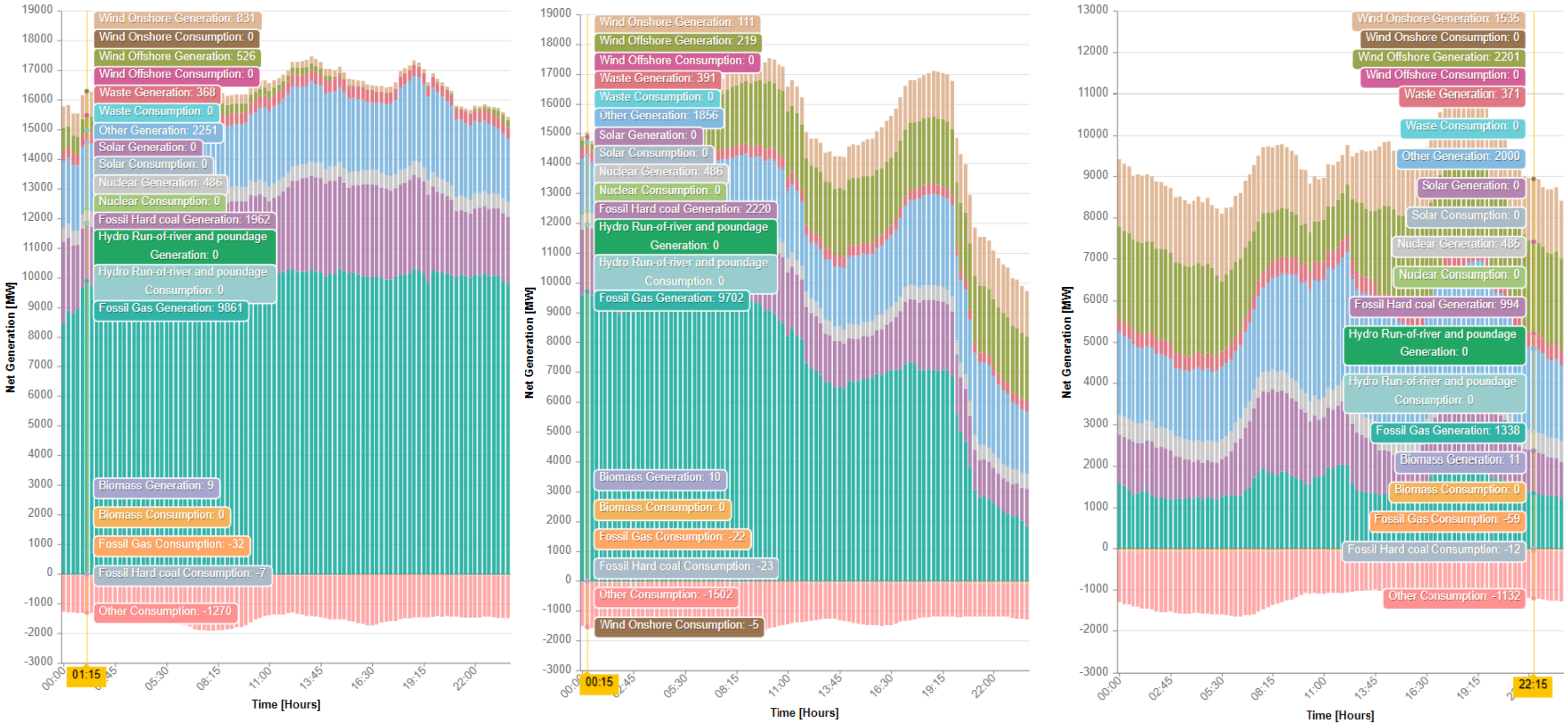


Figure 36 Energy mix for March 9th (left), 10th(centre), and 11th (right) 2021 (source – ENTSO-E).

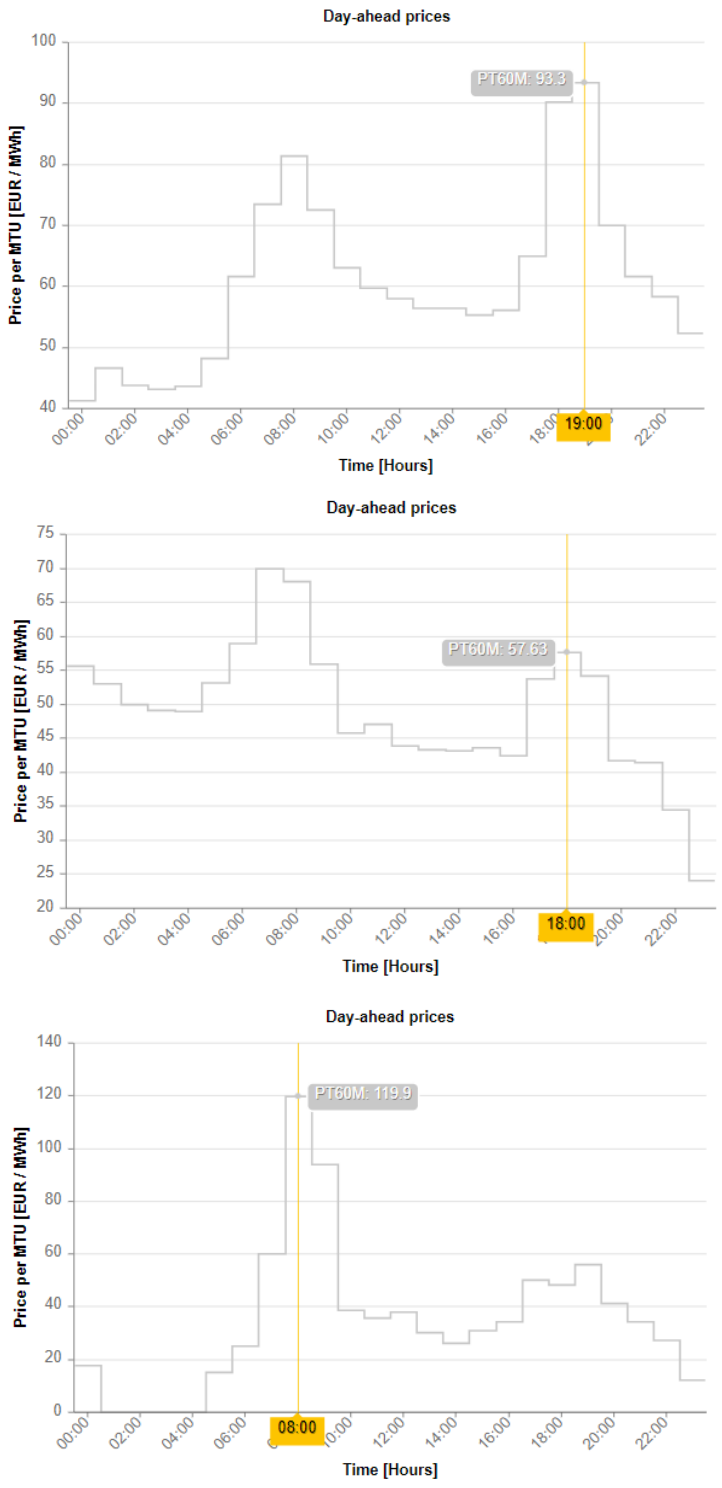


Figure 37 Day-ahead prices for March 9th (top), 10th(centre), and 11th (bottom) 2021 (source – ENTSO-E).

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 an annual basis. Currently, the locations of the measurements are at 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 LEG platform where a LEOSPHERE WINDCUBE V2 LiDAR has been deployed. Five LiDAR replacements have been carried out since the beginning of the campaign, all providing high quality data. The data are publicly available to be used for further purposes (www.windopzee.net).

At the LEG platform, the wind analysis for the 2014-2021 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 189° to 198° and the lower and upper quartiles range from 101° to 263° 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 = 2.122 and c = 11.156 m/s at 141m height).

The wind speed bell distribution is flatter and moderately skewed right at higher heights. 2021 was a moderate year, with wind speed in the average, and in general lower than 2020.

The analysis of shear shows an annualized range of 0.07 to 0.08 considering the entire data period between sequential sensor heights of the LiDAR. For 2021, the calculated day and night time shear was found to be approximately 0.06, slightly lower than the annualized range of the whole period.

Veer was found to be consistent between all sequential pairs of approximately 1 degree, and an overall difference approximately 9 degrees between the lower and most upper sensor heights.

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 making financial decisions 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 has revised their targets and has 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 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 LEG is carried out on the authority of the Ministry of Economic Affairs and Climate Policy of The Netherlands.

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A Technical specifications of the LiDAR selected: WINDCUBE V2

Functioning: Four beams are sent successively in four defined directions along a 28° scanning cone. The laser pulses are backscattered by aerosol particles in the air (such as dust, water droplets, aerosol etc.) that move with the wind speed. The collected backscattered light contains information on wind speed and wind direction which can be calculated by using a Doppler induced laser wave length shift [24]. The LIDAR take measurements at 10 different heights.

The safety measures for the specific activities of how to handle the LiDAR are defined in the specifications and in the Annex. "*the WINDCUBEv2 is a class 1M laser product and the system should be handled with caution. It is important not to stare directly into the beam with optical instruments like telescopes or binoculars. The laser beam is eye-safe according IEC EN 60825-1, January 2008*" (see Annex A for additional details).

Table 12 Adjustments of the heights above Mean Seal Level from the default configuration

Id	LiDAR height	Adjustments (MSL)
1	40	62
2	68	90
3	93	115
4	118	140
5	143	165
6	168	190
7	193	215
8	218	240
9	243	265
10	268	290

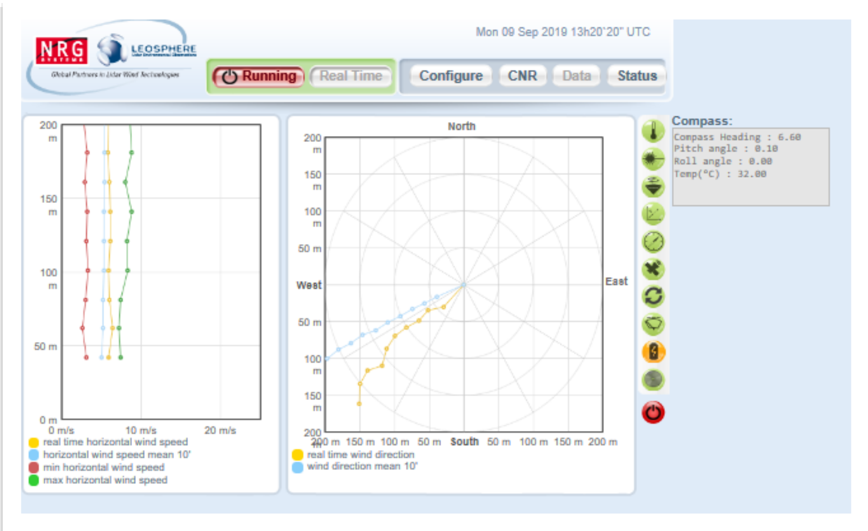
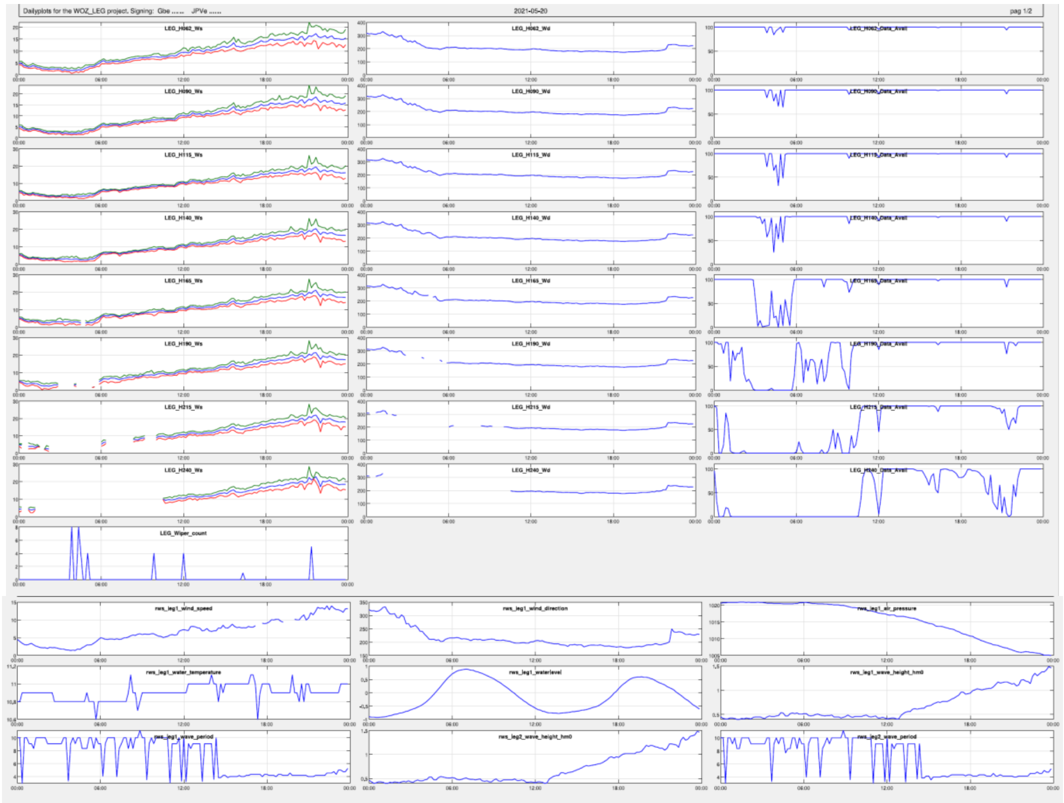


Figure 38 Example of screenshot WINDCUBE V2.

Example of Daily Plot



Specifications

MEASUREMENTS

Range	40m to 200m
Data sampling rate	1s
Number of programmable heights	12
Speed accuracy	0.1m/s
Speed range	0 to +60m/s
Direction accuracy	2°

ELECTRICAL

Power supply	18-32V DC / 93 to 264 VAC 50-60 Hz
Power consumption	45W

ENVIRONMENTAL

Temperature range	-30°C to +45°C / -22 °F to 108°F
Operating humidity	0 .. 100 %RH
Housing classification	IP67
Shocks & vibration	ISTA / FEDEX 6A
Safety	Class 1M IEC/EN 60825-1
Compliance	CE

TRANSPORTATION

Size	System : 543 x 552 x 540mm Transport case : 685 x 745 x 685mm
Weight	System : 45 kg Transport case : 21 kg

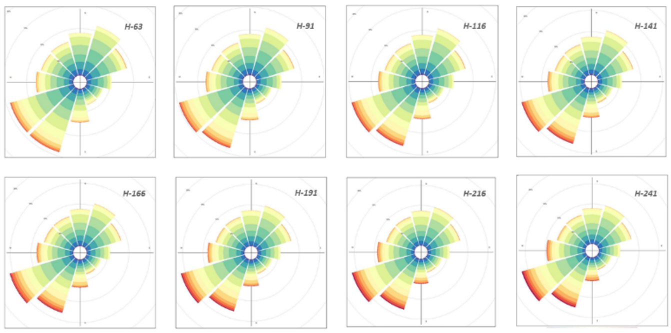
SOFTWARE/DATA

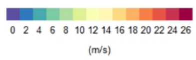
Data format	ASCII
Data storage	SSD and compact flash (backup storage)
Data transfer	LAN/USB
Standard WINDSOFT™ Software	Configuration & control Real time display Diagnostic
Output data	1s/10min horizontal & vertical wind speed Min & max, direction, SNR Quality factor (data availability) GPS coordinates

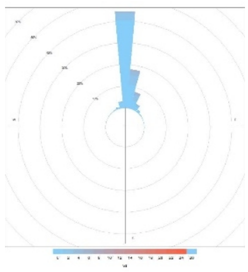
B Annual weather conditions during the campaign at LEG

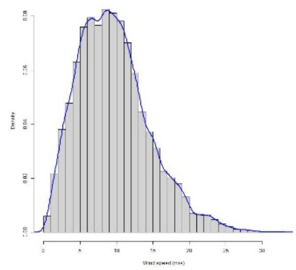
This section contains visual and statistical descriptive summary about the annual weather conditions per year at the LEG from 2021 backwards in time to 2015. The annual prevailing wind direction recorded was South-West, at different heights, as indicated by the wind roses (top). Although the predominant 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



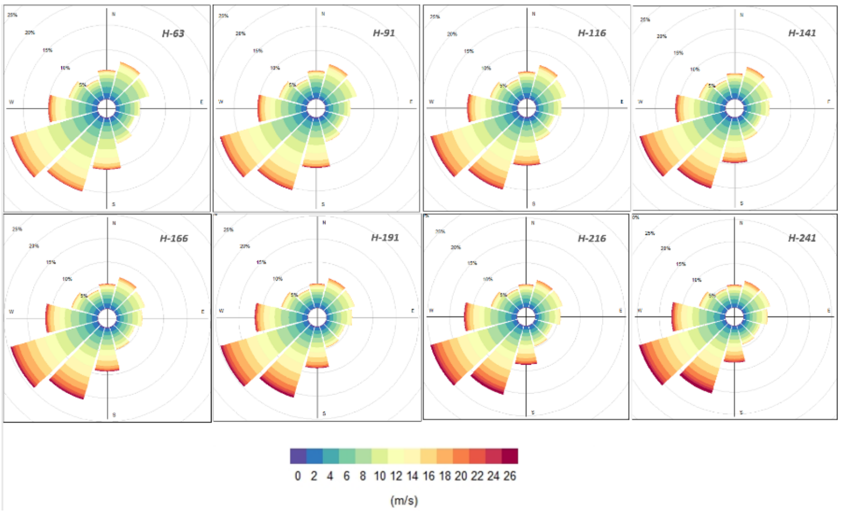




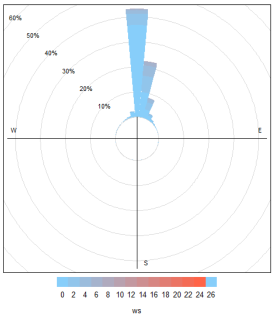


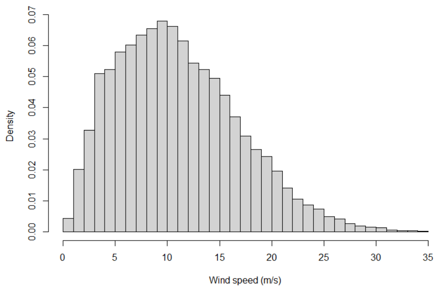
H (m)	63	91	116	141	166	191	216	241
Ws - Min	0.06	0.13	0.07	0.09	0.04	0.13	0.04	0.06
Ws – 1st q	5.46	5.6	5.67	5.73	5.77	5.83	5.88	5.97
Ws - Median	8.19	8.41	8.54	8.65	8.75	8.86	8.98	9.11
Ws - Mean	8.53	8.807	8.978	9.128	9.267	9.394	9.518	9.64
Ws - 3rd q	11.22	11.58	11.78	11.95	12.09	12.225	12.36	12.48
Ws – Max	26.41	27.84	28.8	29.74	30.53	31.25	31.93	32.62
Wd - 1st q	75.80	77.25	77.90	78.90	80.80	83.10	84.30	83.60
Wd - Median	207.90	209.00	209.80	210.60	211.80	213.40	214.50	217.00
Wd - Mean	183.30	184.06	184.50	185.00	186.00	187.10	188.00	189.30
Wd - 3rd q	261.60	261.90	261.80	262.10	262.50	263.00	263.90	265.40

B.2 2020



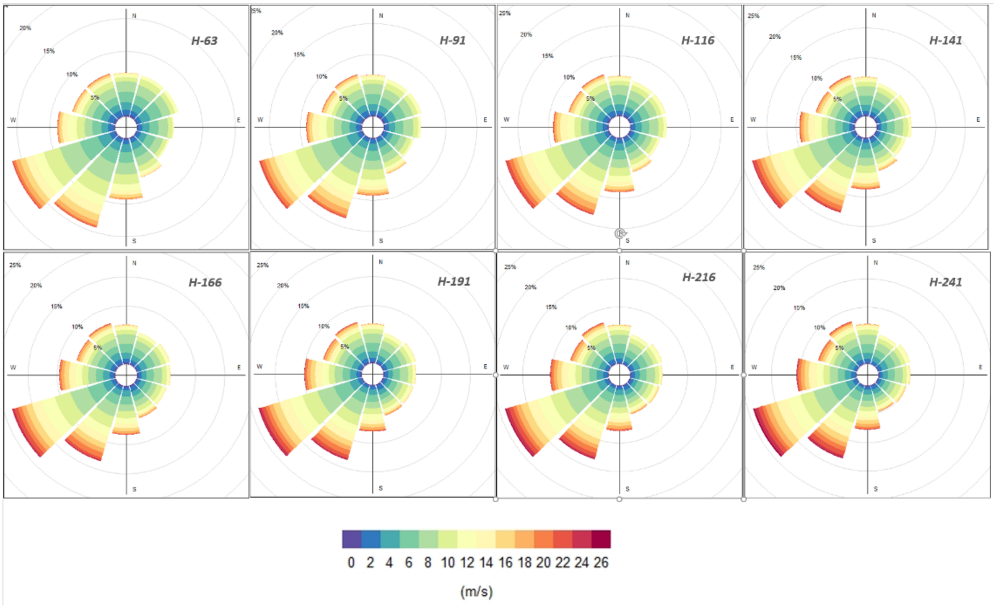
2019

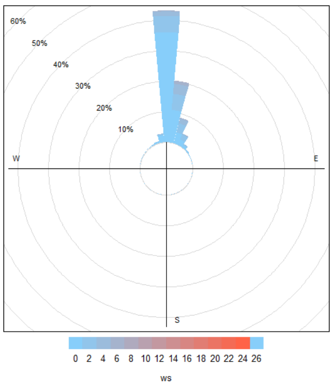


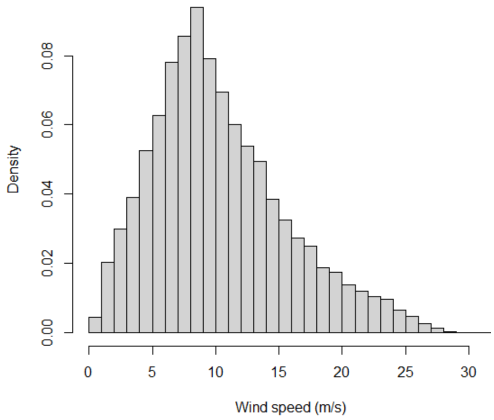


H (m)	63	91	116	141	166	191	216	241
Ws - Min	0.27	0.21	0.13	0.20	0.18	0.21	0.19	0.28
Ws – 1st q	6.01	6.14	6.18	6.21	6.26	6.31	6.41	6.53
Ws - Median	9.25	9.51	9.67	9.79	9.91	10.02	10.17	10.35
Ws - Mean	9.56	9.89	10.11	10.30	10.47	10.64	10.83	11.04
Ws - 3rd q	12.57	13.07	13.42	13.74	14.02	14.26	14.52	14.81
Ws – Max	27.18	28.25	29.48	30.37	31.40	32.46	33.58	34.66
Wd - 1st q	118.10	121.30	123.80	125.80	127.30	129.80	132.40	135.10
Wd - Median	208.60	209.80	211.00	212.00	213.20	214.50	216.10	218.10
Wd - Mean	188.30	189.60	190.70	191.50	192.30	193.40	194.70	196.10
Wd - 3rd q	250.50	251.20	252.00	252.50	253.10	253.90	254.80	256.20

B.3 2019

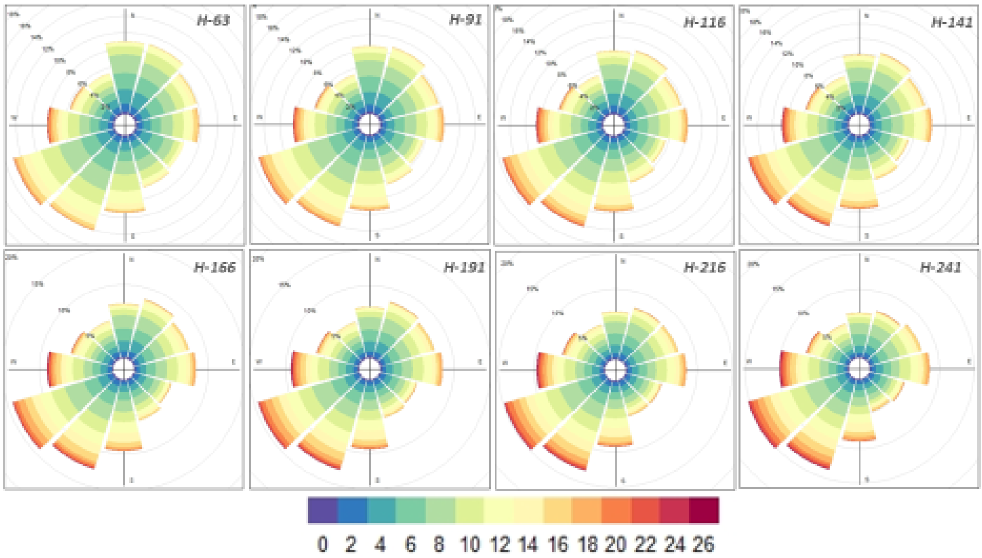


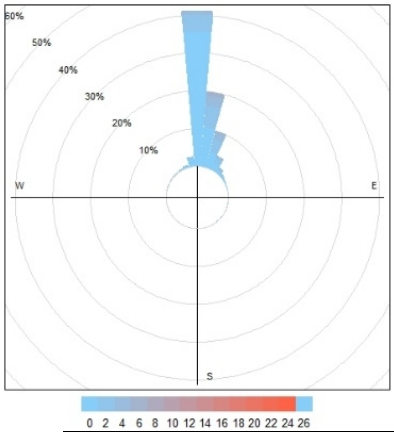


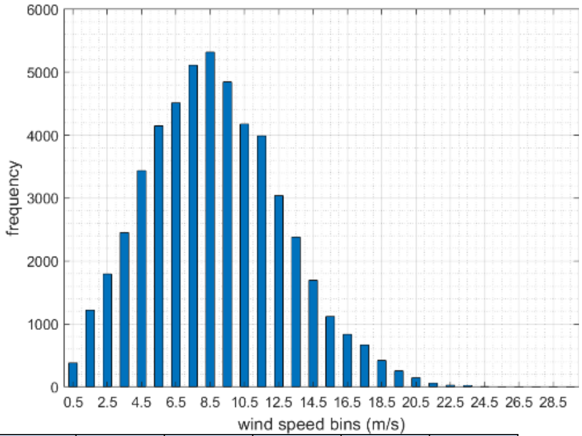


H (m)	63	91	116	141	166	191	216	241
Ws - Min	0.25	0.10	0.23	0.20	0.27	0.19	0.14	0.24
Ws – 1st q	5.94	6.09	6.15	6.19	6.26	6.34	6.42	6.54
Ws - Median	8.47	8.75	8.87	9.01	9.11	9.20	9.28	9.40
Ws - Mean	8.91	9.25	9.45	9.62	9.79	9.97	10.15	10.34
Ws - 3rd q	11.36	11.92	12.24	12.51	12.73	12.96	13.20	13.42
Ws – Max	26.65	27.53	28.15	28.89	29.61	30.24	30.74	31.13
Wd - 1st q	120.60	121.30	123.60	126.10	128.80	130.60	131.50	132.90
Wd - Median	210.60	212.60	214.20	215.50	216.90	218.70	220.40	222.50
Wd - Mean	193.70	195.00	196.40	197.40	198.60	199.90	200.80	202.20
Wd - 3rd q	258.80	260.10	261.20	262.00	262.70	263.90	264.60	266.70

B.4 2018

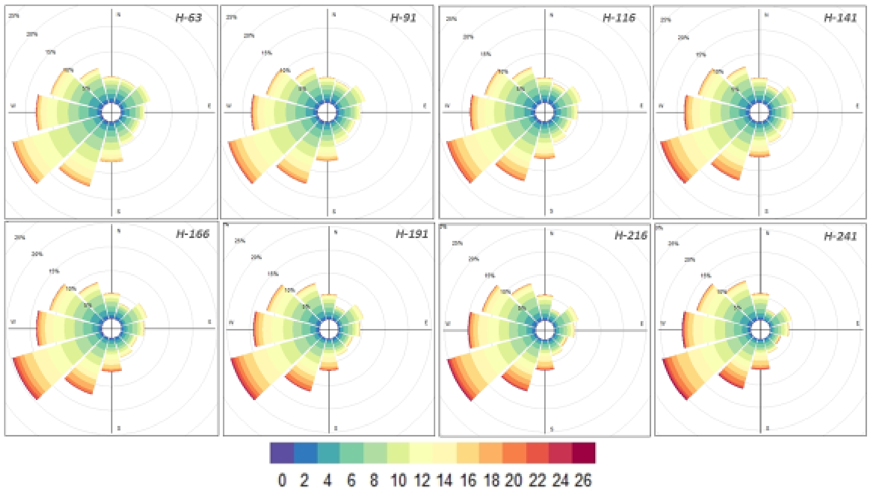


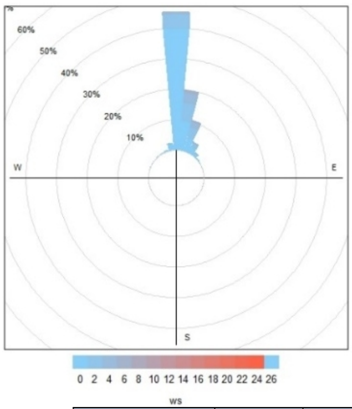


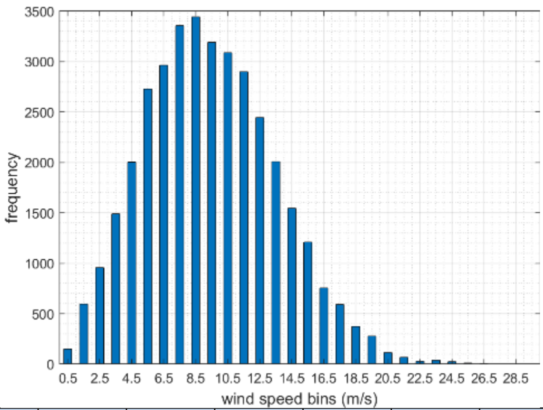


H (m)	63	91	116	141	166	191	216	241
Ws - Min	0.22	0.19	0.23	0.18	0.15	0.15	0.17	0.22
Ws – 1st q	5.89	6.05	6.13	6.22	6.31	6.39	6.47	6.57
Ws - Median	8.56	8.84	9.02	9.16	9.31	9.44	9.54	9.64
Ws - Mean	8.80	9.15	9.36	9.55	9.72	9.88	10.03	10.19
Ws - 3rd q	11.41	11.93	12.25	12.52	12.75	12.93	13.08	13.28
Ws – Max	33.02	34.38	35.23	36.08	36.97	37.50	37.91	38.27
Wd - 1st q	84.30	85.00	86.60	87.50	89.10	90.50	92.70	95.30
Wd - Median	190.20	191.30	192.90	194.30	196.10	197.70	200.00	202.90
Wd - Mean	175.50	176.20	177.40	178.10	179.30	180.20	181.70	183.50
Wd - 3rd q	249.20	249.50	249.90	250.20	250.90	251.30	252.30	253.70

B.5 2017

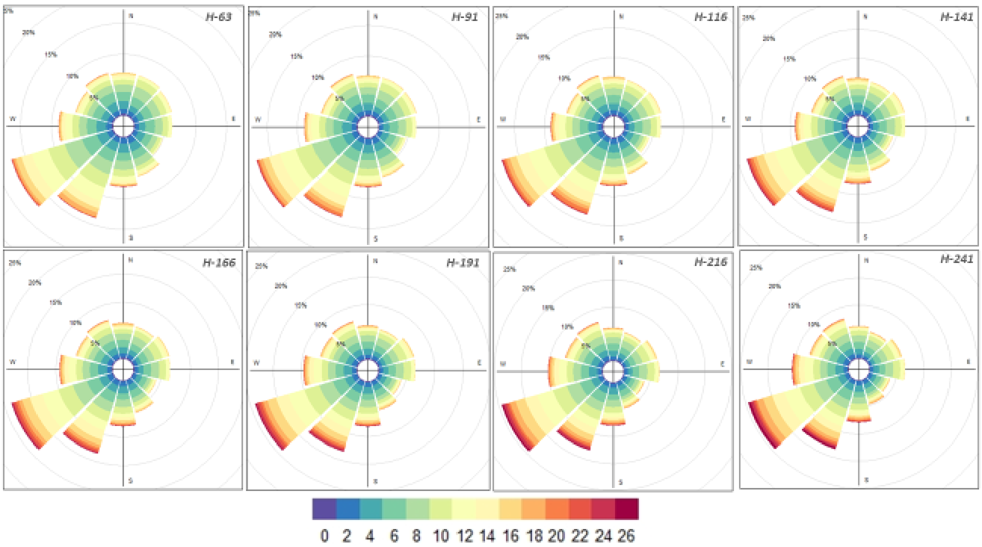


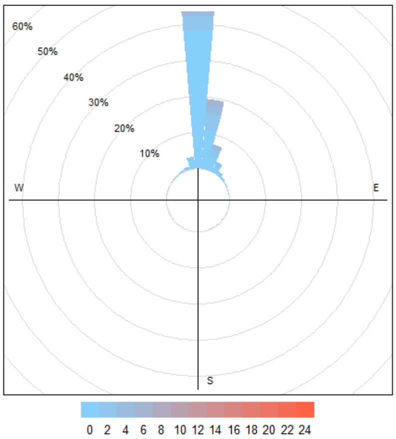


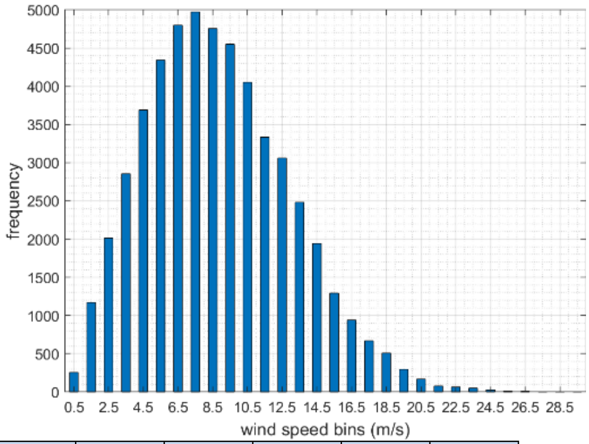


H (m)	63	91	116	141	166	191	216	241
Ws - Min	0.27	0.12	0.19	0.14	0.19	0.22	0.26	0.38
Ws – 1st q	6.40	6.57	6.65	6.75	6.91	7.02	7.16	7.29
Ws - Median	9.13	9.46	9.69	9.88	10.05	10.17	10.34	10.51
Ws - Mean	9.40	9.75	10.00	10.23	10.45	10.64	10.82	11.01
Ws - 3rd q	12.12	12.69	13.05	13.36	13.67	13.91	14.09	14.29
Ws – Max	27.52	29.06	30.06	30.90	31.51	32.14	32.57	32.98
Wd - 1st q	156.30	158.90	161.10	164.20	169.20	175.40	181.30	187.70
Wd - Median	229.20	230.70	232.00	233.60	235.80	238.10	240.00	242.70
Wd - Mean	209.30	210.90	212.20	214.00	216.30	219.00	221.80	225.70
Wd - 3rd q	275.20	276.80	278.00	279.60	281.10	282.80	284.50	286.70

B.6 2016

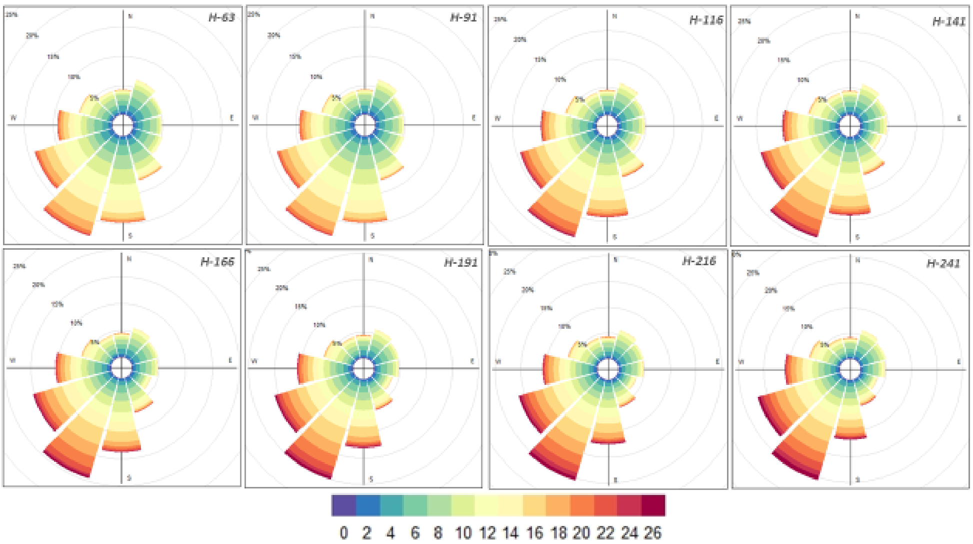


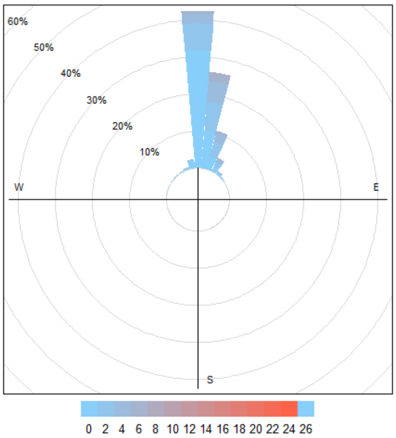


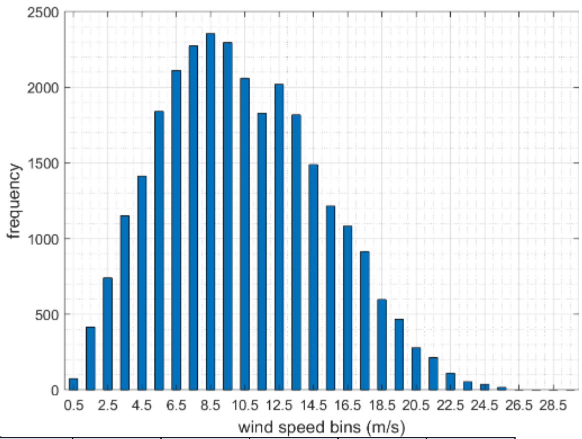


H (m)	63	91	116	141	166	191	216	241
Ws - Min	0.30	0.29	0.25	0.30	0.19	0.28	0.30	0.25
Ws – 1st q	5.71	5.79	5.86	5.93	5.99	6.07	6.16	6.24
Ws - Median	8.40	8.60	8.76	8.88	9.02	9.14	9.29	9.40
Ws - Mean	8.81	9.05	9.24	9.40	9.56	9.72	9.90	10.04
Ws - 3rd q	11.52	11.88	12.15	12.35	12.52	12.71	12.91	13.06
Ws – Max	32.07	33.46	34.07	34.74	35.46	35.81	36.25	36.60
Wd - 1st q	115.60	117.60	119.20	119.70	119.10	120.80	124.80	131.30
Wd - Median	211.40	212.20	213.40	214.60	215.70	217.40	219.90	222.10
Wd - Mean	191.60	192.30	193.20	193.70	194.00	195.20	197.50	200.20
Wd - 3rd q	257.50	257.50	257.70	257.90	258.30	259.50	262.00	264.70

B.7 2015



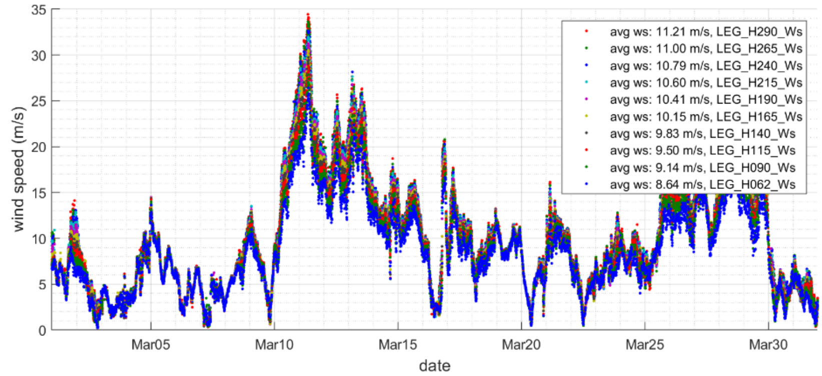


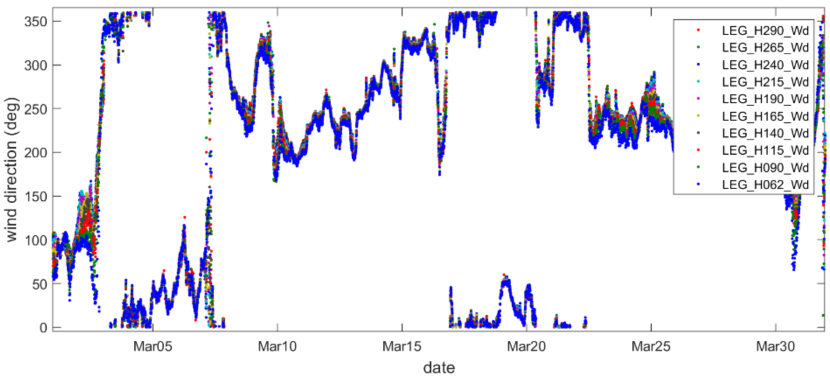


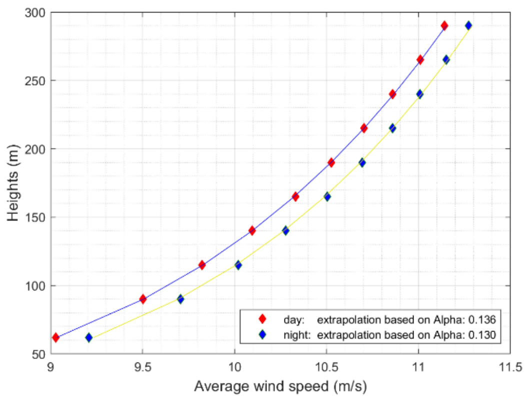
H (m)	63	91	116	141	166	191	216	241
Ws - Min	0.50	0.50	0.23	0.26	0.28	0.20	0.24	0.25
Ws – 1st q	6.72	6.93	7.08	7.23	7.32	7.43	7.52	7.57
Ws - Median	9.87	10.30	10.60	10.87	11.07	11.27	11.44	11.59
Ws - Mean	10.30	10.76	11.11	11.42	11.67	11.89	12.10	12.28
Ws - 3rd q	13.54	14.27	14.81	15.28	15.68	16.02	16.30	16.59
Ws – Max	26.56	27.58	28.31	29.48	30.79	31.91	32.78	33.77
Wd - 1st q	141.30	142.80	145.85	149.50	152.10	154.50	155.80	157.40
Wd - Median	201.30	202.50	204.10	205.90	207.60	209.30	210.70	212.20
Wd - Mean	191.40	192.04	193.16	194.40	195.50	196.60	197.20	198.10
Wd - 3rd q	248.30	249.20	249.70	250.40	251.00	251.60	252.00	252.70

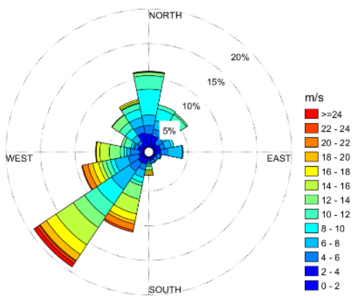
C Weather conditions analyses during the monthly reporting

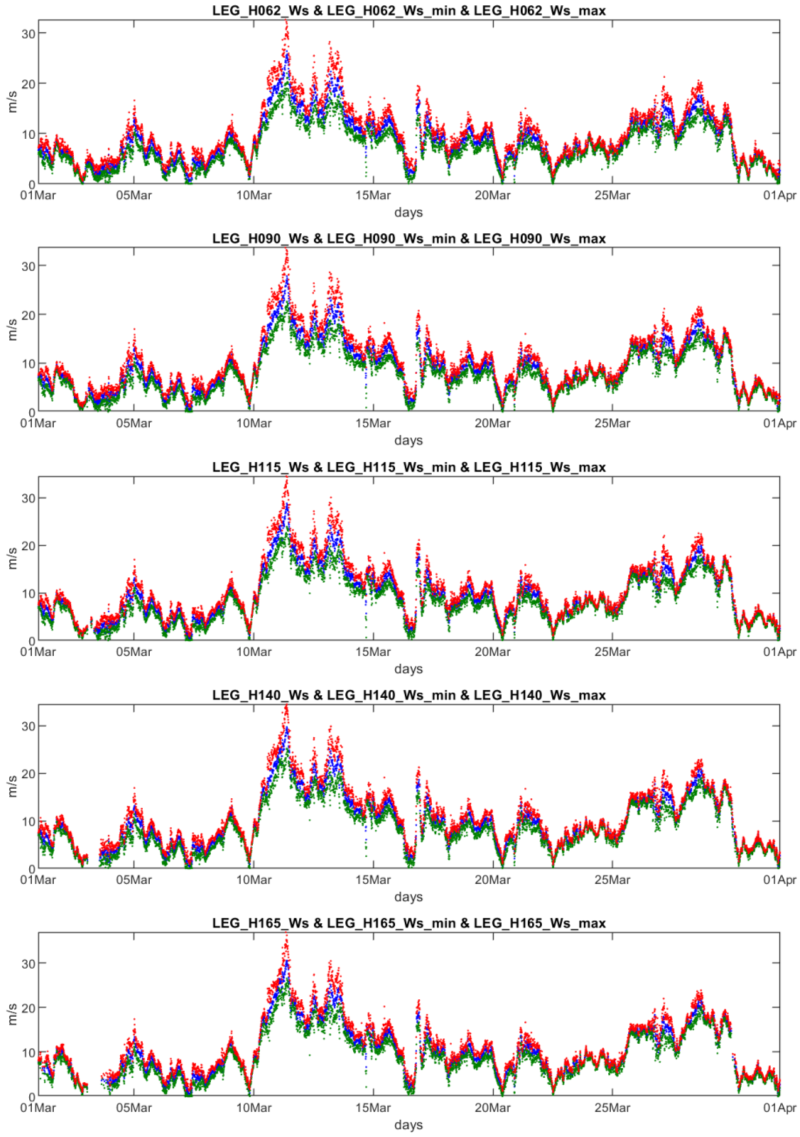
Weather conditions were analysed through different signalling figures including wind speed and direction signals, wind shears and dominant winds. Maximum, minimum and mean wind speed and directions time series are also analysed each month. The figures below show visual examples of the monthly reporting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



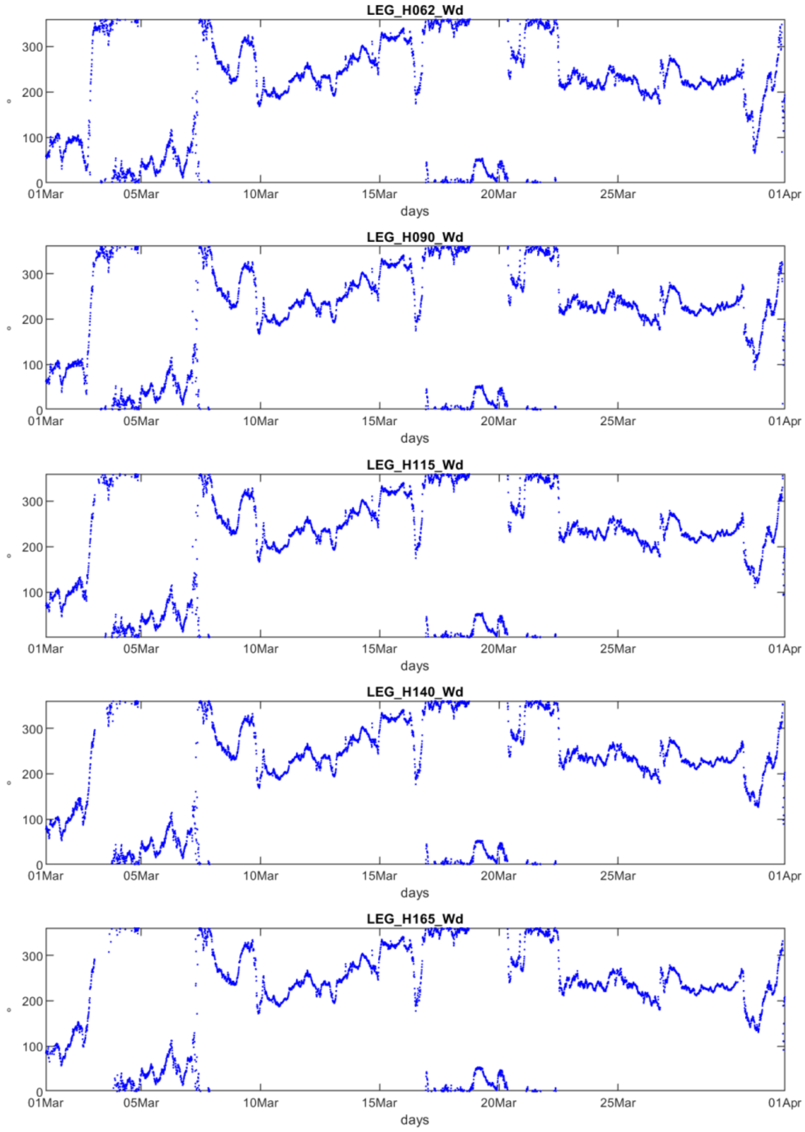








legend: [blue]: signal 1, [green]: signal 2, [red]: signal 3



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