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TNO report**TNO 2021 R11202**

Offshore wind energy deployment in the North
Sea by 2030: long-term measurement
campaign.
Lichteiland Goeree, 2014-2020

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Contents

Executive summary.....	3
1 Leading position to support future offshore wind deployment in Europe.....	4
1.1 The importance of high quality measurement campaigns	4
1.2 TNO activities over the life cycle of the campaigns	6
1.3 Open-access and public datasets.....	6
2 Measurement campaign at LEG	7
2.1 Installation plan of instrumentation	7
2.2 Onsite installation and operational status	8
2.3 Health and safety measures	8
3 High quality data	9
4 Wind conditions at LEG	11
4.1 Weather conditions during the period 2014-2020	11
4.2 Annual wind statistics.....	15
4.3 Comparison of LiDAR and KNMI measurements	17
4.4 Comparison of LiDAR measurements at the K13a, EPL and LEG platform	21
4.5 Past weather events	23
5 Cross-sectoral synergies and further applications of measured data	28
6 Conclusions	30
7 Acknowledgements	32
8 References.....	33
Appendices	
A Technical specifications of the LiDAR selected: WINDCUBE V2	
B Annual weather conditions during the campaign at LEG	
C Weather conditions analyses during the monthly reporting	

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 at least 11.5 GW by 2030 corresponding to the 40% of the current electricity consumption. In 2020, the strongest offshore wind deployment in Europe took place in The Netherlands with 1.493 GW [1].

The Dutch Ministry of Economic Affairs and Climate Policy has agreed that TNO performs measurement campaigns in the North Sea from 2014 until 2030 at different locations, reviewed on annual basis. Currently, the locations of the measurements are Lichteiland Goeree platform (LEG), Europlatform (EPL) and Wintershall Noordzee B.V. platform K13a, under the project "2021 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, analysis, reporting and dissemination of the data. This report refers to the analysis of the measurement campaign at LEG from 2014 to 2020.

The weather analysis indicates that the measured data captures the variability of the local and regional climate of the area, including past extreme weather events. Particularly, during the winter of 2019-2020 five extreme events occurred in the form of storms with strong winds. The LiDAR was capable to capture the storms measuring maximum wind speeds above 35 m/s from the height of 91m and average wind speeds above 30 m/s at 141m.

The accuracy and high quality data obtained, the average data availability over the 7 year of the measurement campaign is about 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 valuation of the wind farm site and for the financial decision to ensure the profitability of the business plans.

1 Leading position to support future offshore wind deployment in Europe

1.1 The importance of high quality 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 [2]). 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 this area.

In the Netherlands, the national government aims to develop an offshore wind portfolio of 11.5 GW by 2030 from the 1.493 GW at the end of 2020 (Figure 1), corresponding to the 40% of the current electricity consumption.

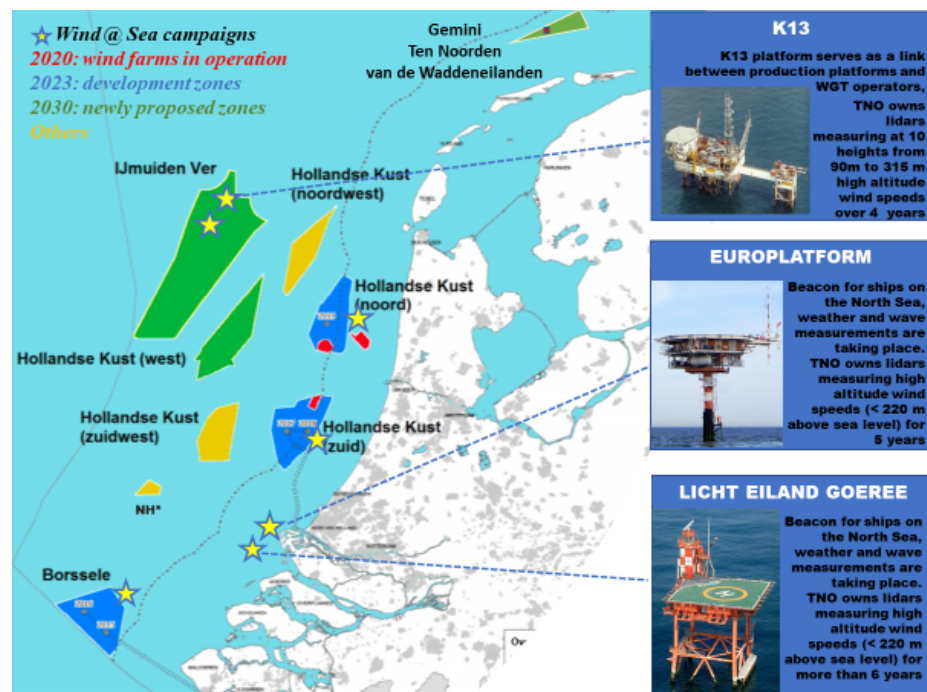


Figure 1 Locations of current and future offshore Dutch wind farms and measurement campaigns executed by TNO under the 'Wind op zee' framework over the Dutch North Sea.

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.

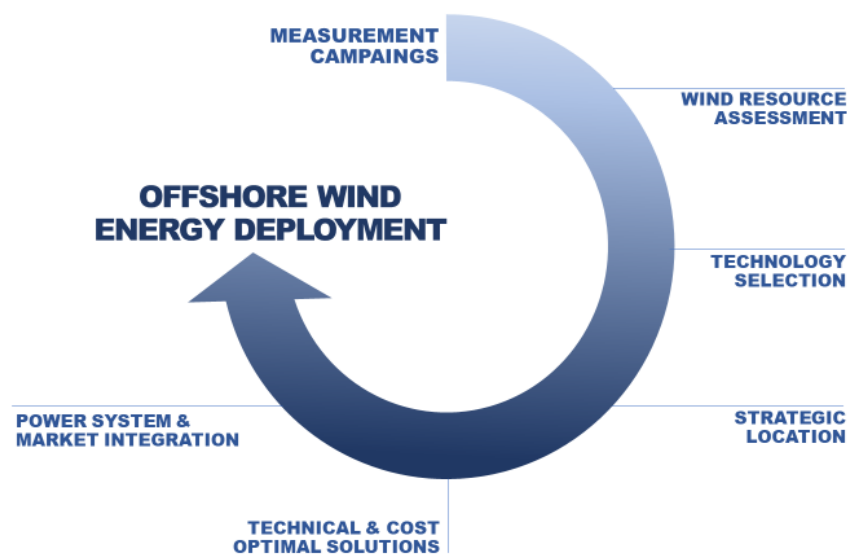


Figure 2 Process to ensure the profitability of the wind offshore deployment.

Under the Dutch wind offshore future plans, the Dutch Ministry of Economic Affairs and Climate Policy has agreed that within the ‘2021 *Wind Conditions @ North Sea*’ project, TNO performs measurement campaigns in the North Sea from 2014 until 2030 at different locations: Lichteiland Goeree (LEG), Europlatform (EPL) and Wintershall platform K13a (Figure 1).

TNO has produced a series of reports about the measurement campaigns carried out at those locations for wind conditions including 2020. The reports [3] and [4] include wind conditions analysis for the K13a platform; [5] for the LEG platform, [6] and [7] for the EPL platform. This report includes the wind conditions for 2014-2020 at the LEG platform. As the campaign is foreseen to continue running, 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. Before the integration of LiDAR 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.

1.3 Open-access and public datasets

The data measured in the “2021 Wind Conditions @ North 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 verification 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 “2021 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:

Gonzalez-Aparicio, I., Pian A., Verhoef J.P., Bergman G, van der Werff, P.A., (2021) Offshore wind energy deployment in the North Sea by 2030: long-term measurement campaign. Lichteiland Goeree, 2014-2020.TNO 2021 R11202.

Indicate in the publication the date at which the data have last been accessed (e.g. *Last accessed May 2021*).

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-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 [8] [9]. The second phase includes onsite installation and 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.

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 3). 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.

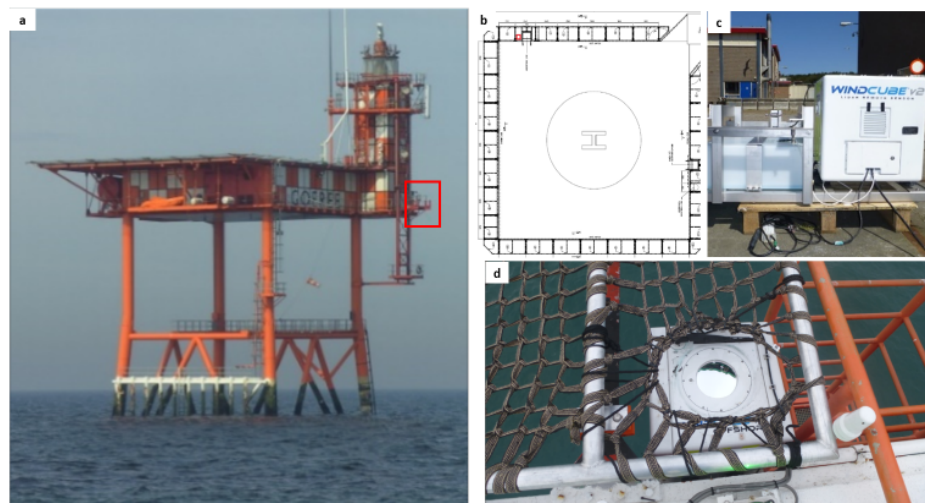


Figure 3 a) Front and b) top view of Lichteiland Goeree platform [LAT LON coordinates: 51.92503°N, 3.66844°E], helicopter deck at a height of 24.58m and the accommodation deck at 20.04m above mean sea level; c) mounting frame to place the LiDAR at the selected location in the platform and d) final installation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

To ensure good quality measurements it is crucial to select the right location for the LiDAR on the platform [8]. 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 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 [9] [10] [11]. 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 MSL [12]. 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 [13].

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 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, more detailed information in the Annex A. . 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 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. The heights considered are 63, 91, 116, 141, 166, 191, 216, 241, 266 and 291 m above the LLWS (Lowest Low Water Spring).

Frequency of the data are 10-minutely 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 2020 at 23:50 hr. UTC although the campaign is still running.

The measurements heights reported in the 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 2 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 4 and Table 3 the data availability depends on the height of the measurements. For heights up to 200m, the data available is on average 90%, while up to 266 m the availability decreases to 63%. At 291 m the availability was about 47%. 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 3 are biased by incomplete years and LiDAR system replacements or downtime periods. Please note that the measurements started in November 2014 and please also note that in 2015 data have not been available from May to August. That is why the variability in those years is higher. For this report heights above 241 m are not considered for further analysis.

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

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

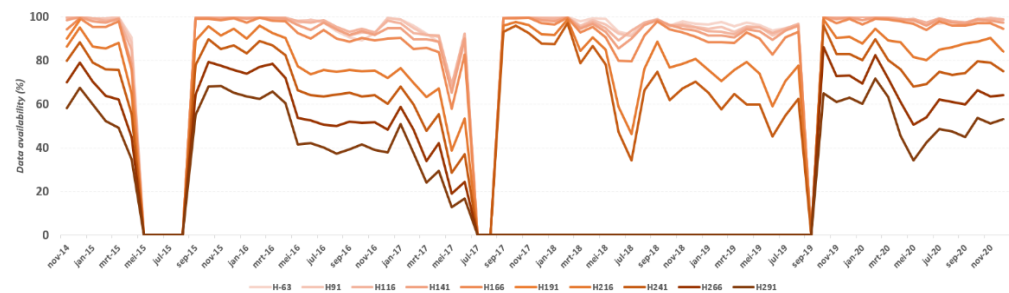


Figure 4 Monthly averages of the data available (%) measured by the LEOSPHERE WINDCUBE V2 LiDAR by height at the LEG platform.

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, [14] 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.

4 Wind conditions at LEG

This section provides an overview of the weather conditions during the campaign at the LEG platform for the entire period 2014-2020 and on annual wind statistics (section 4.1 and 4.2, respectively). 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.

The third section shows a 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.

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). In this report, special attention is given to the extreme events that occurred during winter 2020 since they considerably influenced the average conditions.

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

4.1 Weather conditions during the period 2014-2020

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 [15], [16].

At the LEG platform, the weather analysis for 2014-2020 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 190° to 199° and the lower and upper quartiles range from 116° to 260° at all heights (Table 4). Wind roses charts (Figure 5) indicate that at higher heights the wind intensity increases; with more frequent winds >26 m/s.

Table 4 Descriptive statistics for the wind speed (Ws) and direction (Wd) at different heights for the 2014-2020 period at the LEG platform.

H (m)	63	91	116	141	166	191	216	241
Ws – Min	0.22	0.10	0.13	0.14	0.15	0.15	0.14	0.22
Ws – 1 st quartile	6.07	6.21	6.28	6.35	6.43	6.51	6.61	6.70
Ws - Median	8.85	9.14	9.31	9.47	9.61	9.74	9.86	10.00
Ws - Mean	9.25	9.59	9.82	10.02	10.20	10.38	10.57	10.75
Ws - 3 rd quartile	12.03	12.55	12.89	13.18	13.43	13.67	13.90	14.12
Ws -98 p	19.11	20.03	20.83	21.55	22.23	22.86	23.42	23.96
Ws - Max	33.02	34.38	35.23	36.08	36.97	37.50	37.91	38.27
Wd - 1 st quartile	116	117	120	121	123	125	128	132
Wd - Median	208	209	211	212	214	215	217	219
Wd - Mean	190	191	192	193	194	196	197	199
Wd - 3 rd quartile	256	257	257	258	259	260	260	260

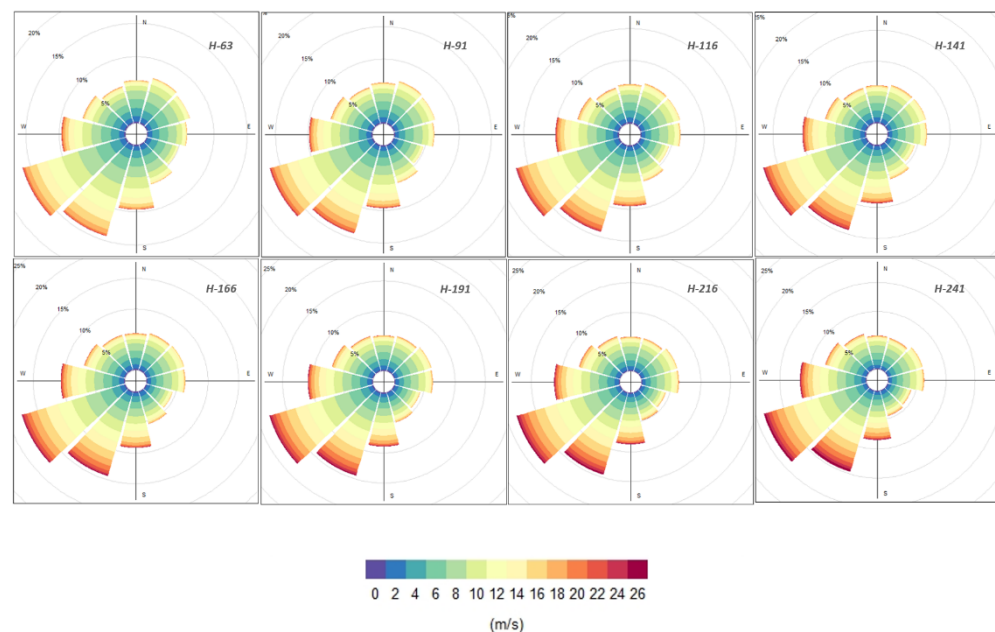


Figure 5 Wind roses at different heights showing the wind prevailing direction for the 2014 -2020 period.

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:

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

The shape parameter describes the wind behaviour according to its value: the parameter scale 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 2014-2020, the Weibull distribution show that $k = 2.133$ and $c = 11.311$ m/s at 141 m height (see table in Figure 6).

The Figure 6 (bottom) indicates how the distribution is flattening and moderately skewed right with higher heights including the k and c parameters for each height. For the 2014-2020 period at 141 m height, the k parameter is similar to the k at EPL and K13a platforms.

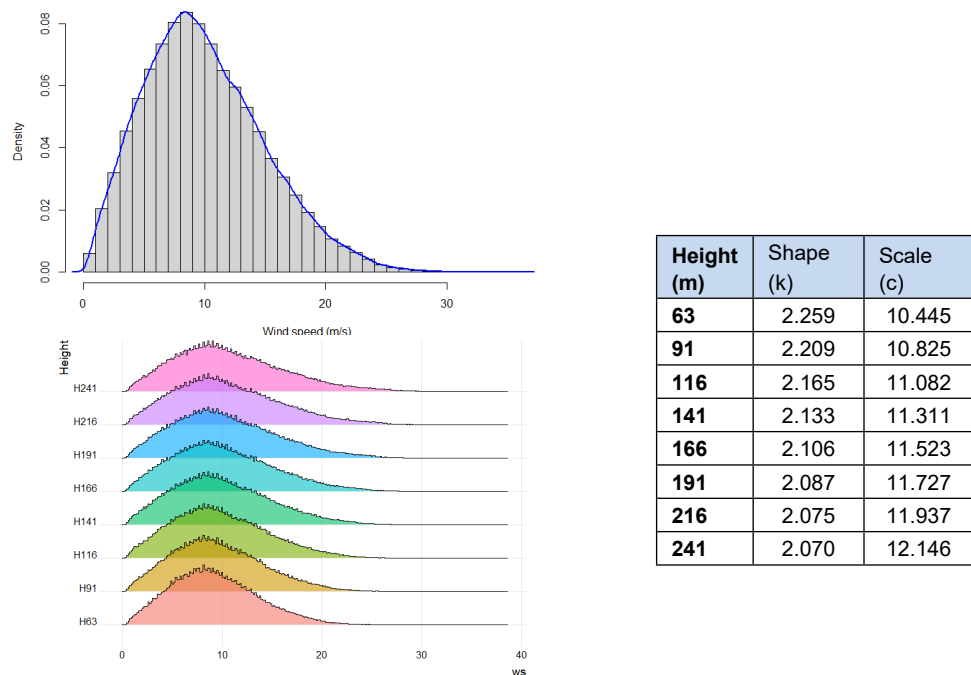


Figure 6 (top) Weibull distribution and curve fitting at 141 m height and (bottom) Weibull distributions at different heights for the measurement campaign with k and c parameters (table) at LEG for 2014-2020.

The temporal variability of the wind speed and direction analyses are relevant indicators to support system capacity assessments such as the long-term storage needs under a high RES integrated system, as the vision and ambitions of the National Climate Agreement to reach a 95% RES power system by 2050 [17].

The Figure 7 presents the seasonal variation, monthly and diurnal cycle at different heights. A clear seasonal and monthly pattern can be observed both for wind speed and direction at different heights. There is a drop in the wind speed (5 m/s) from winter to summer months, due to the change in temperatures over the sea surfaces along the year. The seasonal changes of the wind resource are mainly dominated by the general circulation and it is also explained by the cycle derived from vertical mixing occurred by the lower-atmosphere and land energy balance.

However, the variability each hour is less pronounced than at monthly scales. At the 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 [14], [18] and [5]. Such studies present additional description over the temporal variability of horizontal and vertical wind profiles at different offshore locations over the Dutch North Sea.

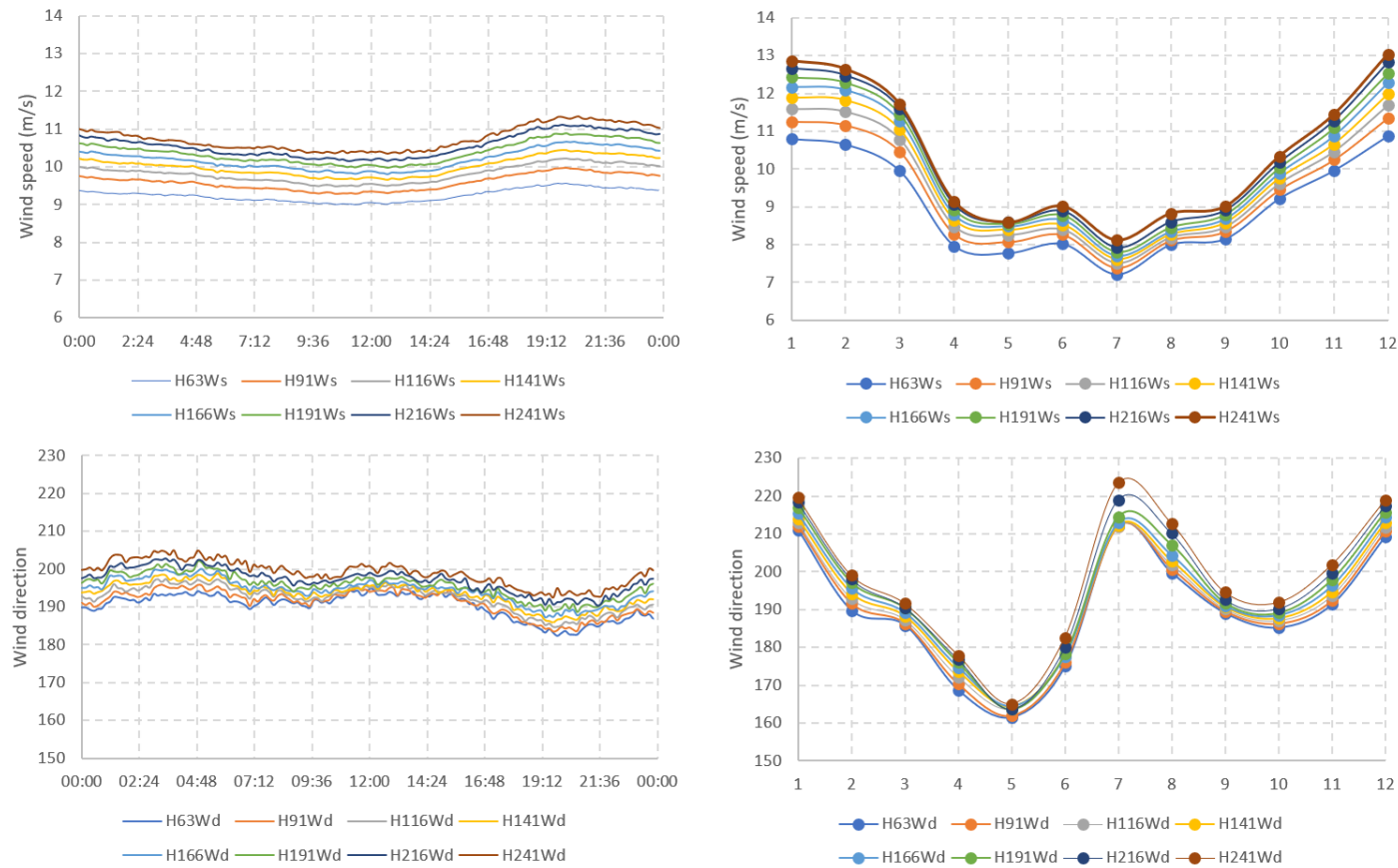


Figure 7 a) Monthly wind speed and direction averages and b) average daily cycles at different heights for the 2014-2020 period.

4.2 Annual wind statistics

As regards the wind regimes and intra-annual variability; the Figure 8 and Figure 9 present the annual Weibull distribution parameters at all heights. The c parameter was very similar each year. Since the value of k is inversely proportional to wind variability, that is, large k values indicate less wind variability. In 2020, lower k values with respect to other years indicate higher wind speed variability and larger spread. The same occurs with the c parameter in 2020, with higher wind speeds than the average (see statistics of Table 5). It is worthwhile to mention that 2020 was a year characterized by numerous extreme events, mainly with more storms than previous winters and higher winds during February (see chapter 4.5) being the reason that k parameters deviates from the 2014-2020 average, as also observed in the reports at EPL [7] and K13a [4]. In 2014 and 2015, due to low data availability and high wind speeds, very high c parameters are shown in Figure 8.

On the temporal evolution, Figure 10 shows the monthly averaged wind speed per year. Months with no data represents the period of LiDAR replacements (see Figure 4 for data availability). There is no particular trend at monthly or at seasonal level: the months with highest wind speeds occurred in winter, mainly in November and December 2015 and February 2020. The lowest wind speeds were registered in summer, mainly in July and August. 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.

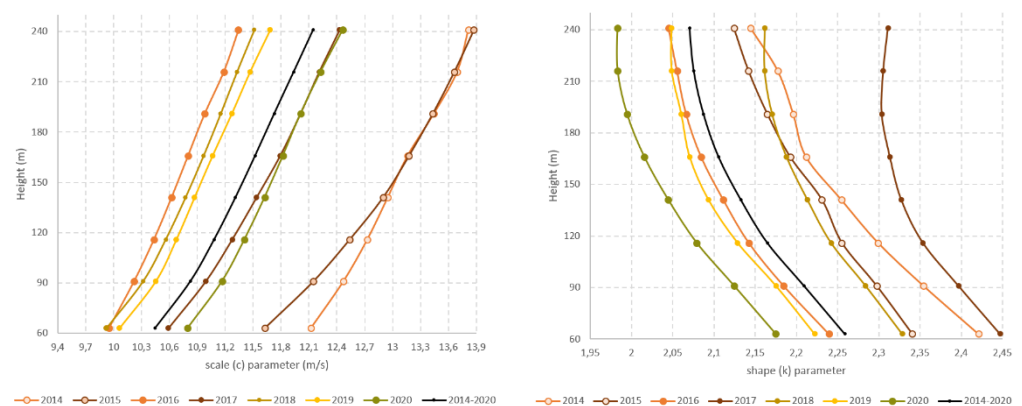


Figure 8 Annual Weibull (left) scale and (right) shape parameters at different heights at the LEG platform from 2014 to 2020.

Table 5 Descriptive annual statistics of the wind speed (W_s) and direction (W_d) at 141m height at the LEG platform.

H141 (m)	2015	2016	2017	2018	2019	2020
W_s (m/s)- Min	0.26	0.3	0.14	0.18	0.2	0.20
W_s (m/s)- 1st q	7.23	5.93	6.75	6.22	6.19	6.21
W_s (m/s)-Median	10.87	8.88	9.88	9.16	9.01	9.79
W_s (m/s)- Mean	11.42	9.404	10.23	9.547	9.62	10.30
W_s (m/s)- 3rd q	15.28	12.35	13.36	12.52	12.51	13.74
W_s (m/s)- Max	29.48	34.74	30.9	36.08	28.89	30.37
W_d (°)- 1st q	149.5	119.7	164.2	87.5	126.1	125.8
W_d (°) Median	205.9	214.6	233.6	194.3	215.5	191.5
W_d (°)- Mean	194.4	193.7	214	178.1	197.4	190.0

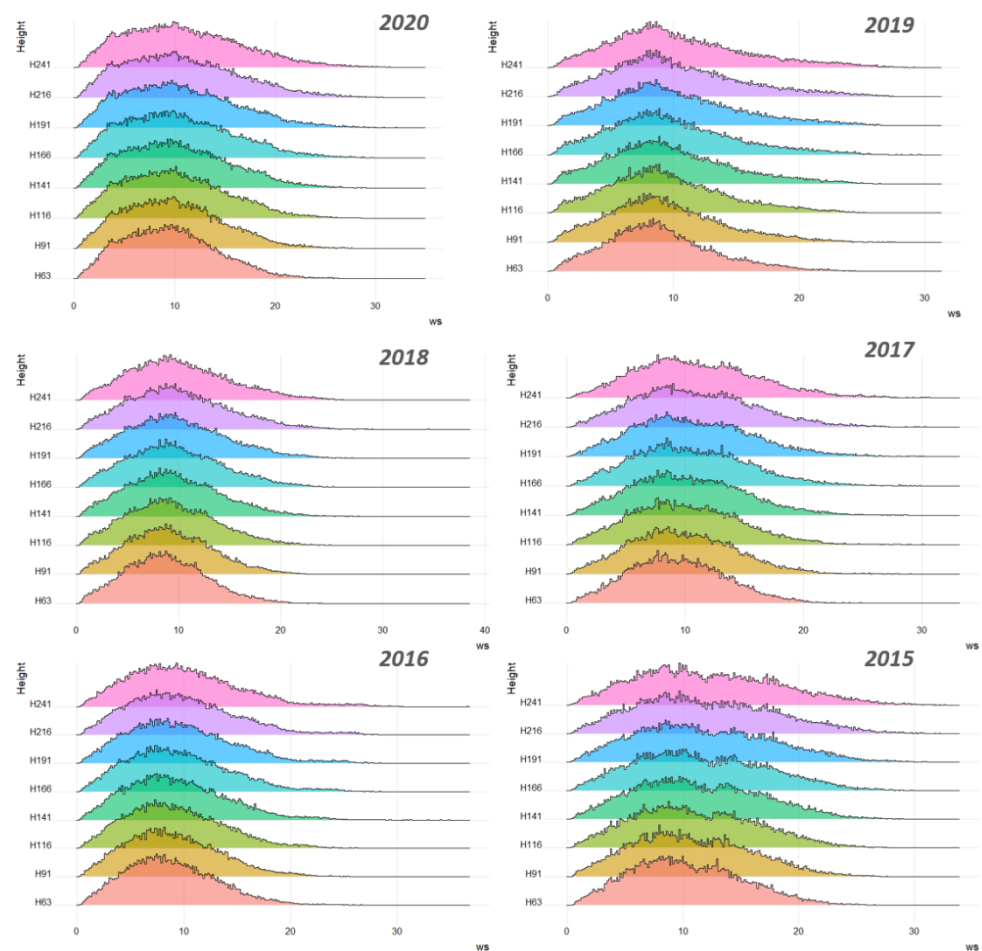


Figure 9 Annual Weibull distributions at different heights at the LEG platform for the 2015-2020 period.

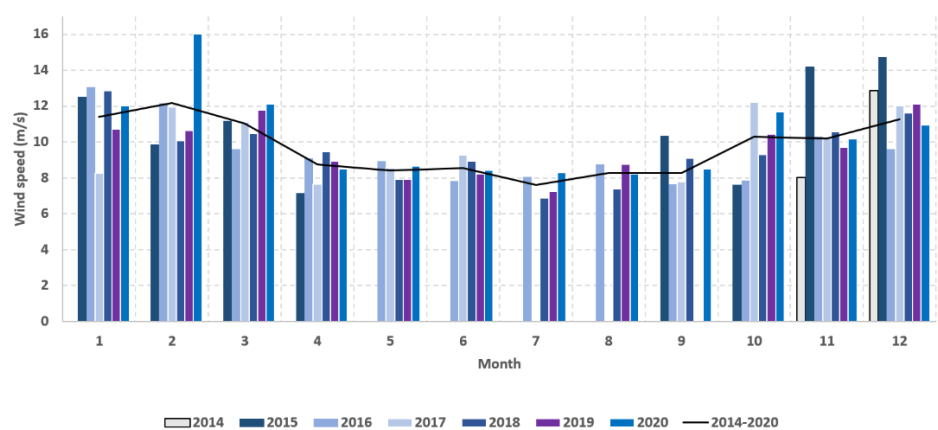


Figure 10 Annual wind speed (m/s) monthly averages bars at 141 m height and 2014-2020 monthly average (black line). Note: measurements started in November 2014; in 2015 date are not available from May to August (Figure 4) that is why the variability in those years is higher.

4.3 Comparison of LiDAR and KNMI measurements

The comparison of the two data measurements of the LiDAR and KNMI met mast at LEG platform is carried out by statistical analysis to evaluate the variability, trend and spread through correlation charts, boxplots and Taylor diagrams. The purpose of this comparison is to check whether the LiDAR has measured correctly by comparing with a nearby source. As well, this source is there for meteorological purposes, but does not meet the wind energy sector's high demand, i.e. it is not IEC compliant (no yearly calibration of sensor, disturbances from structures on the wind measurements, etc.).

The Pearson correlations, P , gauge similarity in pattern between the two datasets. The Figure 12 shows the distribution and scatter plots of the LiDAR at 63 m height and met mast at about 38 m height measurements, before and after the filtering. The outliers and non-valid measurements (0.15% of the total sample) have been filtered out assuming that differences between wind speeds of both datasets higher than 4 m/s are not representative. For example, the effect of an helicopter passing by the platform may have disturbed the measurements at specific 10-minutely interval.

Additional comparison between KNMI and LiDAR measurements is presented in Figure 13. The wind speed duration curves (hourly wind speed values sorted in ascending order) of each dataset are significantly similar, showing that the LiDAR measurements (in blue) registered same variability and spread than KNMI (in orange). In absolute terms, mean and distributions of wind speed and direction are almost identical.

The Taylor diagrams are used to comparatively assess the two different time series with the Pearson correlation coefficient, the root mean square error (RMSE) and the standard deviation (Figure 14). For each dataset, three statistics are plotted: the P coefficient is related to the azimuthal angle; the centered RMSE in the simulated field is proportional to the distance from the point on the x-axis and the standard deviation of the simulated pattern is proportional to the radial distance from the origin. Considering the KNMI dataset as reference, the LiDAR is characterized with normalized standard deviation close to 1 and RMSE ~ 0 , indicating the validity of the dataset, for wind speed (in red) and direction (in blue).

Table 6 Summary descriptive statistics for LiDAR measurements (by TNO) and met mast (by KNMI) at the LEG platform, for 2014-2020.

Ws (m/s)	KNMI (38 m)	LiDAR (63 m)
Mean	7.98	9.25
Max.	27.80	33.02
Std dev.	3.95	4.33
Wd (°)	KNMI (38 m)	LiDAR (63 m)
Mean	197	190
Min./ Max	0 / 360	0 / 360
Std dev.	93	95

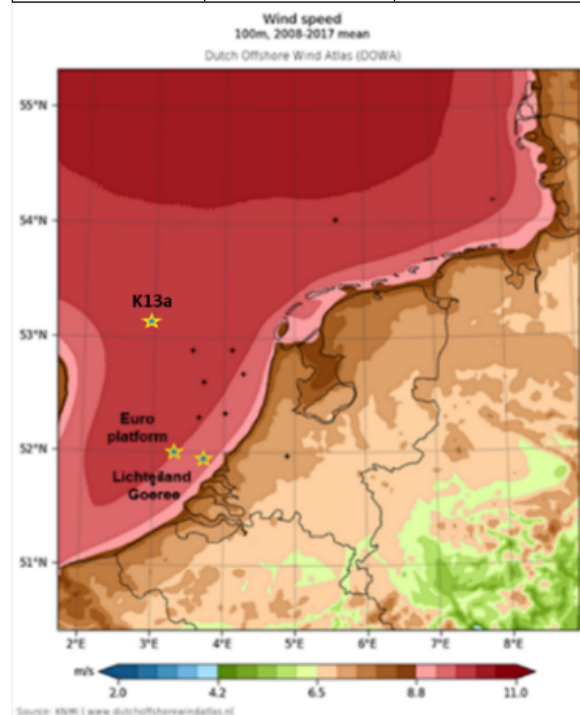
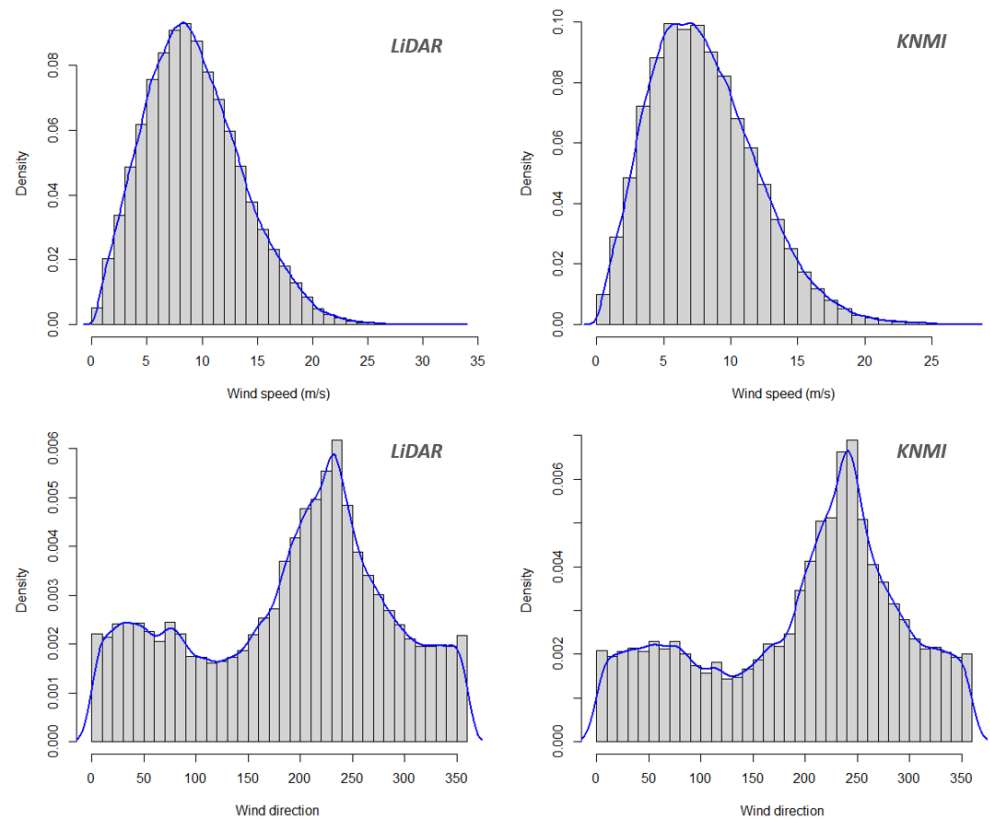
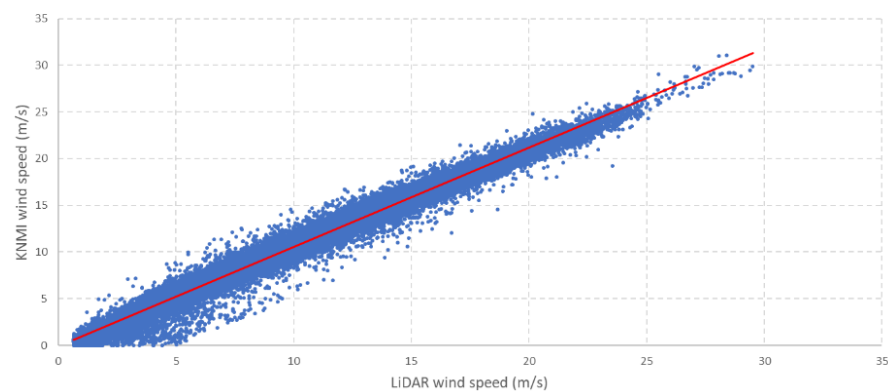


Figure 11 100 m mean wind speed between 2008-2017 provided by the Dutch Offshore Wind Atlas.



a)



b)

Figure 12 (a) Distribution histograms the wind speed (m/s) and wind direction (°) between the LiDAR at 63 m height and KNMI at 38 m height measurements at the LEG platform, before the filtering of the outliers; b) scatter plot between LiDAR (x-axis) and KNMI measurements (y-axis) after the filtering of the outliers.

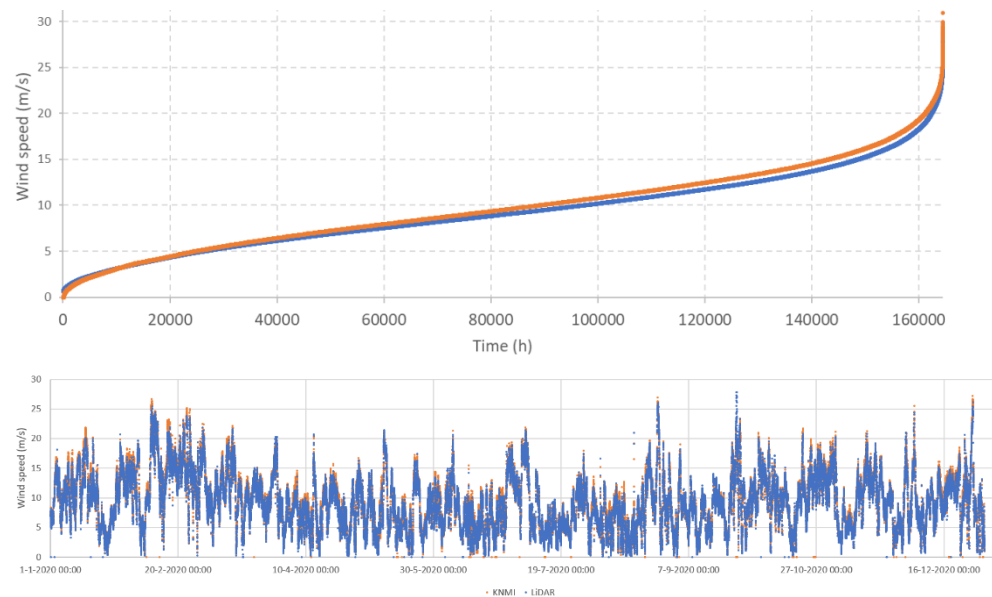


Figure 13 Comparison of the (top) wind speed duration curves for 2020 between LiDAR (blue) and KNMI (orange) and (bottom) time series for the year 2020 between LiDAR (blue) and KNMI (orange) measurements at the LEG platform.

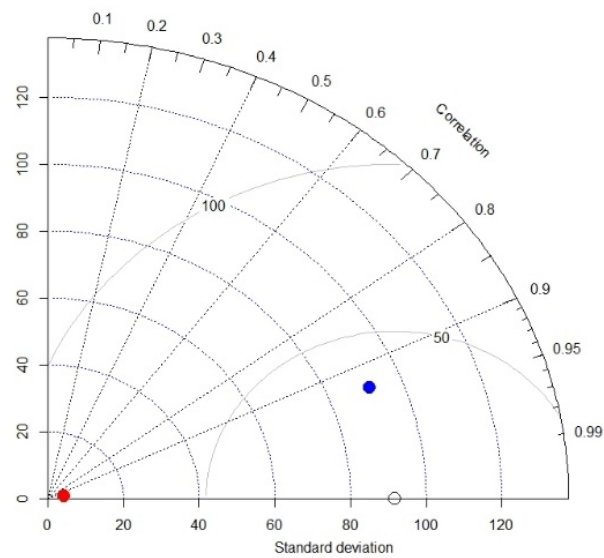


Figure 14 Taylor diagram for wind speed (red) and wind direction (blue) for KNMI as reference and LiDAR at the LEG platform. X and Y axis represent the Standard deviation, white marker represent normalized standard deviation with RMSE ~ 0 and correlation = 1.

4.4 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 figures 15 and 16, after homogenizing by excluding non-available data. Figure 15 shows the Weibull c and k parameters per height averaged over 2016-2020 period. 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, mainly due to the different local situations as distance to shore (Figure 15).

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.

Considering the average and maximum wind speeds at the three platforms at 141 m height, the Figure 16 shows that K13a dataset has a distribution with the highest averaged wind speeds (see the interquartile range - 25p, 50p and 75p – and the whiskers). On the contrary, LEG dataset is characterized by a distribution with the lowest averaged wind speeds. At the extreme values (outliers of the boxplot), average wind speeds distributions follow offshore wind patterns. It is however not at the maximum wind speeds when the outliers are similarly spread. From the basic statistics, the three platforms reflect the expected higher values at K13a, then at EPL and then at LEG. Comparing EPL and LEG performance by the Taylor diagrams and considering the LEG dataset as reference, EPL is characterized with normalized standard deviation close to 1 and RMSE ~ 0 , indicating the validity of both datasets (Figure 17).

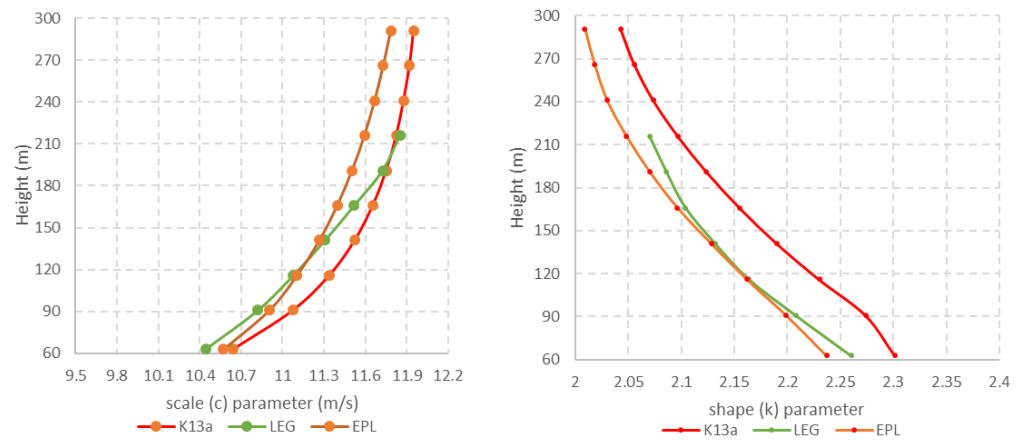


Figure 15 (left) Weibull distribution c and (right) k parameters for all heights at K13a, EPL and LEG over averaged 2016-2020 period.

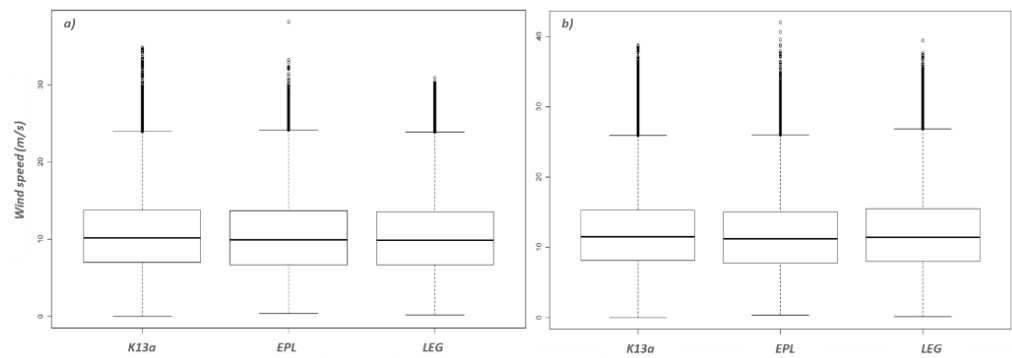


Figure 16 Boxplots of the (left) averaged and (right) maximum wind speed at 141m height at the K13a, EPL and LEG platforms for 2016-2020 period.

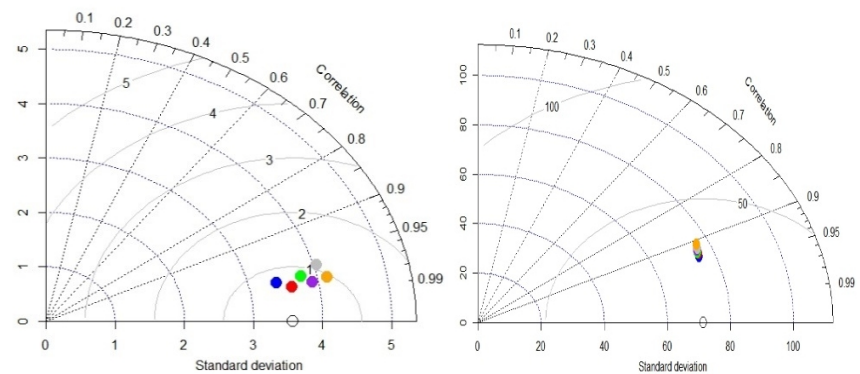


Figure 17 Taylor diagrams for (left) wind speed (m/s) and b) wind (blue = 63m, red = 91m, green = 116 m, purple = 141 m, grey = 166 m, yellow = 191).

4.5 Past weather events

The capacity of the power system with high RES share, the flexibility and storage needs, fluctuations on power prices and the occurrence of the curtailment of a large amount of wind turbines are influenced by the extreme weather situations. In this context, measurement campaigns become a relevant element to assess the energy/power system behavior. This section shows that i) the LiDAR measurement campaign at the LEG platform registered high quality data during wind extreme situations and ii) past extreme weather events have effects on the power system and in the electricity prices, becoming key to understand the future market needs.

4.5.1 LiDAR performance during past extreme events

During winter 2019-2020 several extreme events (five named storms) occurred in the Netherlands, affecting the averaged climatic conditions of the period analyzed, mainly the month of February 2020 - as it has been described in the sections 4.1 to 4.3 *wind conditions*. These extreme events characterized by high winds were also recorded by the LiDAR at the LEG platform, registering pressure drops as well during the storms, aligned with the low pressure systems in the isobar maps (Figure 17-19). Below each extreme event is listed, from “most recent” to “earliest”:

- From the 28th of February to 1st of March 2020, the *storm Jorge* brought further strong winds and heavy rain in late-February. Weather impacts from storm Jorge were in general less severe than previous storms (Ciara and Dennis), but flooding problems continued in the aftermath of these earlier storms and as a result of further rain falling on already saturated ground.
- From the 15th to 16th of February 2020, the *storm Dennis* brought very strong winds, but the worst of the impacts were from the rain. The storm Dennis was driven by a powerful Atlantic jet stream reaching the Netherlands on the 16th of February. The analysis chart indicated that during the storm Dennis the low pressure dominated the north Atlantic with rain-bearing fronts and strong winds sweeping across the UK and the Netherlands.

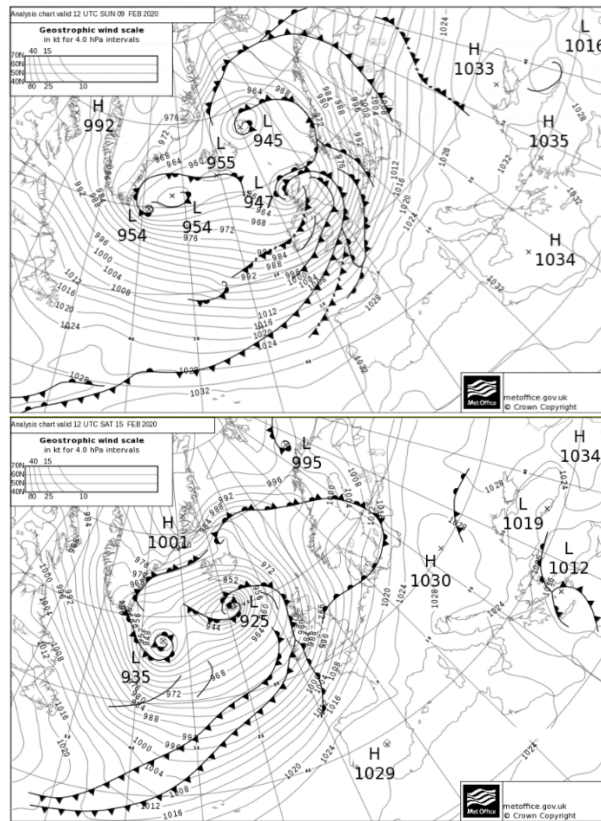


Figure 18 Analysis chart over the North Sea UK and Dutch coast on the a) 9th and b) 16th of February 2020. [image extracted from the Met Office, UK, copyright Met Office / NASA/ NOAA].

- On the 8th and 9th February 2020 the storm Ciara was the third named storm of the 2019/2020 season and the most severe storm of the winter season so far, issuing for both strong wind and heavy rain. In terms of gust speeds this was the most significant storm across the Netherlands overall since winter 2014, bringing also persistent heavy rain.
- 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 19 c and d show the analysis chart at 00 UTC 9 December 2019¹. The rest of December was also characterized by high wind conditions.
- On the 2nd of November 2019, 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 19a) shows the low pressure system moving rapidly east across England and North Sea. The image from the satellite (Figure 19b) on the same day shows the cloud over the North Sea [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/2020/2020_01_storm_brendan.pdf

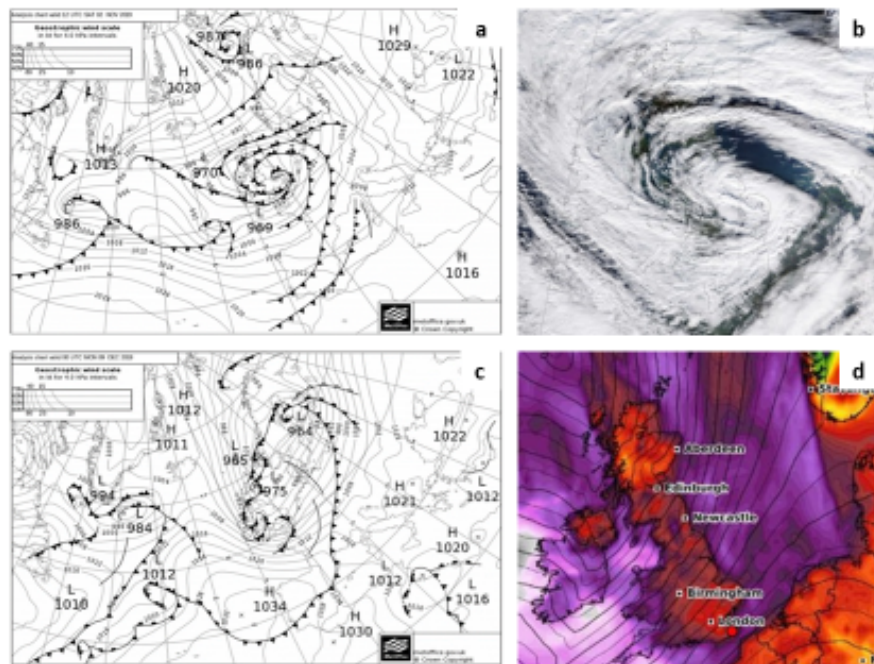


Figure 19 Analysis chart (a) and satellite image (b) over the North Sea UK and Dutch coast on the 2nd of November 2016. C) isobars and d) zooming out the isobars over UK and The Netherlands representing the Atiyah storm on the 8th of December 2019 [image extracted from the Met Office, UK, copyright Met Office / NASA/ NOAA].

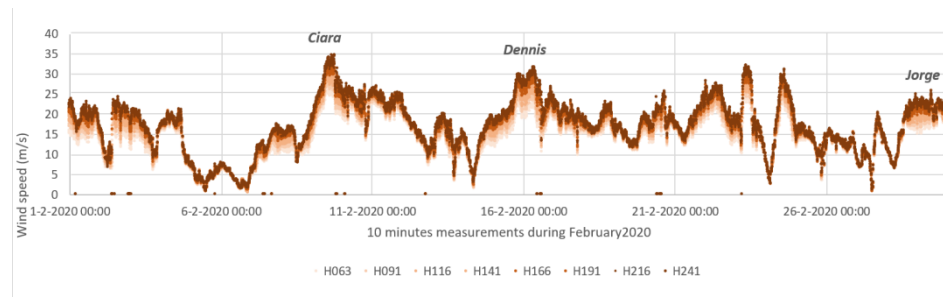


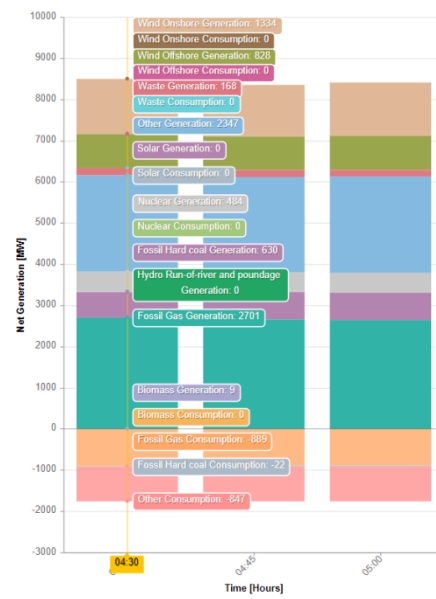
Figure 20 Wind speed (m/s) at different heights measured at LEG during February 2020.

4.5.2 *Effects on the power system and electricity prices fluctuations during February 2020*

During the prevalence of the Ciara storms on the night of the 8th - 9th of February 2020 in the Netherlands, the electricity prices dropped below 5 €/MWh (between 4-6 am) (Figure 21a) when annual average price was about 42 €/MWh ([ENTSO-E dataset](#)). During those hours, the energy mix consist of 2.3 GW RES generation (mainly from onshore and offshore wind), 3.3 GW from conventional sources (gas and coal) and 0.5 GW of nuclear energy (Figure 21b). During that afternoon under calm wind conditions, conventional sources dominated the energy system and the prices reached 45 €/MWh. The energy mixed between 18:00 and 19:00 on the same day consisted of 1.1 GW RES generation, 7.2 GW from conventional sources (6.1 GW gas and 1.1 GW coal) and 0.5 GW of nuclear energy.

The Figure 21.c shows the impact of wind energy on prices, with highest winds, the prices tend to drop.

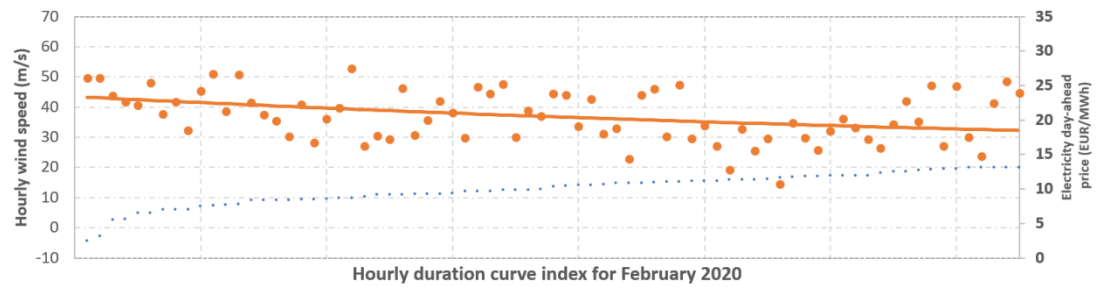
At the end of 2020, the installed capacity of offshore wind was 1.493 GW to be increased to 11.5 GW in 2030 and the ambition of 60GW by 2050. This means that relying on a 95% RES system the weather events will be a driving feature creating more uncertainty in the system, higher volatility on the prices, increasing the flexibility needs and storage requirements.



a)



b)



c)

Figure 21 (a) energy mix at 5 am on the 9th of February 2020 with highest impact of Chiara storm in the Netherlands. (b) Hourly day-ahead prices in the Netherlands during the 9th of February 2020 (day ahead prices [source – ENTSO-E](#)). (c) hourly duration curve of day-ahead prices and hourly wind speeds associated during February 2020.

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 [19] 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 [20].

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 towards a decarbonised system by 2050, 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 22).

- 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 and new available dataset at higher spatial resolution and different heights such as Dutch Offshore Wind Atlas ([DOWA](#)) and New European Wind Atlas ([NEWA](#)). 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 [21], [22].

- 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.**

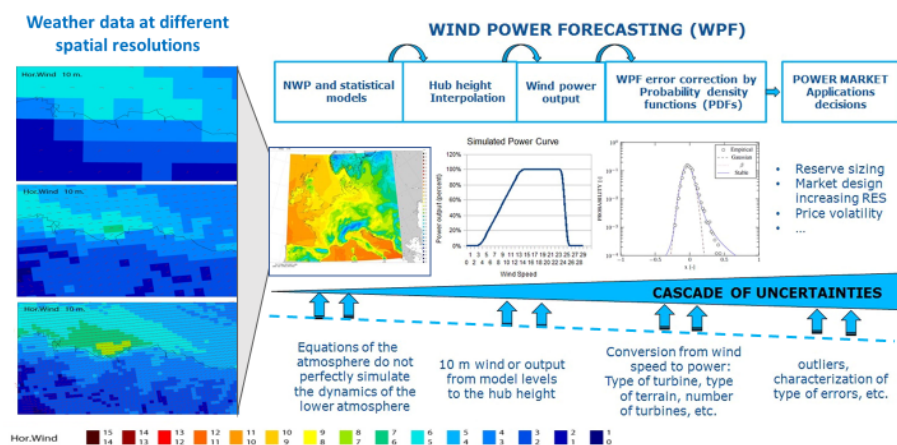


Figure 22 The need of accurate wind resource data and to increase the spatial resolution in power system modelling for more accurate power market applications and decisions.

6 Conclusions

Within the Dutch project “2021 Wind Conditions @ North Sea”, the Dutch Ministry of Economic Affairs and Climate Policy has agreed that TNO performs measurement campaigns in the North Sea from 2014 until 2030 at different locations, reviewed on annual basis. Currently, the locations of the measurements are 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 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 wind analysis for the 2014-2020 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 190° to 199° and the lower and upper quartiles range from 116° 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 ($k = 2.133$ and $c = 11.311$ m/s at 141m height).

The wind speed bell distribution is flattener and moderately skewed right with higher heights, with more frequent wind speeds >26 m/s. 2020 year was atypical year with strong high winds, recorded five extreme events registering storms with wind speeds over 30 m/s at the height of 141m.

These mesoscale events led to bias from the averaged-period conditions on Weibull distributions, statistics and vertical profiles at each site analyzed. The LiDAR was capable to capture the storms measuring wind speeds above 30 m/s at heights above 200m.

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 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 [23]. The LiDAR takes measurements at 10 different heights (Table 5).

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 7 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

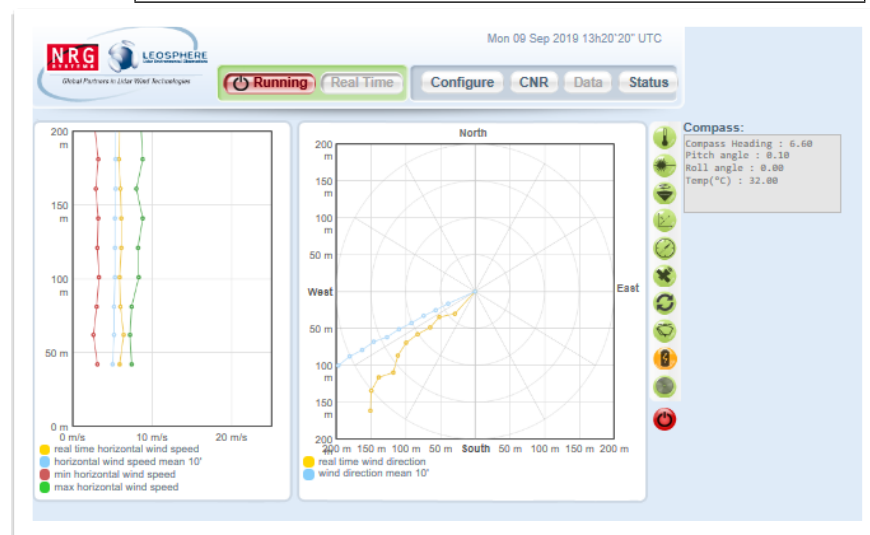
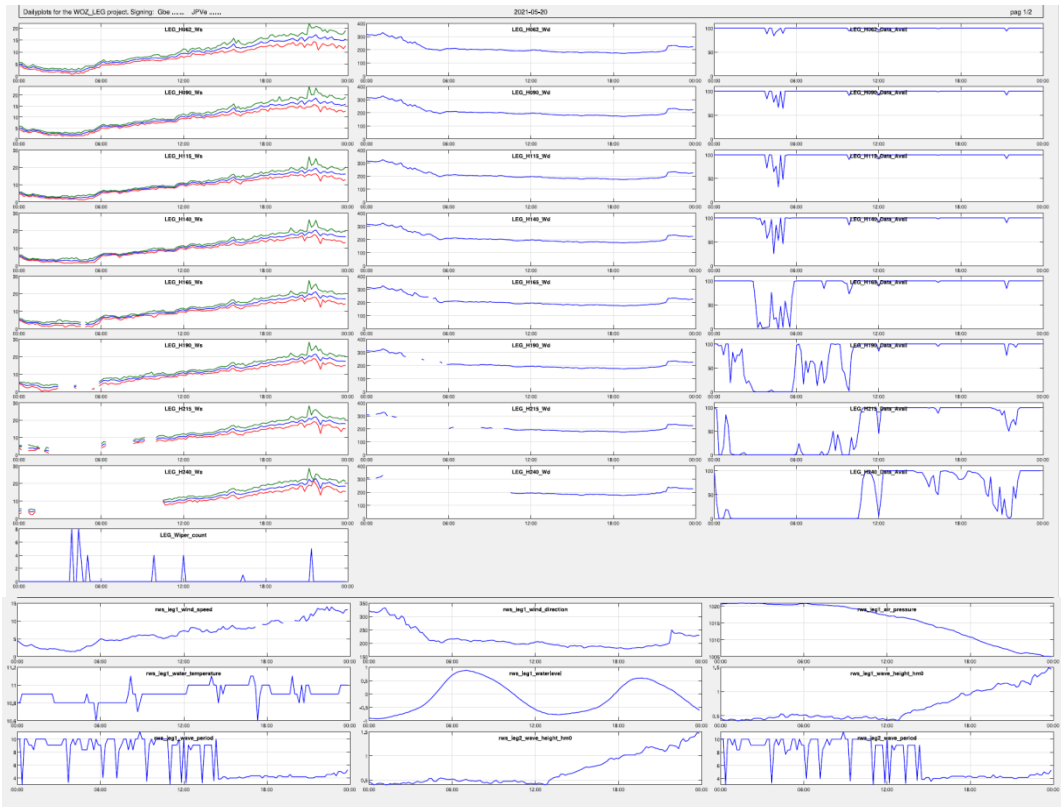


Figure 23 Example of screenshot WINDCUBE V2.

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

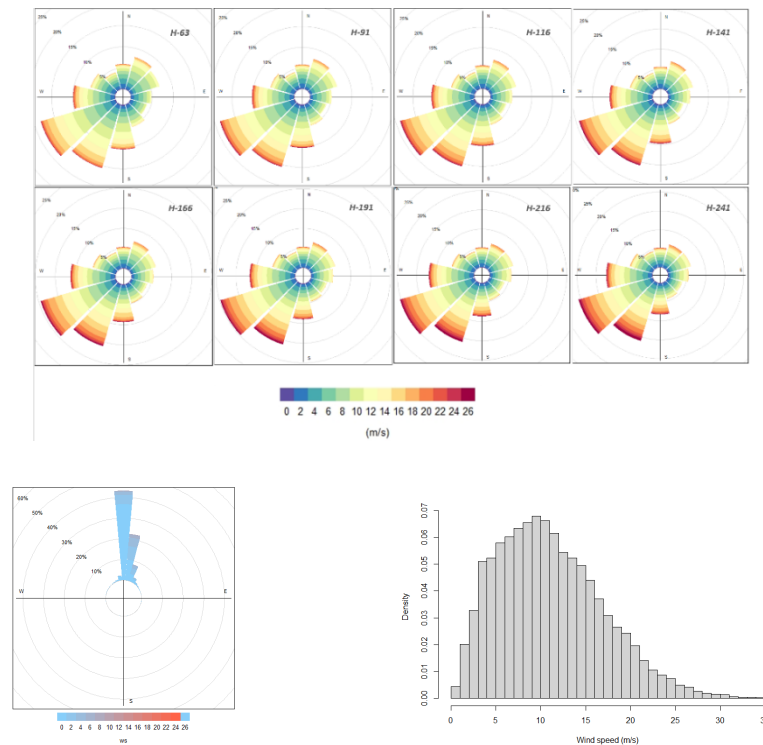
SOFTWARE/DATA

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

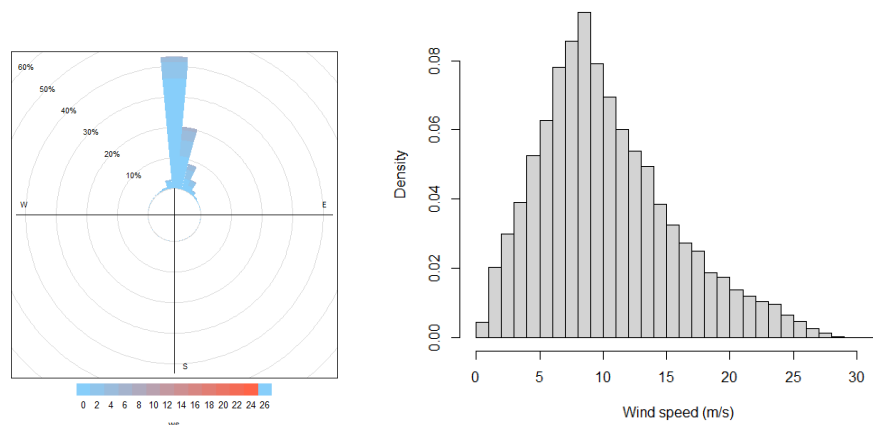
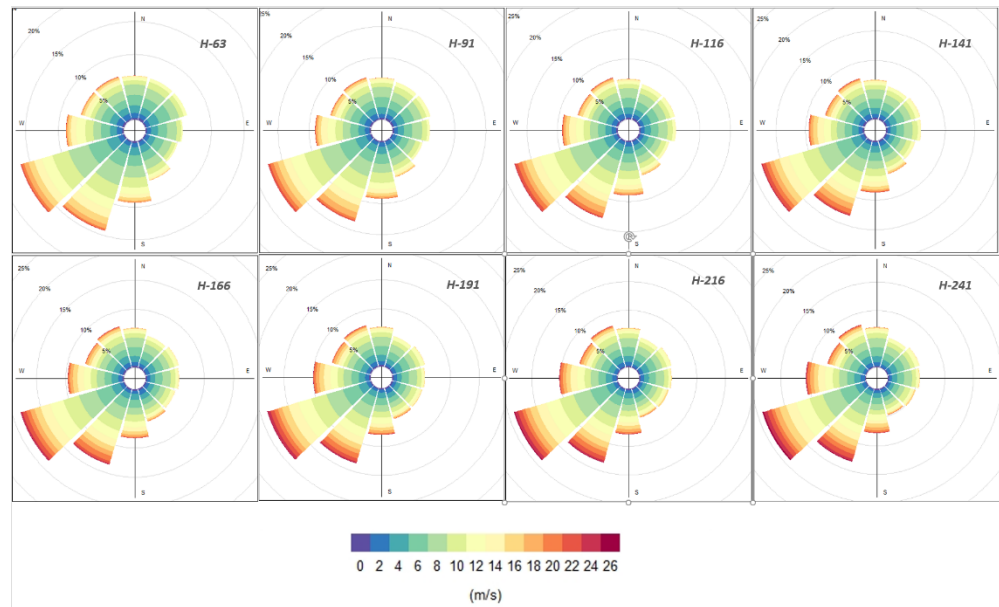
This section contains visual and statistical descriptive summary about the annual weather conditions per year at the LEG from 2020 backwards in time to 2015. The annual prevailing wind direction recorded was South-West, at different heights, as indicated by the wind roses (top). Although the predominant 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 2020



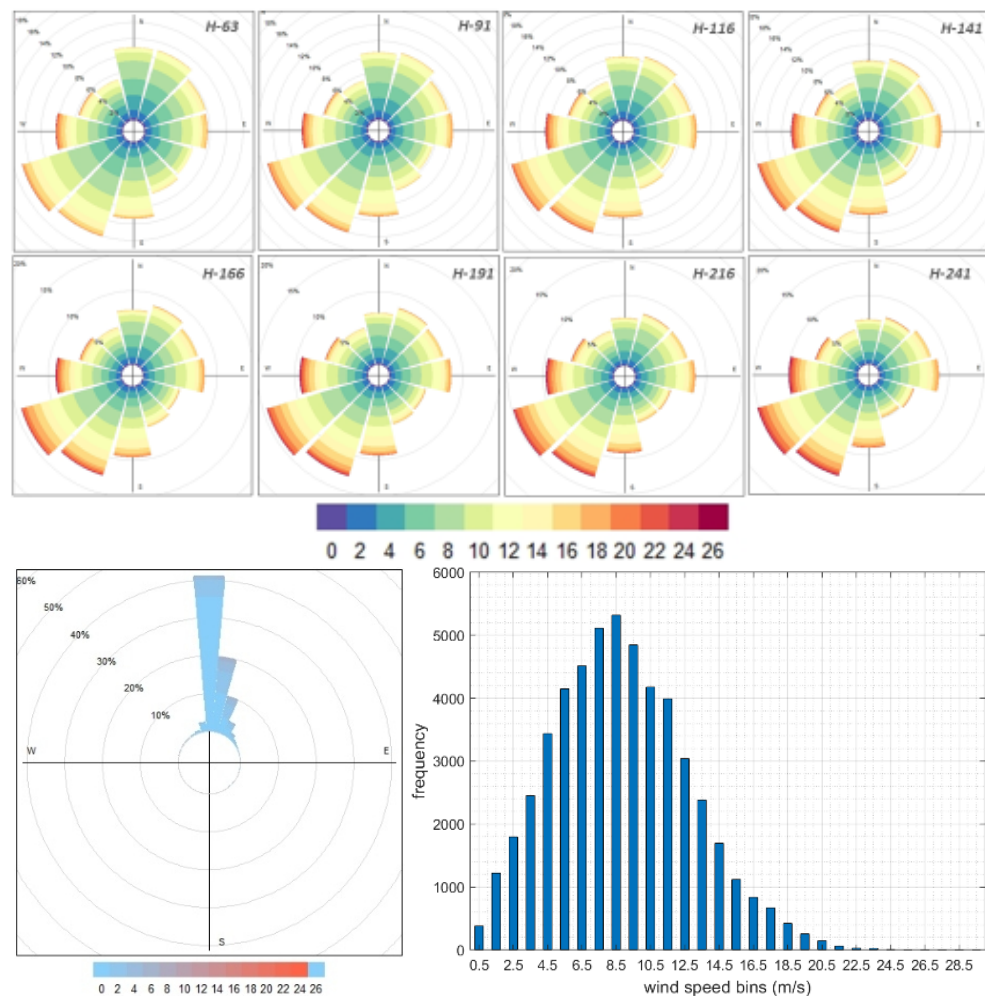
H (m)	63	91	116	141	166	191	216	241
Ws - Min	0.27	0.21	0.13	0.20	0.18	0.21	0.19	0.28
Ws - 1 st q	6.01	6.14	6.18	6.21	6.26	6.31	6.41	6.53
Ws - Median	9.25	9.51	9.67	9.79	9.91	10.02	10.17	10.35
Ws - Mean	9.56	9.89	10.11	10.30	10.47	10.64	10.83	11.04
Ws - 3 rd q	12.57	13.07	13.42	13.74	14.02	14.26	14.52	14.81
Ws - Max	27.18	28.25	29.48	30.37	31.40	32.46	33.58	34.66
Wd - 1 st 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 - 3 rd q	250.50	251.20	252.00	252.50	253.10	253.90	254.80	256.20

B.2 2019



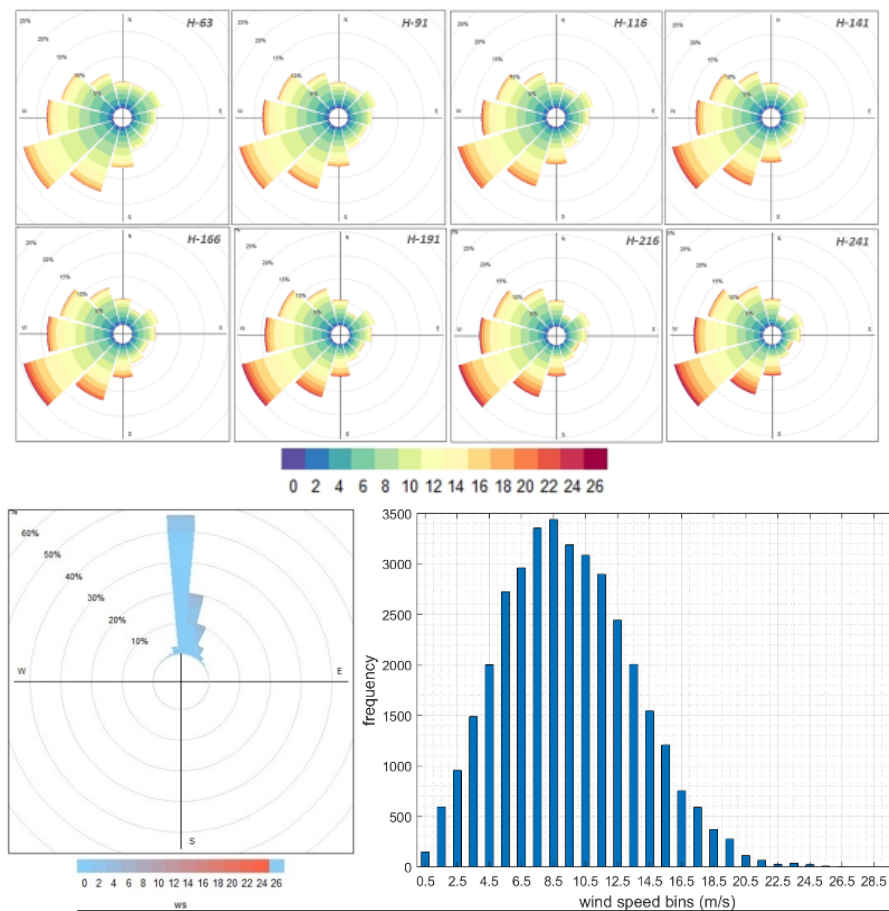
H (m)	63	91	116	141	166	191	216	241
Ws - Min	0.25	0.10	0.23	0.20	0.27	0.19	0.14	0.24
Ws - 1 st q	5.94	6.09	6.15	6.19	6.26	6.34	6.42	6.54
Ws - Median	8.47	8.75	8.87	9.01	9.11	9.20	9.28	9.40
Ws - Mean	8.91	9.25	9.45	9.62	9.79	9.97	10.15	10.34
Ws - 3 rd q	11.36	11.92	12.24	12.51	12.73	12.96	13.20	13.42
Ws - Max	26.65	27.53	28.15	28.89	29.61	30.24	30.74	31.13
Wd - 1 st 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 - 3 rd q	258.80	260.10	261.20	262.00	262.70	263.90	264.60	266.70

B.3 2018



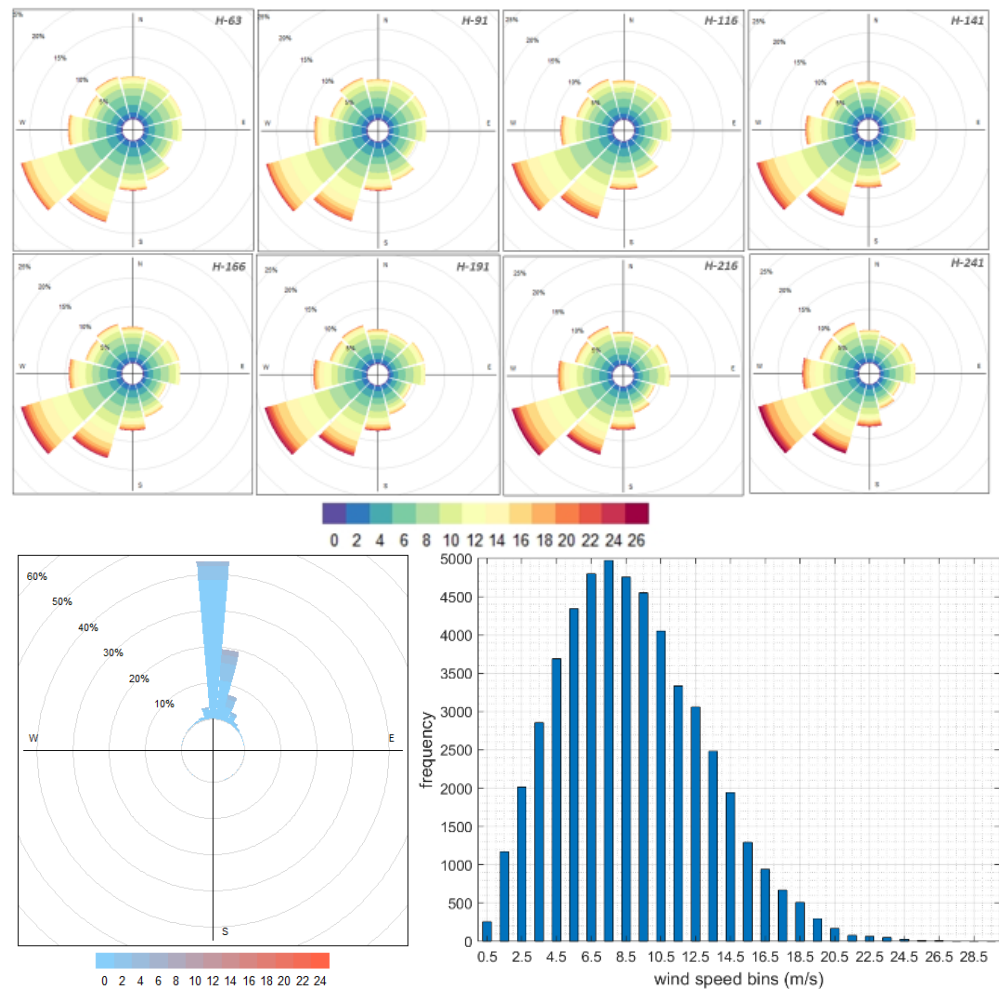
H (m)	63	91	116	141	166	191	216	241
Ws - Min	0.22	0.19	0.23	0.18	0.15	0.15	0.17	0.22
Ws - 1 st q	5.89	6.05	6.13	6.22	6.31	6.39	6.47	6.57
Ws - Median	8.56	8.84	9.02	9.16	9.31	9.44	9.54	9.64
Ws - Mean	8.80	9.15	9.36	9.55	9.72	9.88	10.03	10.19
Ws - 3 rd q	11.41	11.93	12.25	12.52	12.75	12.93	13.08	13.28
Ws - Max	33.02	34.38	35.23	36.08	36.97	37.50	37.91	38.27
Wd - 1 st 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 - 3 rd q	249.20	249.50	249.90	250.20	250.90	251.30	252.30	253.70

B.4 2017



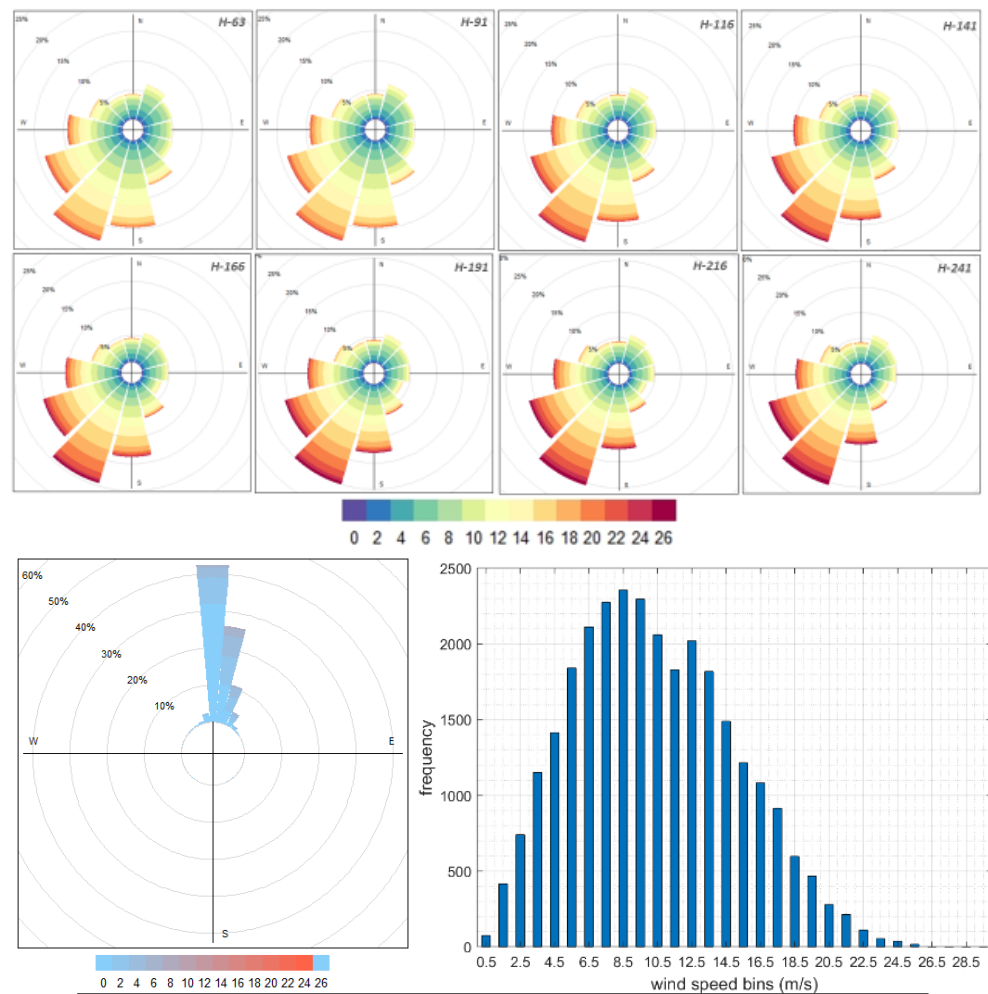
H (m)	63	91	116	141	166	191	216	241
Ws - Min	0.27	0.12	0.19	0.14	0.19	0.22	0.26	0.38
Ws - 1 st q	6.40	6.57	6.65	6.75	6.91	7.02	7.16	7.29
Ws - Median	9.13	9.46	9.69	9.88	10.05	10.17	10.34	10.51
Ws - Mean	9.40	9.75	10.00	10.23	10.45	10.64	10.82	11.01
Ws - 3 rd q	12.12	12.69	13.05	13.36	13.67	13.91	14.09	14.29
Ws - Max	27.52	29.06	30.06	30.90	31.51	32.14	32.57	32.98
Wd - 1 st 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 - 3 rd q	275.20	276.80	278.00	279.60	281.10	282.80	284.50	286.70

B.5 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 - 1 st 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 - 3 rd 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 - 1 st 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 - 3 rd q	257.50	257.50	257.70	257.90	258.30	259.50	262.00	264.70

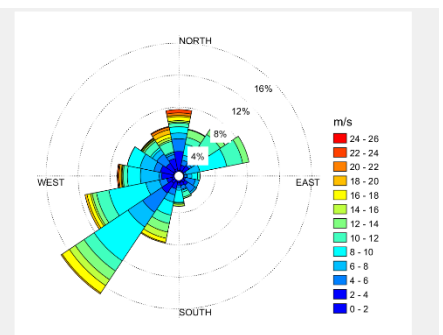
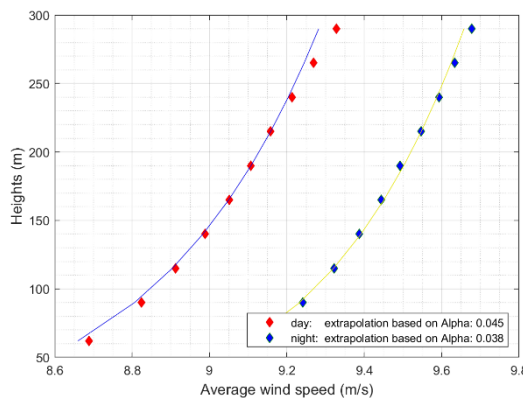
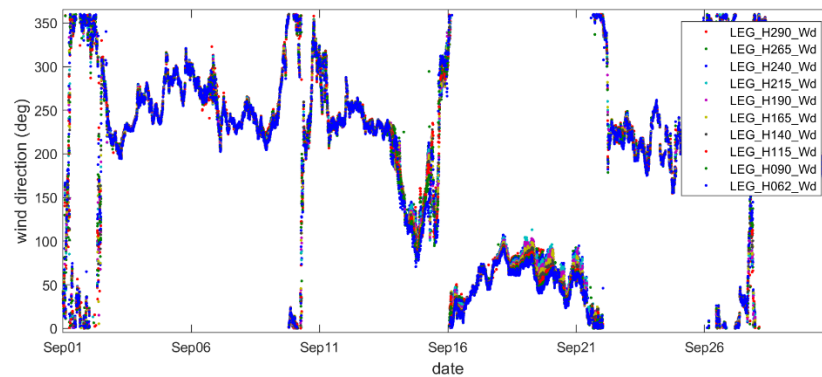
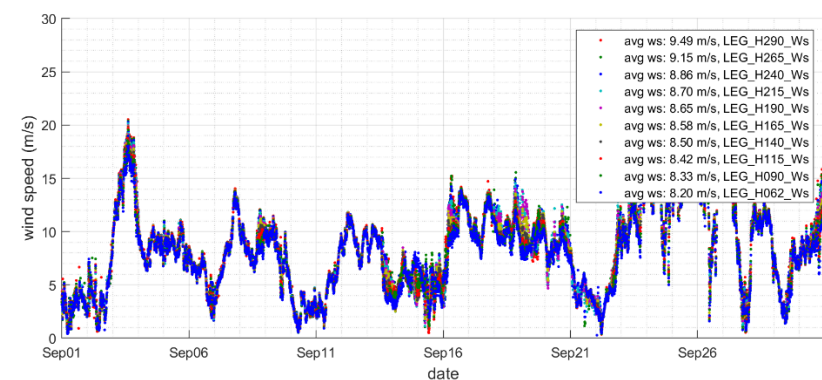
B.6 2015

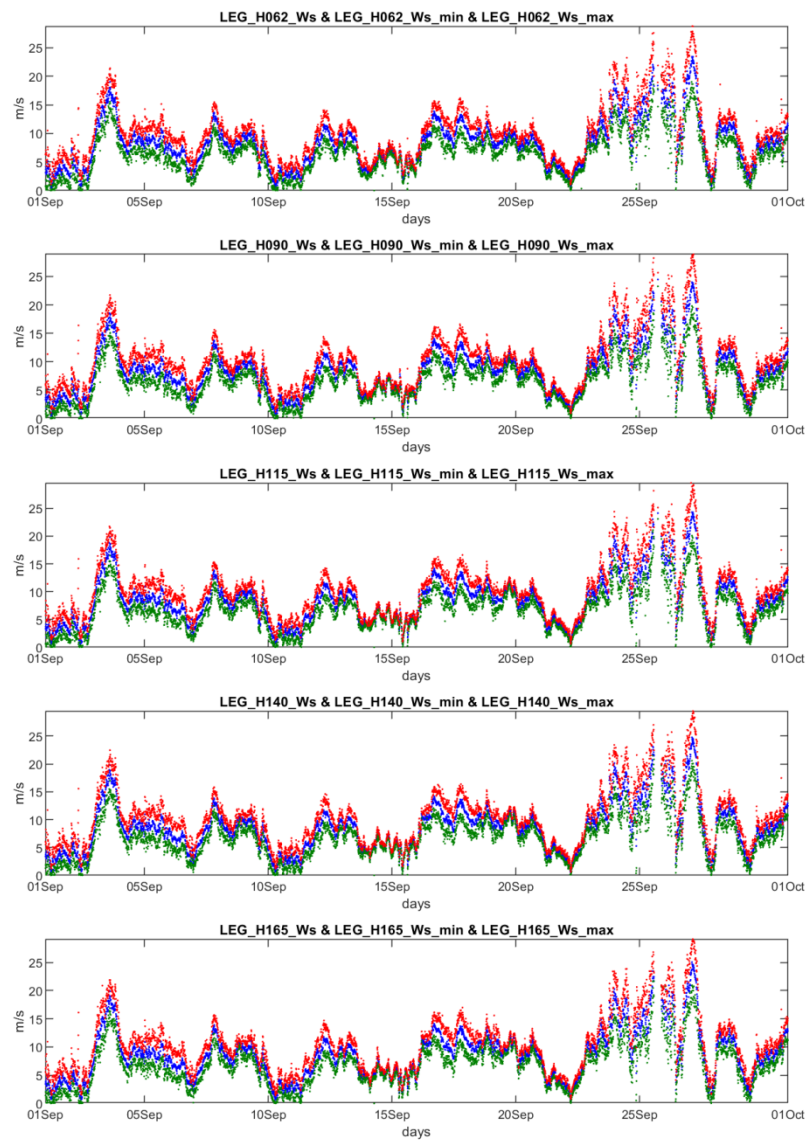


H (m)	63	91	116	141	166	191	216	241
Ws - Min	0.50	0.50	0.23	0.26	0.28	0.20	0.24	0.25
Ws - 1st q	6.72	6.93	7.08	7.23	7.32	7.43	7.52	7.57
Ws - Median	9.87	10.30	10.60	10.87	11.07	11.27	11.44	11.59
Ws - Mean	10.30	10.76	11.11	11.42	11.67	11.89	12.10	12.28
Ws - 3rd q	13.54	14.27	14.81	15.28	15.68	16.02	16.30	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

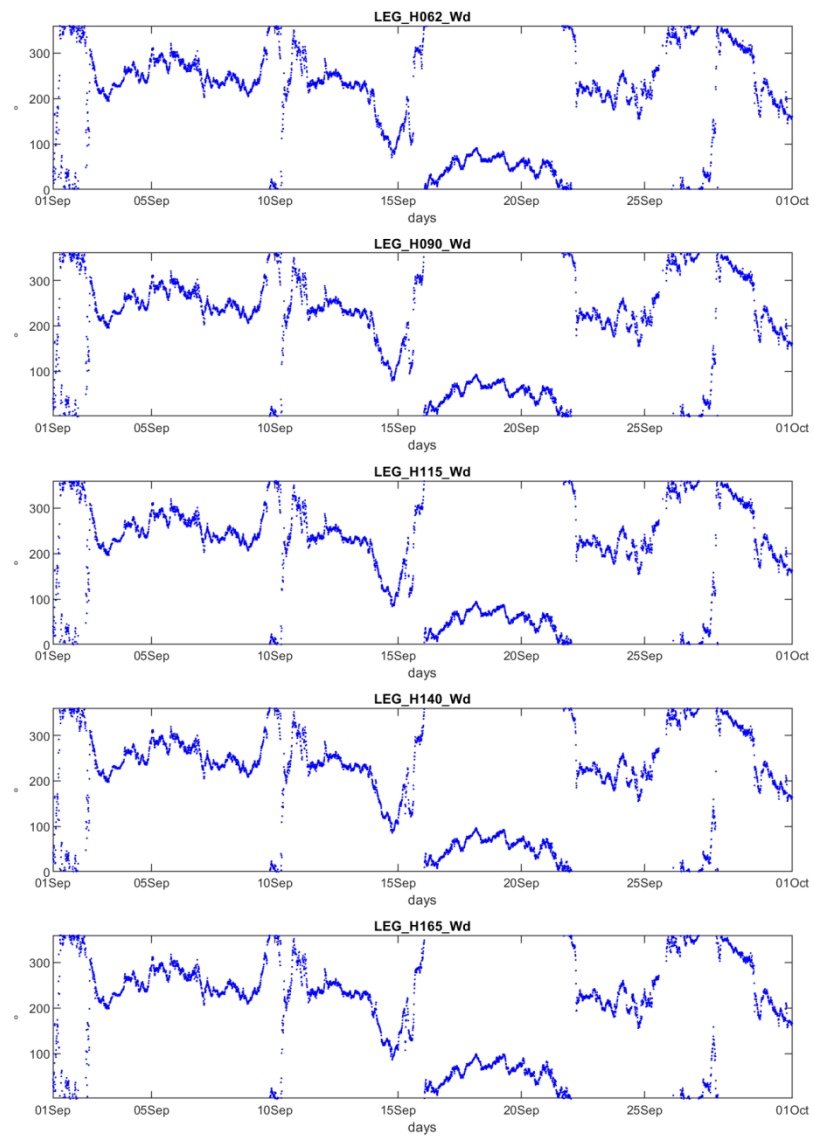
C Weather conditions analyses during the monthly reporting

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 were also analysed each month. The figures below show visual examples of the monthly reporting in September 2020 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