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TNO report

TNO 2020 R10511

Offshore wind energy deployment in the North Sea by 2030: long-term measurement campaign. Lichteiland Goeree, analysis for 2014-2019

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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. In the Netherlands, the national government aims to develop an offshore wind portfolio of 11.5 GW by 2030 from the current 0.9 GW corresponding to the 40% of the current electricity consumption.

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: Lichteiland Goeree (LEG), Europlatform and K13a, under the project *Wind@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, analysing, reporting and dissemination of the data.

The weather analysis at the LEG platform indicates that the data captures the variability of the local and regional climate of the area, including past extreme weather events. Accurate and long term meteorological measurements are crucial for the feasibility and wind site of the plant valuation and for the financial decision to ensure the profitability of the business plans. In addition, the accuracy and high quality data obtained, render this dataset valuable for additional applications in the energy sector.

1 Leading position to support future offshore wind deployment in Europe

1.1 The importance of high standard measurement campaigns

Offshore wind energy is one of the main pillars of the renewable energy sources (RES) needed for the Energy Transition in Europe (A European Green Deal [1]). Offshore wind plans aim to increase installed capacity from 22 GW at the beginning of 2020 to 75 GW by 2030. The North Sea is key for this transformation, since over 70% of existing and planned European offshore wind farms will be located in the area.

In the Netherlands, the national government aims to develop an offshore wind portfolio of 11.5 GW by 2030 from the current 0.9 GW (Figure 1), corresponding to the 40% of the current electricity consumption.

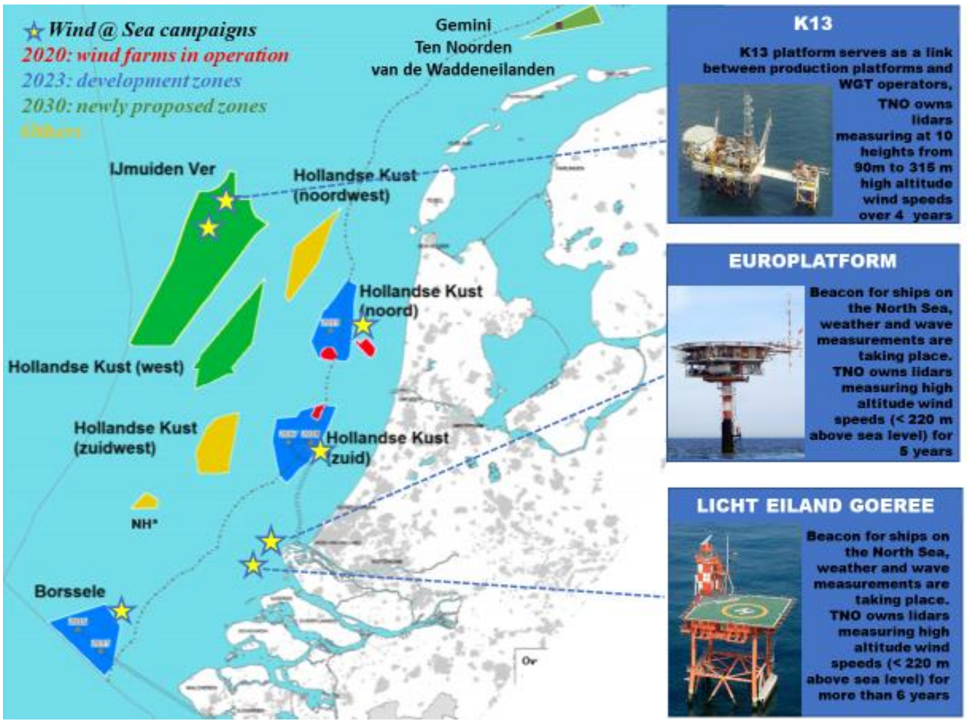

Figure 1 Locations of current and future offshore Dutch wind farms and the activities run by TNO under the Wind@Sea framework on measurement campaigns over the Dutch North Sea.

Meeting those ambitious targets entails major investments. The business plans behind those investments need high standards to obtain profitable wind farms. These challenges require policymakers, system planners and other stakeholders to address basically two issues:

- Analyze the wind resources on-site to identify strategic locations and determine the appropriate technology,
- Find technical- and cost-optimal solutions for the integration of offshore wind into the power system and market.

The feasibility of wind site assessments are crucial to ensure the profitability of the plant. These assessments are based on measurement campaigns of the meteorological conditions over the designated areas (Figure 2).

Although investments on measuring campaigns are not comparable with the costs of the construction of a new wind farm; the selection of appropriate measurement equipment and its correct installation are essential. Measuring equipment placed in a determined location must perform as specified to ensure the right quality of data essential for producing accurate wind site assessments. A small discrepancy of even 3% in the evaluation of wind speed data drastically multiplies during assessment calculations and may produce misleading results which later translate in significant economic losses.

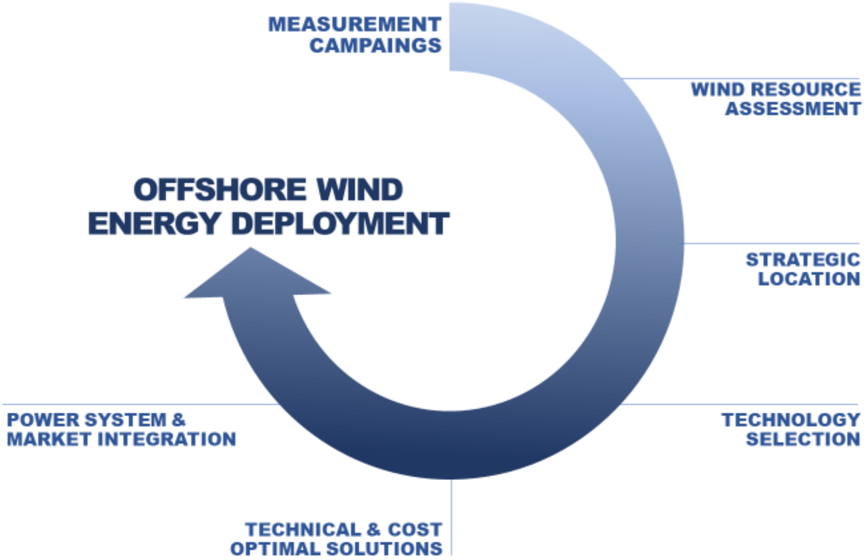

Figure 2 Process to ensure the profitability of the wind offshore deployment.

Under the Dutch wind offshore future plans, the Dutch Ministry of Economic Affairs and Climate Policy has agreed that within the *Wind@Sea* project, TNO performs measurement campaigns in the North Sea from 2014 until 2030 at different locations: Lichteiland Goeree (LEG), Europlatform (EPL) and K13a (Figure 1).

TNO has produced a series of reports about the measurement campaigns carried out at those locations. This report refers to the measurement campaign at the LEG platform. The second report includes the description and data analysis of the campaign at EPL. The third report comprises the campaign at K13a. The complete series of reports includes the analysis from the beginning of the campaign until the end of 2019. As the campaign is foreseen until 2030, further analysis will be published annually per site.

1.2 TNO activities over the life cycle of the campaigns

TNO has a leading role on measuring campaigns for the offshore wind sector in the Dutch North Sea, with more than 10 years of experience. Meteorological masts (met mast) have been widely used before the integration of the LiDAR in offshore wind resource assessments: for example, at the met-mast Ijmuiden (MMIJ), the weather conditions over the *Hollandse Kust* site have been assessed (Figure 1); at the Offshore Wind farm Egmond aan Zee (OWEZ) and at Borssele, HKN and HKZ (using floating LiDAR's).

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) to support wind turbine prototype certification, from small (330 kW) to larger turbines (12MW). 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, analysing, reporting and dissemination of the data.

1.3 Open-access and public datasets

The data measured in the *Wind@Sea* project are retrieved and post-processed before making the information publicly accessible through the web-service https://www.windopzee.net/en/. Post-processed data are reported each month for validation purposes and each year the external report is published online.

Users can download the data by clicking on "Location/data", after free registration. To use Wind@Sea measured data in publications, further research or commercial purposes, users must acknowledge the use of the data as:

1. Citation of this report with the type of data used LOCATION and DATE:
   Gonzalez-Aparicio I., Verhoef J.P., Bergman G. (2020) *Offshore wind energy deployment in the North Sea by 2030: long-term measurement campaigns. Lichteiland Goeree analysis for 2014-2019*. TNO 2020 R10511
2. Indicate the date of the last accessed the data used in the publication (e.g. *Last accessed 15th May 2020*).

The data is shared in .csv format. In the case of LEG measurement campaign: https://www.windopzee.net/en/locations/lichteiland-goeree/data/

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

2 Measurement campaign at LEG

Prior to the measurement campaign, the initial phase is formed by the set-up of the installation plan of the instrumentation; that is, the evaluation of the platform to place the LiDAR, determination how the measurement equipment will be mounted and the agreement with Rijkswaterstaat about the installation and safety measures [2], [3].

The second phase includes onsite installation (calibration of the instrumentation, and electrical infrastructure) and the operational activities (control, maintenance and replacements of the instrumentation).

Health and safety aspects are also part of the measurement campaign activities.

2.1 Installation plan of 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 3a). 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, Dutch Ministry of Infrastructure and the Environment).

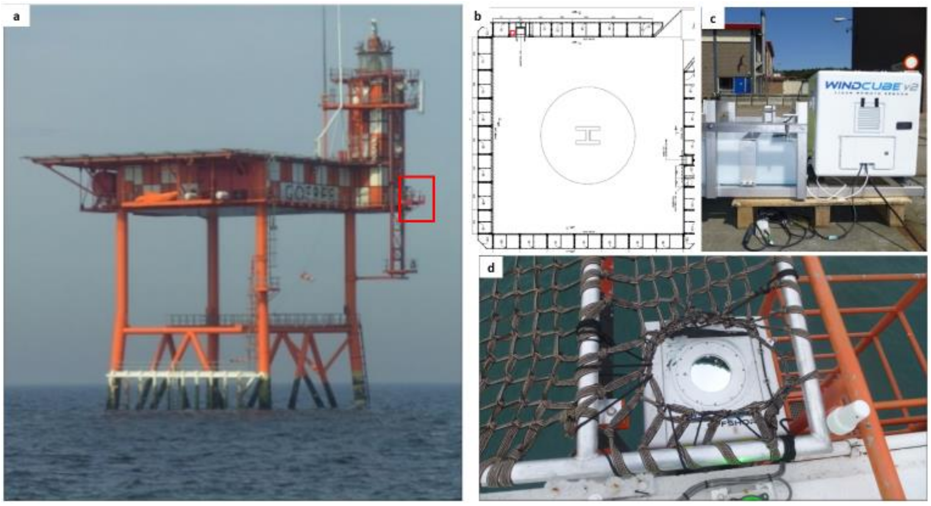

Figure 3. a) Front and b) top view of Lichteiland Goeree platform [LAT LON coordinates: 51.92503°N, 3.66844°E], helicopter deck at a height of 24.58m and the accommodation deck at 20.04m above mean sea level; c) mounting frame to place the LiDAR at the selected location in the platform and d) final installation of the LiDAR.

To ensure good quality measurements it is crucial to select the right location for the LiDAR on the platform [2]. At LEG, the suitable place was found beside the cage-ladder on the north-west side of the platform (Figure 3a, 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 3c, d).

2.2 Onsite installation and operational status

The LiDAR selected is the *LEOSPHERE WINDCUBE V2*. The instrument measures wind profiles 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 [4], [3], [5]. Manufacturers guarantee data quality up to 200 m although some V2 LiDAR's can measure beyond that height.

The LiDAR was mounted 23 m above Mean Sea Level (MSL) and provided both wind speed and direction measurements at 10 different elevations between 63 m and 240 m above MSL; 0.5 m below the helicopter platform. The wind direction signals have a directional offset of exactly -135 degrees with a safety net not hindering the laser of the LiDAR. The measured data is timestamped at the start of 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 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 [6].

Table 1 Replacements of LiDAR at LEG.

Id LiDAR	Operational period	Reason for 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 Oct 2021	Periodically replacement

2.3 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. 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 had valid GWO climbing certificates, proving that they know how to work safe at heights.
- TNO employees working on the platform will wear fall-arrest systems, helmets and safety shoes.

The safety measures for the specific activities of how to handle the LiDAR are defined in the specifications. "*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).

3 High quality data

During the measurement period, defective sensors and cables or other malfunctioning of the system can lower the data availability. It can also happen that measured data are hampered by severe meteorological events or the signals are lost due to loss of power and/or signals exceeding their thresholds. For this reason, continuous quality assurance and control techniques are applied during the measurement campaign. Data measured are classified into two categories:

- **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 (Table 2). The heights considered are 63, 91, 116, 141, 166, 191, 216, 241, 266 and 291 m.

Frequency of the data are 10-minutely during 5 year-period, starting the data collection from the 17th November 2014 at 13:00 UTC (Universal Time Coordinates). This report includes a period until the 31st of December 2019 at 23:50 hr. UTC although the campaign is still running until 2030.

Table 2 List of variables measured in the LiDAR during the experimental campaign. Where LEG is the platform; HXX are the different heights measured above the mean sea level (MSL): 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

Figure 4 shows that data availability depends on the height of the measurements. For heights up to 200m, the data available is on average 96%, while up to 266 m the availability decreases to 71%. At 291 m the availability was about 30% (Table 3). During 2017/2018 the two highest levels showed invalid data and therefore, are not considered for further analysis in this report.

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

Year	H 63 (%)	H 91 (%)	H 116 (%)	H 141 (%)	H 166 (%)	H 216 (%)	H 241 (%)	H 266 (%)	H 291 (%)
2014	99.9	99.9	99.9	99.4	97.9	92.4	85.9	76.3	64.6
2015	99.2	99.2	98.7	97.9	96.7	89.1	80.7	69.9	59.0
2016	96.4	97.1	97.3	96.0	93.2	80.7	71.0	59.2	47.5
2017	91.9	92.3	92.4	90.6	86.9	73.0	64.0	35.7	26.4
2018	97.4	96.4	96.1	94.7	91.8	79.6	70.7	NA	NA
2019	96.8	95.7	95.4	94.1	91.3	76.9	64.4	74.3	62.3

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.

The data measured is also compared to and analyzed with KNMI data and with other datasets coming from campaigns of other locations. In particular, [7] 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.

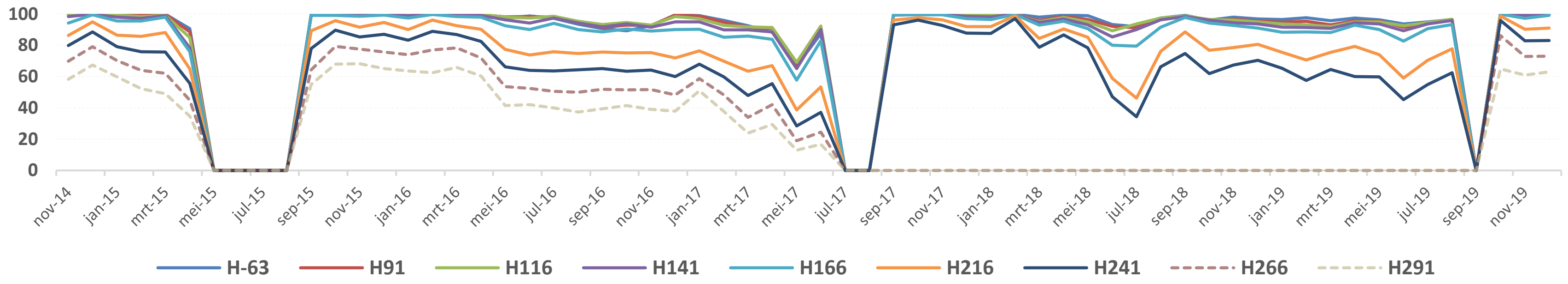

Figure 4 Monthly availability averages of all the variables by height (%). The last two heights are depicted with dashed lines since values are not considered.

4 Weather conditions at LEG

This section provides an overview of the weather conditions during the campaign at the LEG platform between November 2014 and December 2019. 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, showing wind shear and wind veer and vertical profiles over the full period.

In a second chapter, past weather events which occurred between 2014 and 2019 are presented. The aim is to show that the behaviour of such events is also captured and measured by the LiDAR. 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 *Cross-sectoral synergies and further applications of measured data.*

Complementary analysis on weather conditions at LEG can be found in the annexes:

- B. Annual weather conditions during the campaign at LEG.
- C. Weather conditions analyses during the monthly reporting.
- D. Comparison of the wind direction measurements between LEG and Ijmuiden met mast.

4.1 Weather conditions during the period 2014-2019

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 [8], [9].

At the LEG platform, the weather analysis for 2014-2019 shows that the wind profiles are dominated by the effects of the positive NAO. The dominant wind direction is South-West: mean wind direction of the distribution bell ranges from 191° to 200° and the lower and upper quartiles range from 120° to 260° at all heights (Table 4 and Figure 5c). Wind roses charts (Figure 5a) indicate that at higher heights the wind intensity increases; with more frequent winds >26 m/s. The difference of the prevailing wind direction and the wind speed intensity between 241 m and 63 m height can be observed in the wind rose of the Figure 5b.

Wind regimes and intra-annual variability are described by the conventional (two-parameter) Weibull probability density function. The function, dependant on the wind speed v (in m/s), the shape dimensionless parameter, k, and the scale parameter, c (in m/s) is given by:

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

The shape parameter describes the wind behaviour according to its value: the parameter c is proportional to the mean wind speed of the distribution and thus, also increases with height. The value of k is inversely proportional to wind variability, that is, large k values indicate less wind variability. Most sites have typically wind distribution at k hovering round 2. At LEG, during the period 2014-2019, the Weibull distribution show that k = 2.26 and c=10.36 at 63 m height (Figure 6a). Figure 6b indicates how the distribution is flattening and moderately skewed right with higher heights. Figure 7 presents the annual Weibull distribution at all heights over the period indicating that 2017 was a year with a higher k parameter than the 2014-2019 average (shown at 63 m height). The Table 4 also includes the descriptive statistics of the wind speed distribution.

Table 4 Summary of the descriptive statistics for the wind speed and direction at different heights for the 2014-2019 period at the LEG platform.

H (m)	63	91	116	141	166	191	216	241
Ws - Min	0.22	0.10	0.19	0.14	0.15	0.15	0.14	0.22
Ws – 1st quartile	6.05	6.19	6.27	6.36	6.44	6.52	6.62	6.72
Ws - Median	8.75	9.04	9.22	9.38	9.52	9.65	9.76	9.90
Ws - Mean	**9.14**	**9.47**	**9.70**	**9.91**	**10.10**	**10.28**	**10.46**	**10.63**
Ws - 3rd quartile	11.85	12.38	12.72	13.00	13.26	13.49	13.70	13.90
Ws - Max	33.02	34.38	35.23	36.08	36.97	37.50	37.91	38.27
Wd - 1st quartile	117	118.30	120.60	122.30	124.20	126.40	129.60	133.80
Wd - Median	208.40	209.50	211.00	212.50	214.10	215.70	217.70	220.10
Wd - Mean	**191.20**	**192.16**	**193.34**	**194.30**	**195.40**	**196.70**	**198.30**	**200.40**
Wd - 3rd quartile	258.20	258.80	259.50	260.00	260.80	261.80	263.10	264.80

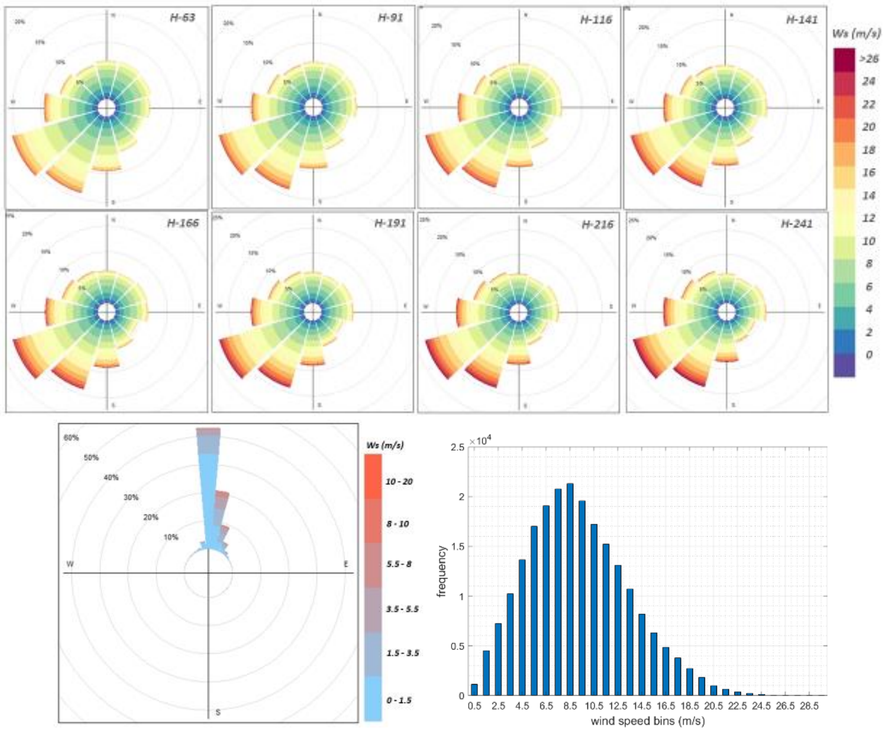

Figure 5 Wind Roses a) at different heights depicting the dominant wind direction and wind veer; b) difference of wind speed and direction between 241 m and 63 m height and c) wind speed frequency distribution (distribution bell) at 63m height for 2014-2019.

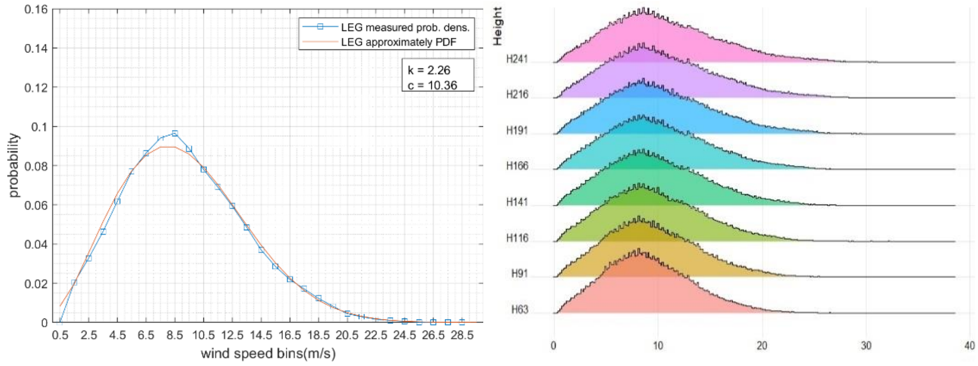

Figure 6 Weibull distributions (left) at 63 m height including k and c parameters and the curve approximation and (right) at different heights for the measurement campaign at LEG for 2014-2019.

The seasonal variation, monthly and diurnal cycle at different heights, are also depicted in the Figure 8. A clear seasonal and monthly pattern can be observed both for wind speed and direction at different heights. A drop in the wind speed can be seen from winter to summer months of about 4-5 m/s, 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.

However, the variability each hour is less pronounced than at monthly scales, the latter, explained by the cycle derived from vertical mixing occurred by the lower-atmosphere and land energy balance. At the LEG platform, the offshore wind speeds vary within margins of 0.5-0.6 m/s on hourly averages and the patterns of wind direction remains in a bias of 10 degrees.

The wind conditions analysed in this report are in line with the assessment presented in [7] and [10]. Such studies present additional description over the temporal variability of horizontal and vertical wind profiles at different offshore locations over the Dutch North Sea. The annex B also includes additional wind analysis on a yearly basis for the LEG platform.

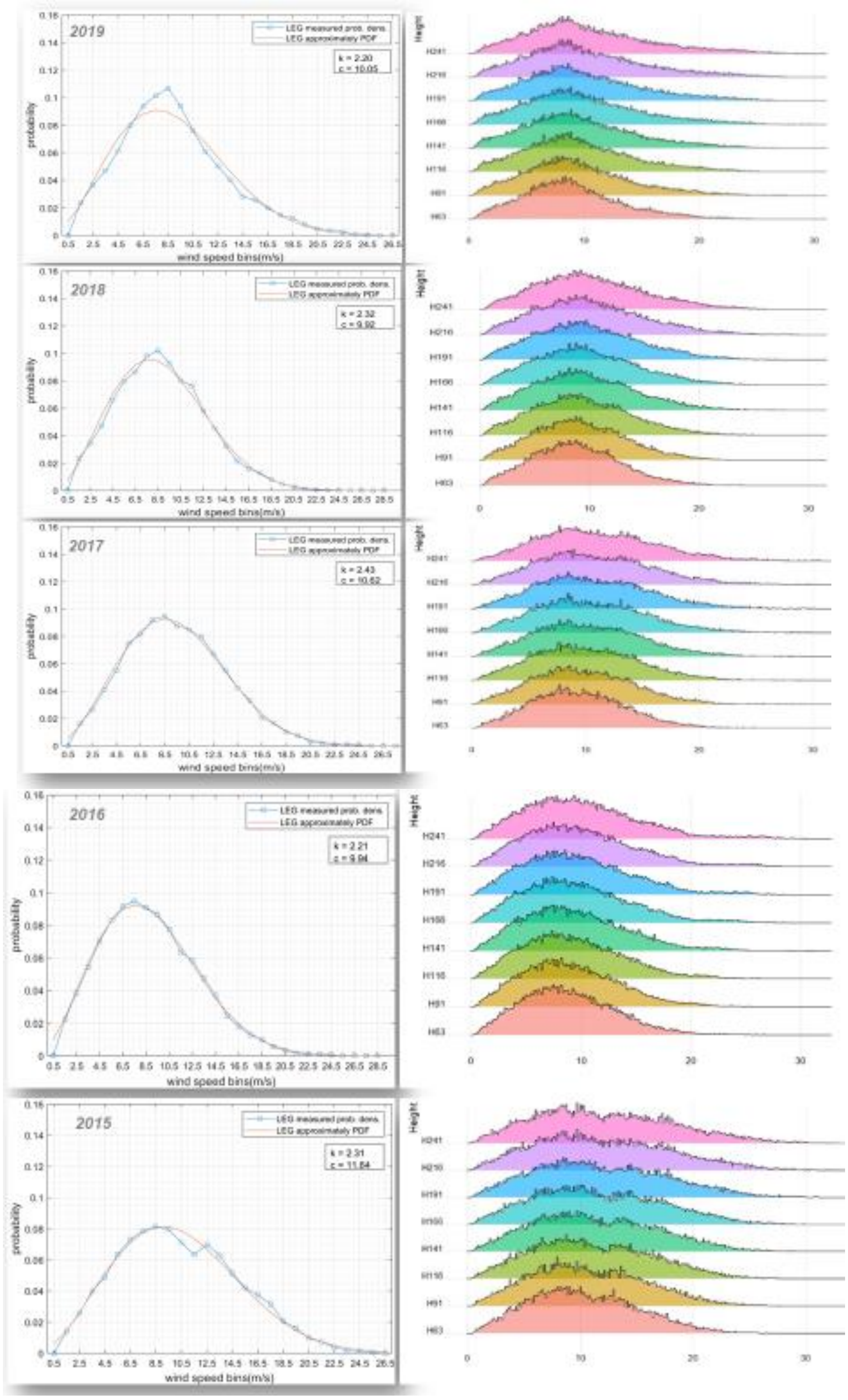

Figure 7 Annual Weibull distributions (left) at 63 m height including the k and c parameters and the curve approximation and (right) at different heights at the LEG platform for the 2014-2019 period.

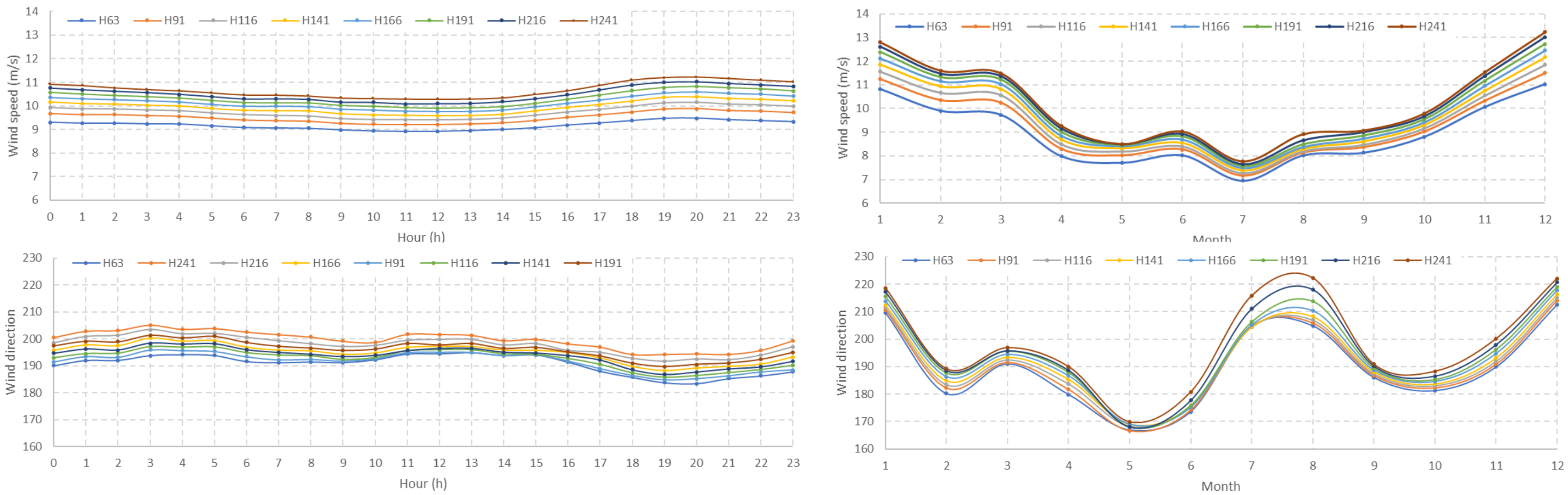

Figure 8 a) Monthly wind speed and direction averages and b) average daily cycles at different heights for the 2014-2019 period.

4.2 Past weather events

4.2.1 Strong winds (2nd November 2019) and storm Atiyah (7th-8th December 2019)

During the months of November and December 2019 two extreme events occurred over the North Sea, enveloping UK and the Dutch coasts.

On the 2nd of November, an area of low pressure brought strong winds over UK in the morning, prevailing during the afternoon in the Dutch coasts. The isobars analysis chart at 12:00 UTC 02 November 2019 (Figure 9a) shows the low pressure system moving rapidly east across England and North Sea. The image from the satellite (Figure 9b) on the same day shows the cloud over the North Sea [image extracted from the Met Office, UK, copyright Met Office / NASA/ NOAA [1]].

During the 8th and 9th of December 2019, the storm Atiyah impacted heavily across Ireland, with storm winds to Wales and south-West England overnight. The Netherlands faced that storm with very high winds too (gusts around 90-100 km/h and high levels of precipitation). Figure 9 c and d show the analysis chart at 00 UTC 9 December 2019[2]. The rest of December was also characterized by high wind conditions.

These two extreme events characterized by high winds were also recorded by the LiDAR at the LEG platform (Figure 10). During the two events, winds between 25 and 30 m/s were recorded by the LiDAR.

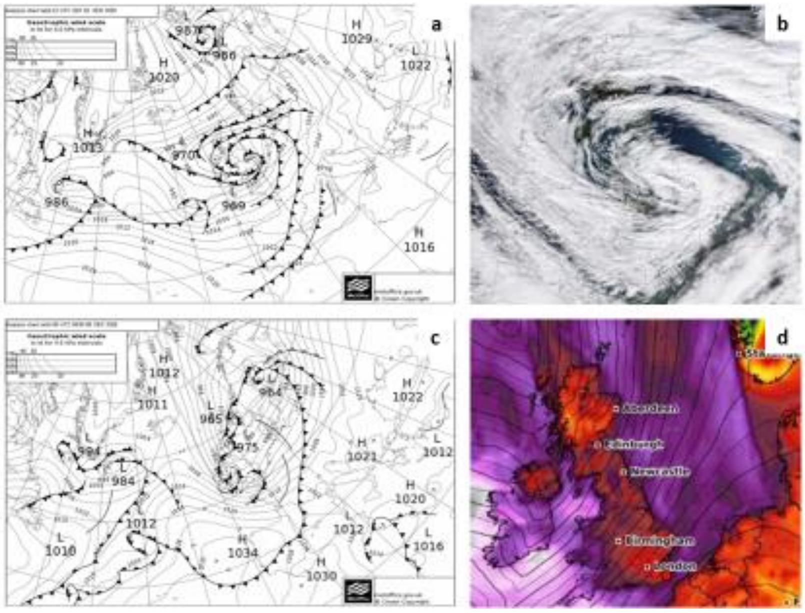

Figure 9 Analysis chart (a) and satellite image (b) over the North Sea UK and Dutch coast on the 2nd of November 2016. C) isobars and d)zooming out the isobars over UK and The Netherlands representing the Atiyah storm on the 7th of December 2019 [image extracted from the Met Office, UK, copyright Met Office / NASA/ NOAA].

[1] https://www.metoffice.gov.uk/binaries/content/assets/metofficegovuk/pdf/weather/learn-about/uk-past-events/interesting/2019/2019_011_november_wind.pdf
[2] https://www.metoffice.gov.uk/binaries/content/assets/metofficegovuk/pdf/weather/learn-about/uk-past-events/interesting/2020/2020_01_storm_brendan.pdf

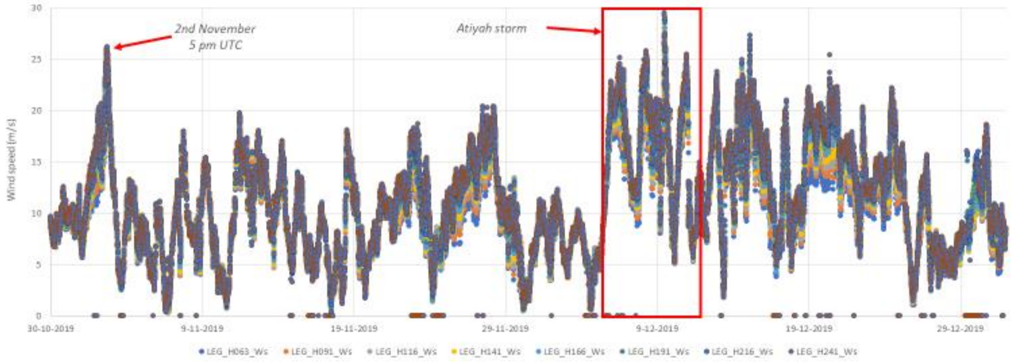

Figure 10 Wind speed at different heights measured during the campaign at LEG in November and December 2019.

4.2.2 Ex-hurricane Ophelia (16th October, 2017)

On the 16th October 2017 ex-hurricane Ophelia brought very strong winds to western parts of the UK and Ireland (Figure 11). The impact on the Dutch coast was characterized by moderate winds (15-20 m/s over the sea). In this period, the LiDAR also recorded moderate winds, showing that after the 16th the wind intensity decreased significantly until calm conditions (< 3 m/s) (Figure 12). In this figure the difference between heights of the wind speed is very clear with 8m/s of a difference between the lowest to the highest level considered in the analysis (63 m to 241 m).

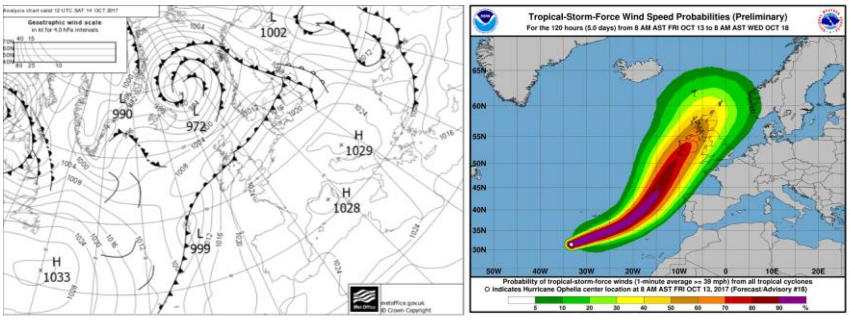

Figure 11 (a) Ophelia hurricane isobars chart approaching UK and the North Sea on the 14th of October 2017, extracted from the Met Office[3] and (b) probability of the storm force development winds on the 13th of October, by NOAA[4] National Hurricane Center.

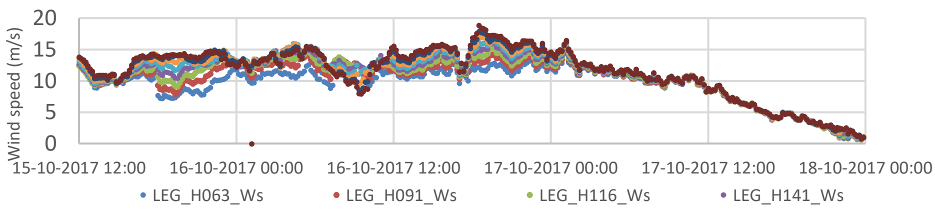

Figure 12 Wind speed time series recorded by the LiDAR during the winds from ex-hurricane Ophelia on the 17th October, 2017.

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[3] https://www.metoffice.gov.uk/binaries/content/assets/metofficegovuk/pdf/weather/learn-about/uk-past-events/interesting/2017/ex-hurricane-ophelia-16-october-2017---met-office.pdf
[4] Extracted from: https://www.businessinsider.nl/hurricane-ophelia-map-shows-how-badly-storm-could-hit-britain-2017-10?international=true&r=US

4.2.3 Strong winds from storm Angus (20th November 2016)

The period of strong winds during the 20th of November in 2016 was also an extreme event since the storm Angus passed through the North Sea causing damages and flooding. Based on the analysis chart from the Met Office[5], for 00:00 UTC the storm brought heavy rain and winds to the south coast of UK. Figure 13 shows that the strongest winds passed over the Dutch coast on the 20th of November before mid-day. The LiDAR at LEG clearly recorded the peak of the storm (Figure 14).

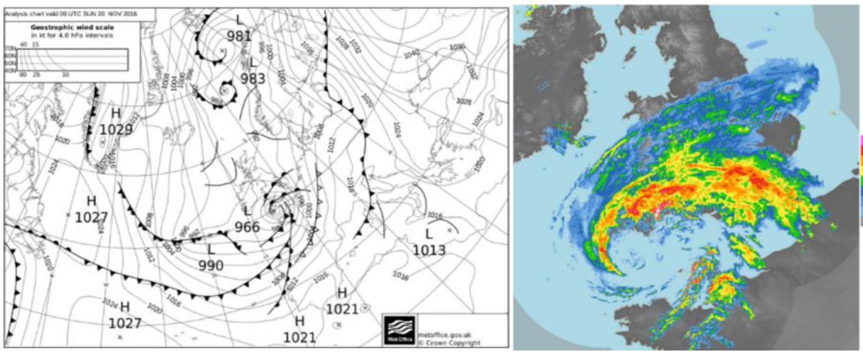

Figure 13 (a) analysis chart and the radar-rainfall image from the storm Angus, reaching the coast of the Netherlands on 20th November 2016, extracted from the Met Office[6].

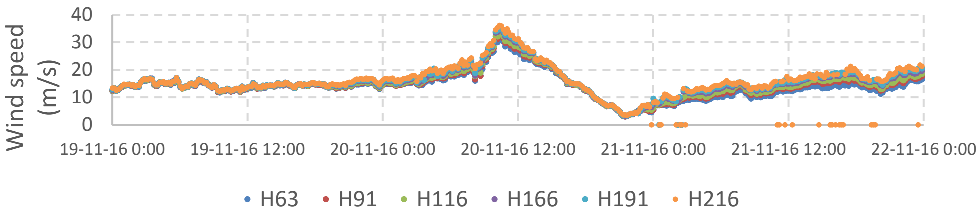

Figure 14 Wind speed time series at different heights recorded by the LiDAR during the measurement campaign at LEG on the 20th of November, 2016.

[5] https://www.metoffice.gov.uk/binaries/content/assets/metofficegovuk/pdf/weather/learn-about/uk-past-events/interesting/2016/strong-winds-and-flooding-from-storm-angus-november-2016---met-office.pdf

[6] https://www.metoffice.gov.uk/binaries/content/assets/metofficegovuk/pdf/weather/learn-about/uk-past-events/interesting/2016/strong-winds-and-flooding-from-storm-angus-november-2016---met-office.pdf

5 Cross-sectoral synergies and further applications of measured data

As shown in previous sections, measurement campaigns play a crucial role for the feasibility and wind site assessments. They are the basis for the financial decision to ensure the profitability of the plant. However, measured data can be very valuable for other applications within the context of wind assessments and beyond.

An assessment of the measurement program by 2023 in the Dutch North Sea for the continuation of the existing campaigns [11] employed by RVO showed the potential of the long-term programs:

- **Long-term measurement campaigns have the potential to become long-stationary historical record for offshore energy assessments and be a reference point for offshore wind atlases to be developed.**
- **High accuracy wind measurements can be also used for pre- and post-verification of floating LiDAR equipment and new emerging technologies.**

The European Technology & Innovation Platform on Wind Energy (ETIP Wind) also addresses the importance of using measurement campaigns to support the fundamental and pioneering research and to create a strong scientific base for the wind energy sector. This groundwork has to address the long-term applications and stimulate possible breakthroughs:

- **Development and validation of high fidelity models. In order to optimise the lay-out of wind power plants, further development on modelling wind resources and wind loads at site level is needed.** Improved accuracy is needed over a wide range of site conditions, with sufficient resolution in both time and space relevant for wind turbines. New measurement techniques and tools at both wind turbine and wind power plant level are necessary. This should be accompanied by experimental tests that help to address challenges related to turbulences, wake, waves and currents and turbine aeroelastic response, as well as the characterization of environmental conditions [12].

Beyond wind farm scales, the measurement campaigns can be used for applications in other energy sectors. The structural transition that the European electricity sector is facing to produce 50% of electricity by RES by 2030, constantly increases the stochastic nature of the power system. As a consequence, planning and scheduling tools for the power sector need to be updated. Modelling the high share of RES – and in particular wind power – crucially depends on the adequate representation of the intermittency and characteristics of the wind resource which is related to the accuracy of the approach for converting wind speed data into power values (Figure 15).

- Generally, output from numerical weather prediction (NWP) models or reanalysis data are used to feed **energy system /power system model and analysis.** One of the main factors contributing to the uncertainty in these conversion methods is the selection of the spatial resolution. Although numerical weather prediction models can simulate wind speeds at higher spatial resolution (up to 1x1 km) than a reanalysis (generally, ranging from about 25 km to 70 km), they require high computational resources and massive storage systems. Therefore, the most common alternative is to use the reanalysis data. However, local wind features could not be captured by the use of a reanalysis technique and could be translated into misinterpretations of the wind power peaks, ramping capacities, the behavior of power prices, as well as bidding strategies for the electricity markets. In this case, measured data could play an important role avoiding the uncertainty of the resolution of the wind resource [13], [14].

- As analysed in chapter 4, the measured data also recorded the extreme climatic events during the campaign. That means, that the behaviour of such events is also captured by the LiDAR making the data useful for further purposes on the power sector and the whole energy system through **assessments on congestion management, impact of climate extremes on the grid**.

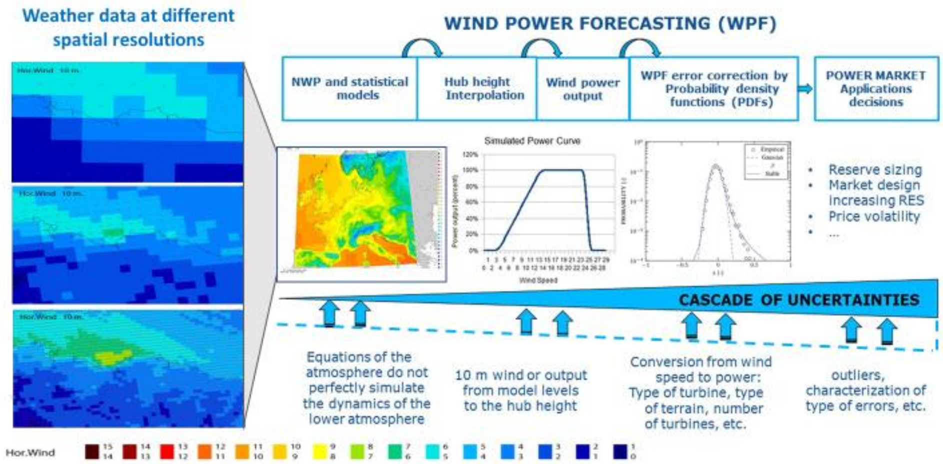

Figure 15 The need of accurate wind resource data and to increase the spatial resolution in power system modelling for more accurate power market applications and decisions.

6 Conclusions

Within the Dutch project *Wind@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: Lichteiland Goeree (LEG), Europlatform (EPL) and 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, Part I of the series, refers to the measurement campaign at the LEG platform where a LEOSPHERE WINDCUBE V2 LiDAR has been deployed. Four 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 weather analysis for the 2014-2019 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 from 191° to 200° and the lower and upper quartiles range from 120° to 260° 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 = 2.26 and c=10.36 at 63 m height). The wind speed bell distribution is flattener and moderately skewed right with higher heights, with more frequent wind speeds >26 m/s. 2017 was atypical year with higher k parameter indicating less wind variability than the 2014-2019 average.

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. Moreover they can be used for pre/ post verification of new sensor equipment.
- 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.

7 Acknowledgements

The measurement campaign at the offshore measurement platform Lichteiland Goeree (LEG) was carried out on the authority of the Ministry of Economic Affairs and Climate Policy of The Netherlands.

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[17] J. Maureira Poveda and D. Wouters, “Wind measurements at Meteorological Mast Ijmuiden,” ECN, 2015.

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 [15]. The LIDAR take measurements at 10 different heights (Table 5).

Table 5 Adjustments of the heights above Mean Seal Level from the default configuration

Id	LiDAR height	Adjustments (MSL)
1	40	63
2	68	91
3	93	116
4	118	141
5	143	166
6	168	191
7	193	216
8	218	241
9	243	266
10	268	291

Figure 16 Example of screenshot WINDCUBE V2.

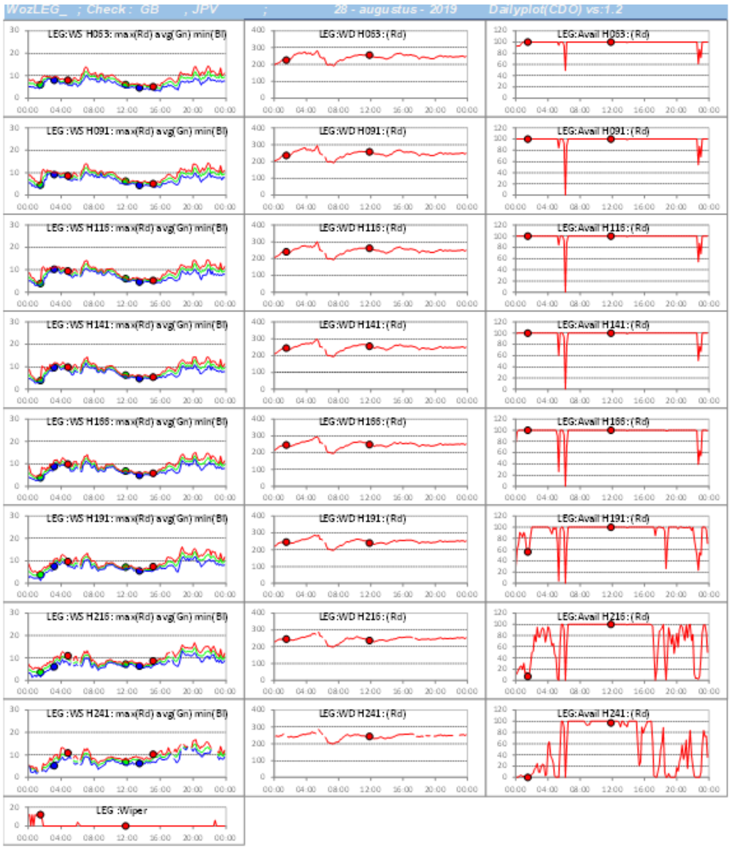


Figure 17 Example of a daily plot during the measurement campaign at LEG

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 540 mm
	Transport case : 685 x 745 x 685 mm
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 weather conditions per year at the LEG from 2019 backwards in time to 2015.

B.1 2019

The prevailing wind direction recorded during 2019 at LEG is South-West, at different heights, as indicated by the wind roses. The figure below shows that although the predominant wind direction is South-West, with lower heights, the North component is stronger. The wind speed and direction between 241m and 63 m, the wind shear and wind veer, can be seen in the right-chart. The main wind speed distributions (m/s vs. frequency) at different heights and the descriptive statistics are also included yearly. The wind direction recorded during 2019 at LEG is South-West, at different heights, as indicated by the wind roses. The figure below shows that although the predominant wind direction is South-West, with lower heights, the North component is stronger. The wind shear and veer between 241 m and 63 m can be seen in the right-chart. The main wind speed distributions (m/s vs. frequency) at different heights and the descriptive statistics are also included yearly.

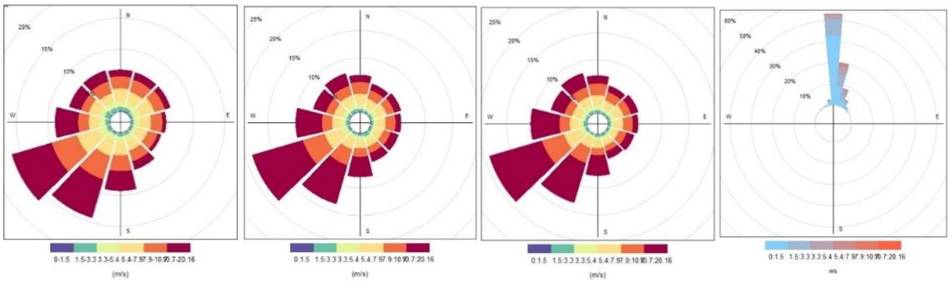
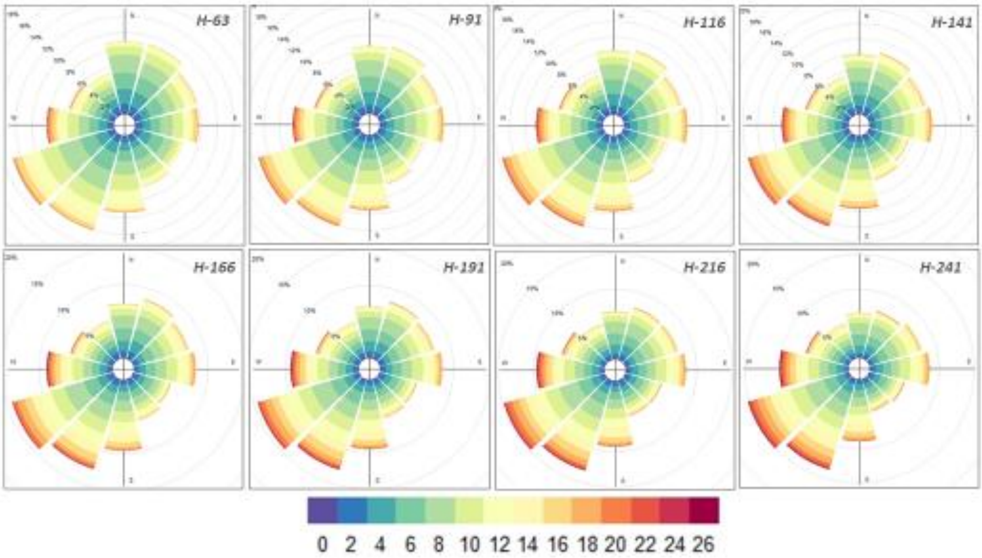
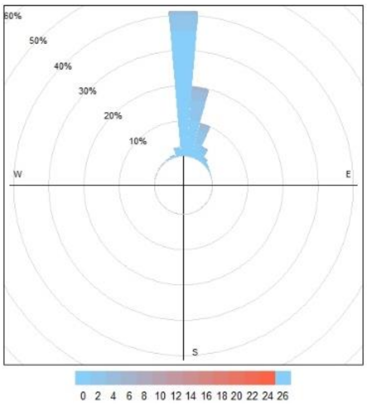


Table B.1 Descriptive statistics of wind speed and direction at different heights in 2019

H (m)	**63**	**91**	**116**	**141**	**166**	**191**	**216**	**241**
Ws - Min	0.25	0.1	0.23	0.2	0.27	0.19	0.14	0.24
Ws – 1st quartile	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	9.2	9.28	9.4
Ws - Mean	8.91	9.25	9.45	9.62	9.79	9.97	10.15	10.34
Ws - 3rd quartile	11.36	11.92	12.24	12.51	12.73	12.96	13.2	13.42
Ws - Max	26.65	27.53	28.15	28.89	29.61	30.24	30.74	31.13
Wd - 1st quartile	120.6	121.3	123.6	126.1	128.8	130.6	131.5	132.9
Wd - Median	210.6	212.6	214.2	215.5	216.9	218.7	220.4	222.5
Wd - Mean	193.7	195	196.4	197.4	198.6	199.9	200.8	202.2
Wd - 3rd quartile	258.8	260.1	261.2	262	262.7	263.9	264.6	266.7

B.2 2018





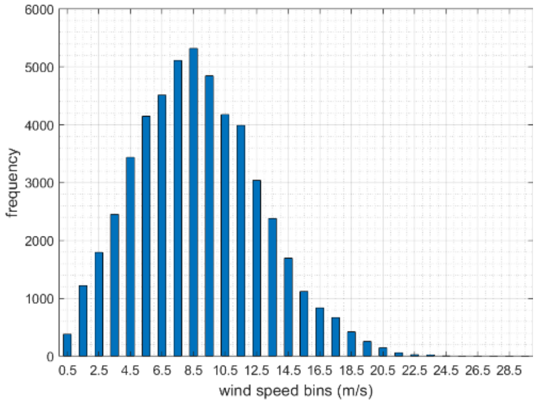
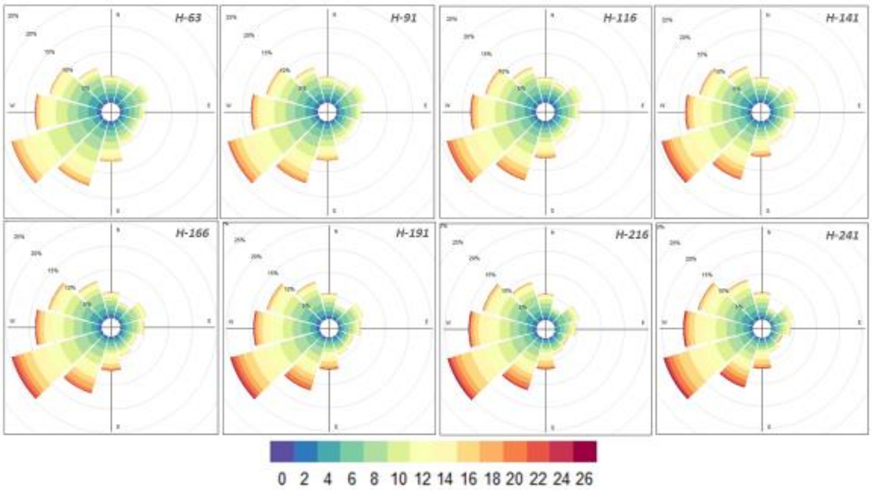
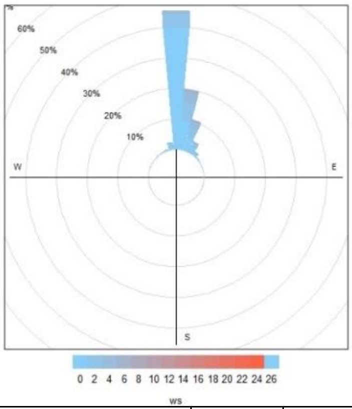


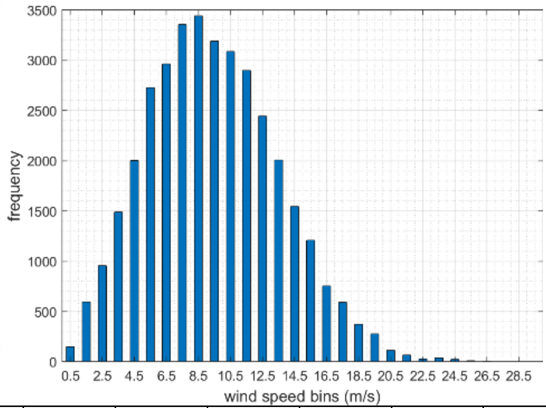
Table B.2 Descriptive statistics of wind speed and direction at different heights in 2018.

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 quartile	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	8.802	9.149	9.361	9.547	9.719	9.879	10.03	10.19
Ws - 3rd quartile	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	37.5	37.91	38.27
Wd - 1st quartile	84.3	85	86.6	87.5	89.1	90.5	92.7	95.3
Wd - Median	190.2	191.3	192.9	194.3	196.1	197.7	200	202.9
Wd - Mean	175.5	176.2	177.4	178.1	179.3	180.2	181.7	183.5
Wd - 3rd quartile	249.2	249.5	249.9	250.2	250.9	251.3	252.3	253.7

B.3 2017

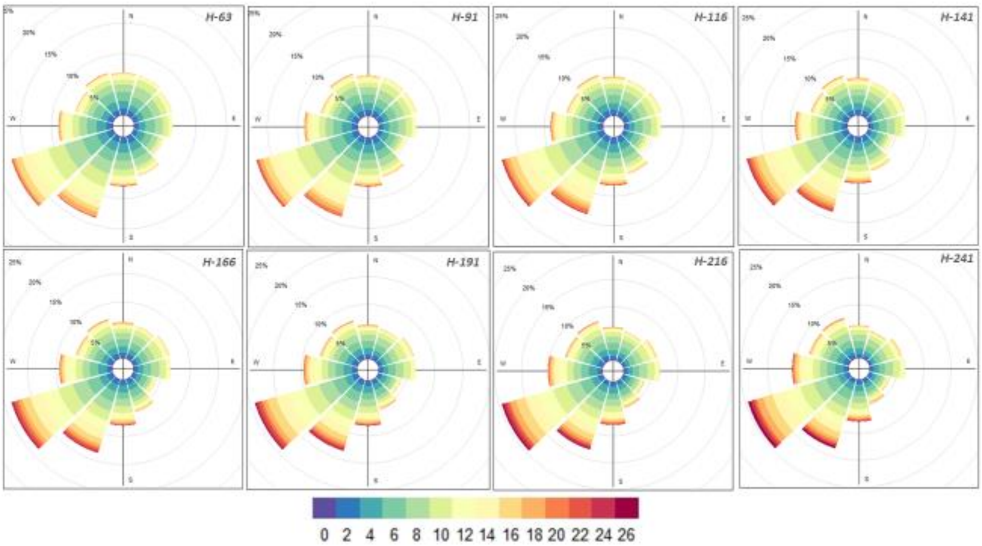


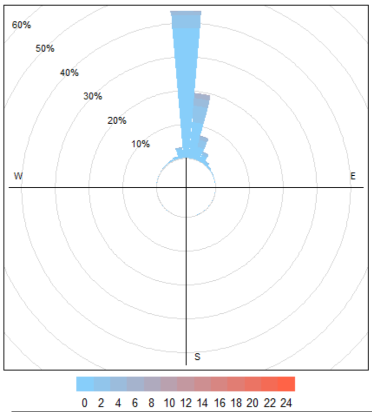


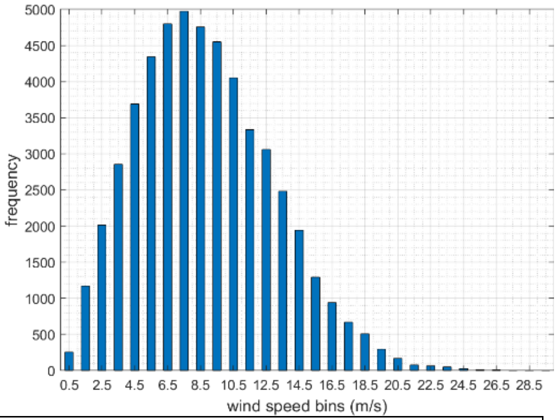


H (m)	**63**	**91**	**116**	**141**	**166**	**191**	**216**	**241**
Ws - Min	0.27	0.12	0.19	0.14	0.19	0.22	0.26	0.38
Ws – 1st quartile	6.4	6.57	6.65	6.75	6.91	7.02	7.16	7.29
Ws - Median	9.13	9.46	9.69	9.88	10.05	10.17	10.34	10.51
Ws - Mean	9.395	9.749	9.997	10.23	10.45	10.64	10.82	11.01
Ws - 3rd quartile	12.12	12.69	13.05	13.36	13.67	13.91	14.09	14.29
Ws - Max	27.52	29.06	30.06	30.9	31.51	32.14	32.57	32.98
Wd - 1st quartile	156.3	158.9	161.1	164.2	169.2	175.4	181.3	187.7
Wd - Median	229.2	230.7	232	233.6	235.8	238.1	240	242.7
Wd - Mean	209.3	210.9	212.2	214	216.3	219	221.8	225.7
Wd - 3rd quartile	275.2	276.8	278	279.6	281.1	282.8	284.5	286.7

B.4 2016

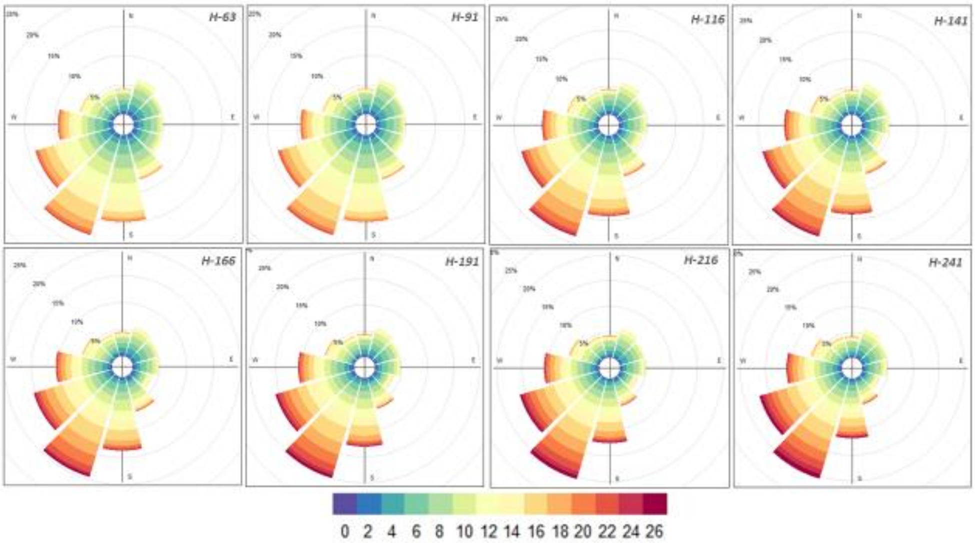


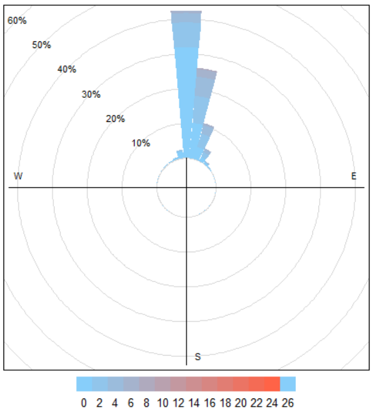


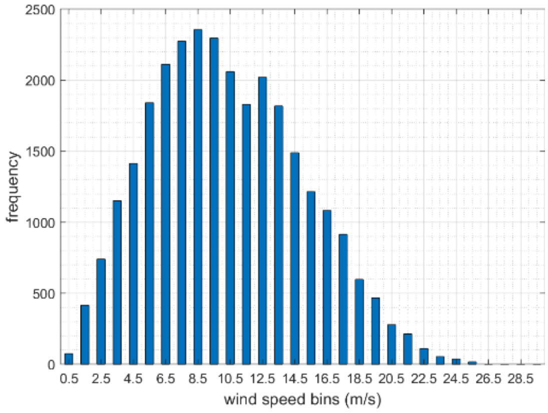


H (m)	**63**	**91**	**116**	**141**	**166**	**191**	**216**	**241**
Ws - Min	0.3	0.29	0.25	0.3	0.19	0.28	0.3	0.25
Ws – 1st quartile	5.71	5.79	5.86	5.93	5.99	6.07	6.16	6.24
Ws - Median	8.4	8.6	8.76	8.88	9.02	9.14	9.29	9.4
Ws - Mean	8.809	9.048	9.237	9.404	9.561	9.718	9.899	10.04
Ws - 3rd quartile	11.52	11.88	12.15	12.35	12.52	12.707	12.91	13.06
Ws - Max	32.07	33.46	34.07	34.74	35.46	35.81	36.25	36.6
Wd - 1st quartile	115.6	117.6	119.2	119.7	119.1	120.8	124.8	131.3
Wd - Median	211.4	212.2	213.4	214.6	215.7	217.4	219.9	222.1
Wd - Mean	191.6	192.3	193.2	193.7	194	195.2	197.5	200.2
Wd - 3rd quartile	257.5	257.5	257.7	257.9	258.3	259.5	262	264.7

B.5 2015







H (m)	**63**	**91**	**116**	**141**	**166**	**191**	**216**	**241**
Ws - Min	0.5	0.5	0.23	0.26	0.28	0.2	0.24	0.25
Ws – 1st quartile	6.72	6.93	7.08	7.23	7.32	7.43	7.52	7.57
Ws - Median	9.87	10.3	10.6	10.87	11.07	11.27	11.44	11.59
Ws - Mean	10.3	10.76	11.11	11.42	11.67	11.89	12.1	12.28
Ws - 3rd quartile	13.54	14.27	14.81	15.28	15.68	16.02	16.3	16.59
Ws - Max	26.56	27.58	28.31	29.48	30.79	31.91	32.78	33.77
Wd - 1st quartile	141.3	142.8	145.85	149.5	152.1	154.5	155.8	157.4
Wd - Median	201.3	202.5	204.1	205.9	207.6	209.3	210.7	212.2
Wd - Mean	191.4	192.04	193.16	194.4	195.5	196.6	197.2	198.1
Wd - 3rd quartile	248.3	249.2	249.7	250.4	251	251.6	252	252.7

C Weather conditions analyses during the monthly reporting

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 were also analysed each month. The figures below show the analysis for January 2019, as an example.

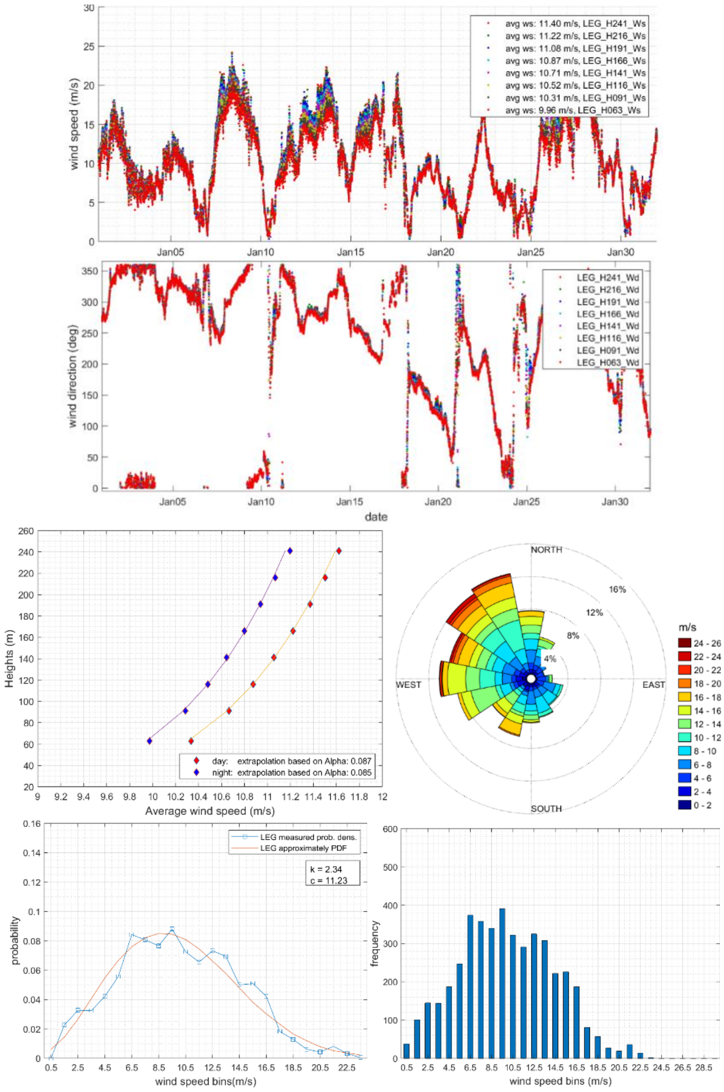


Figure 18 Wind speed (a) and direction (b) signals; (c) wind shear and (d) wind rose over January 2019 at LEG

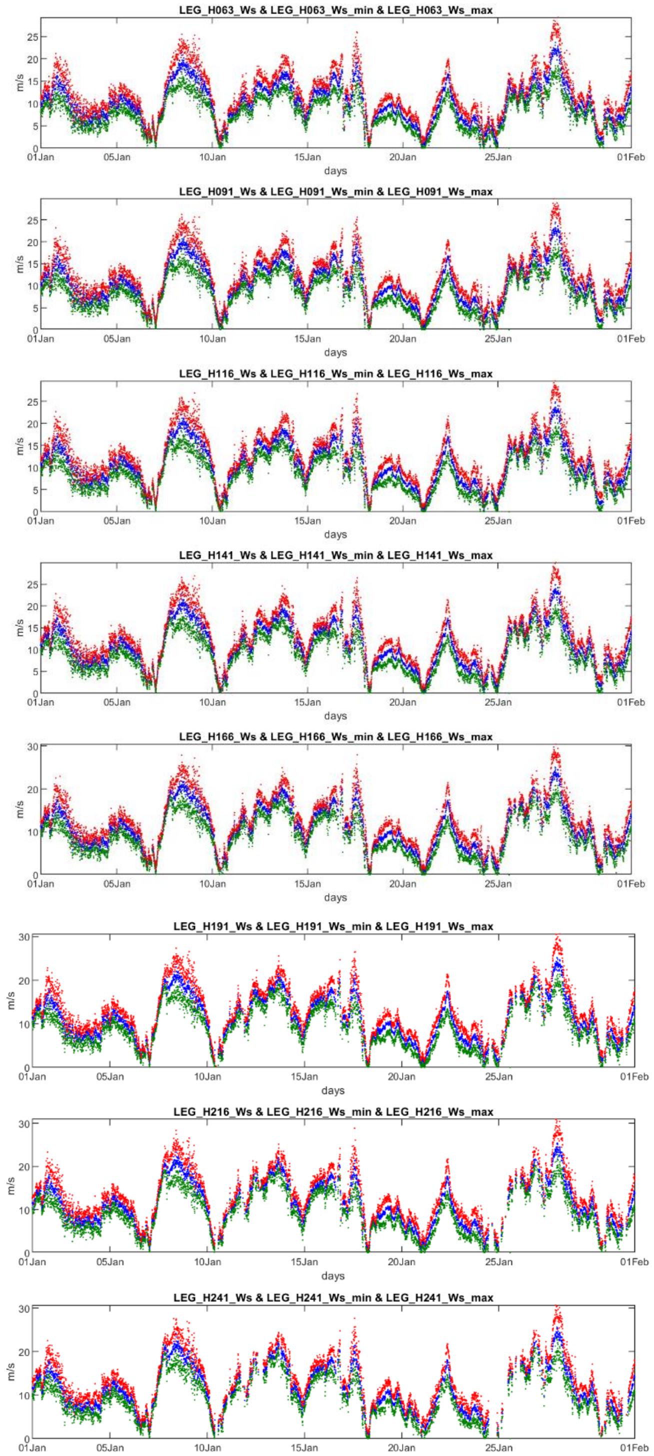


Figure 19 Minimum, maximum and mean wind speed time series over January 2019 at LEG

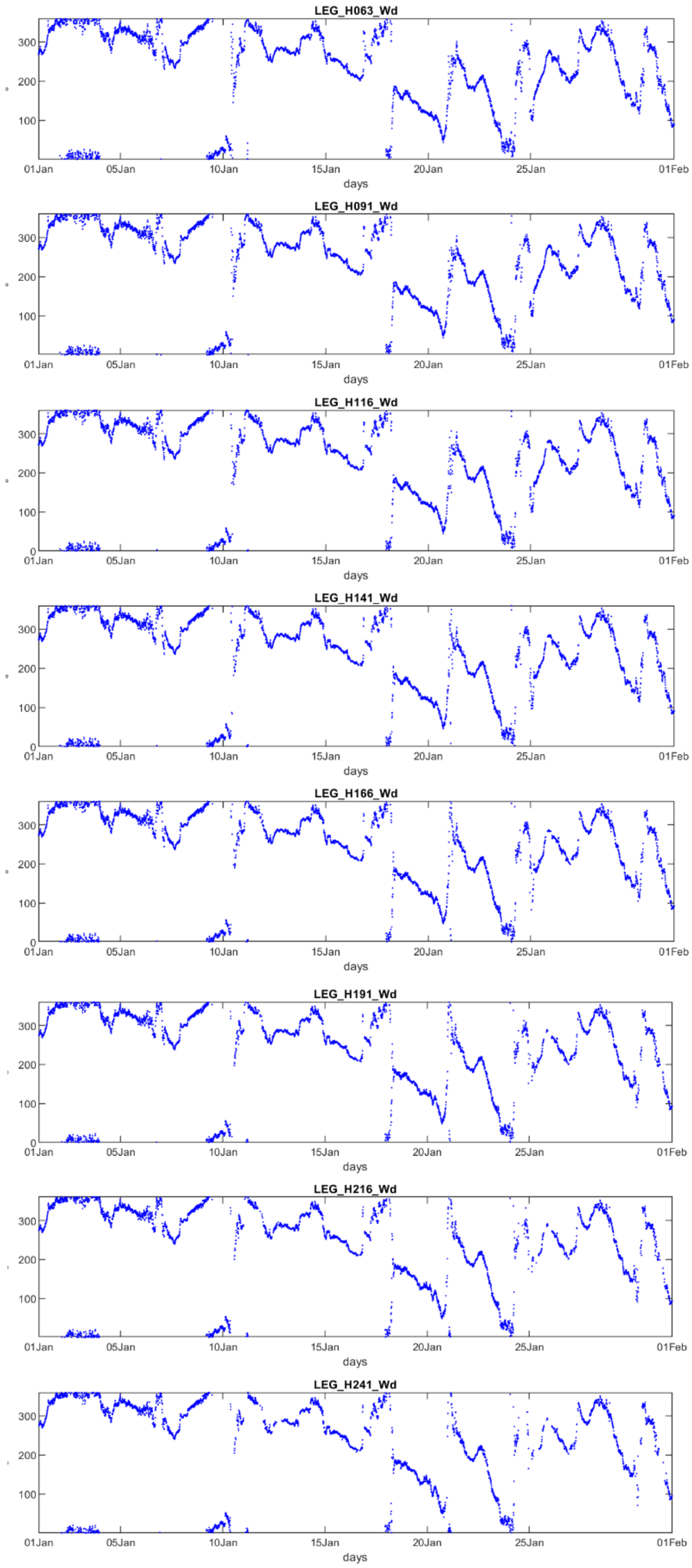


Figure 20 Wind direction time series during January 2019

D Comparison of the wind direction measurements between LEG and Ijmuiden Met mast

For the common period that the measurement campaign at LEG was running with the measurement campaign at Ijmuiden met mast, the wind direction signals were compare for specific moments. The figure below shows an example of the comparison during several days in October 2015 and the good performance between the LiDAR and the met mast.

Additional information of the Ijmuiden measurement campaign at the Met mast can be found in [16], [17].