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Offshore wind energy deployment in the North Sea by 2030: long-term measurement campaign. EPL, 2016-2020

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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 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 *'Wind op Zee' 2021*.

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 EPL from 2016 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 wind speeds above 35 m/s at heights above 200m.

The accuracy and high quality data obtained, render this 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 at least 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.

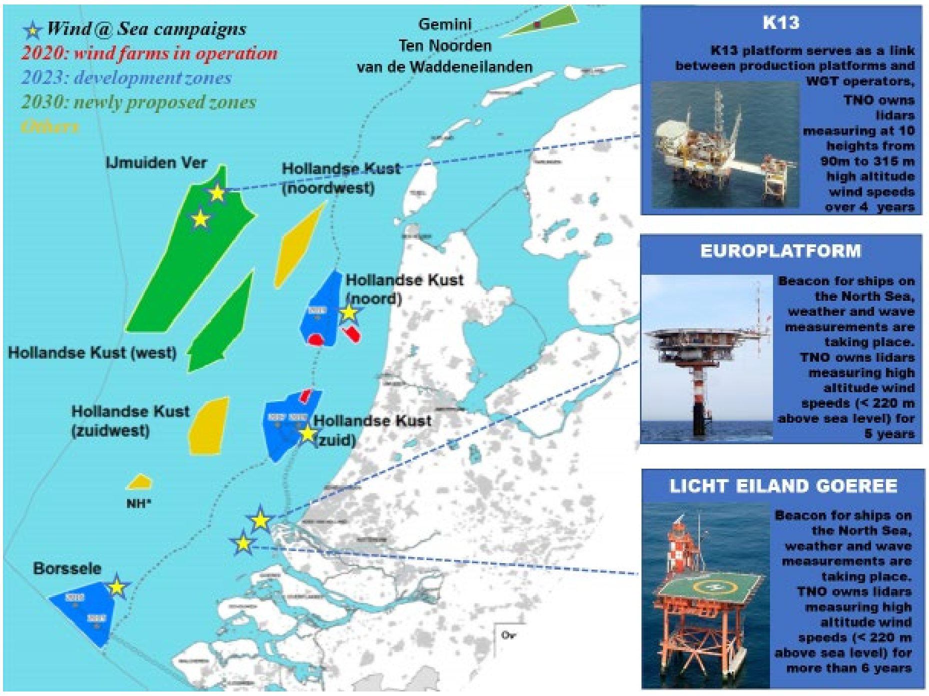


Figure 1 Locations of current and future offshore Dutch wind farms and measurement campaigns executed by TNO under the Wind@Sea framework over the Dutch North Sea.

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.

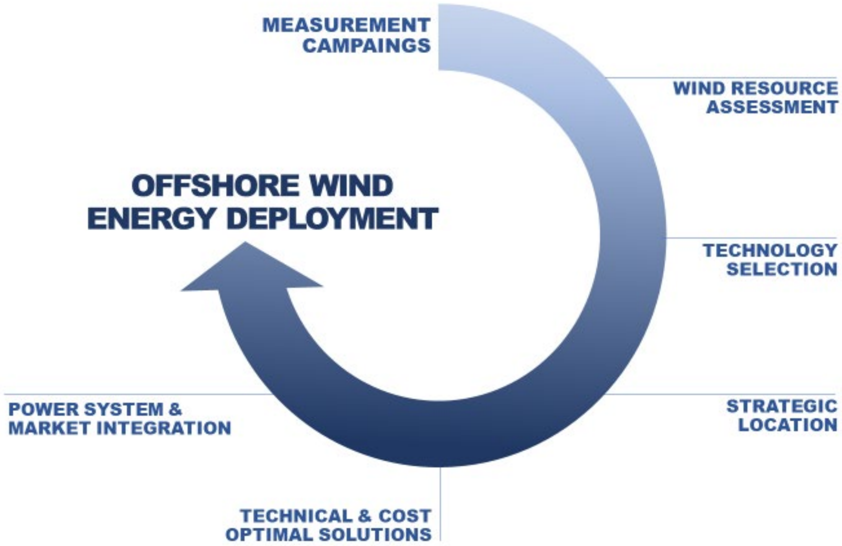


Figure 2 Process to ensure the profitability of the wind offshore deployment.

Under the Dutch wind offshore future plans, the Dutch Ministry of Economic Affairs and Climate Policy has agreed that within the *'Wind op Zee' 2021* 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 2019. The reports [3] and [4] include wind conditions analysis for the K13a platform; [5] for the LEG platform and [6] for the EPL platform. This report includes the wind conditions for 2020 at the EPL platform. 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. 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 *'Wind op Zee' 2021* project are retrieved and post-processed before making the information publicly accessible through the web-service https://www.windopzee.net/. 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 *'Wind op Zee' 2021* 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., Werkhoven E., P.A. van de Werff (2020) Europlatform LiDAR measurement campaign; Instrumentation Report, TNO 2020 R10867
2. Citation of this report:
   Gonzalez-Aparicio, I., Pian A., Verhoef J.P., Bergman G., P.A., van der Werff (2021) Offshore wind energy deployment in the North Sea by 2030: long-term measurement campaign. EPL 2016-2020. TNO 2021 R10919

Indicate in the publication the date at which the data have last been accessed in the publication (e.g. *Last accessed May 2021*).
The data is shared in .csv format. In the case of the EPL measurement campaign: https://www.windopzee.net/en/locations/k13a/data/

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

2 Measurement campaign at EPL

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 [7]. 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 Europlatform (EPL) is located about 45 km from the coast of Hoek van Holland. It includes a helicopter pad and an accommodation deck (Figure 3a). The platform is part of the North Sea Monitoring Network consisting of several permanent monitoring locations. 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) since the early 1980s [8]. These activities are coordinated by the weather meteorological agency (KNMI) and Rijkswaterstaat, Dutch Ministry of Infrastructure and the Water management.

Figure 3 a) Front and b) top view of Europlatform platform (geographical coordinates 51° 59' 52.512" N, 3° 16' 29.316" E) including a helicopter deck at a height of 18.78m above mean sea level with an accommodation deck below; c) original escape ladder location before the LiDAR installation and d) newly built extension to install the LiDAR.

2.2 Onsite installation and operational status

The LiDAR selected is the ZX 300 LiDAR. The instrument measures wind profiles across up to 10 different heights by conically emitting a laser beam into the air, even if an object blocks the laser beam at some positions (see Annex A for additional LiDAR specifications). Before the installation, the LiDAR was first verified at the TNO RSD Verification Facility [9], [10]. To ensure good quality measurements it is crucial to select the right location for the LiDAR on the platform. At EPL, the suitable place was found in the west side of the platform in a newly built extension of an escape ladder between the landing and the deck (Figure 3c, d). The LiDAR was installed with the ‘North’ marker pointing towards the platform [7].

The LiDAR was installed to provide measurements at 10 different heights between 63 m and 300 m above mean sea level. The data is timestamped at the start of 10 minute time frame. This is the same configuration as for the LiDAR at the LEG and K13a platforms. Manufacturers guarantee data quality up to 200 m above the LiDAR although the ZX300 can measure beyond that height too. The analysis of the data at highest levels shows the same quality patterns as at the guaranteed heights (see section 3 and 4). Two different electrical connections are required in order to have the LiDAR fully operational. Firstly, 230V AC power supply connection, provided at the computer room of the platform where the AC-DC power converter of the LiDAR is placed. Secondly, a network connection. The LiDAR is connected by ethernet cable to a TNO laptop located in the computer room.

As defined by TNO’s ISO17025 quality system, the LiDAR should be serviced after one year of operation (Table 1). However, since the start of the campaign at this location, daily control and monitoring of the data show that the device is measuring at the same accuracy without any issue. All operational aspects with respect to installing and maintaining the LiDAR are recorded in a logbook of the team responsible for the measurement campaign.

Table 1 Replacements of LiDAR at the EPL platform.

Id LiDAR	LiDAR in operation	Planned replacement
U308	10-05-2016 to 02-08-2018	First LiDAR operational
U315	02-08-2018 to 23-10-2019	Malfunction power supply of LiDAR
U308	23-10-2019 – Oct. 2021	Periodically replacement with the original LiDAR inspected and verified its performance.

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.
- Toolbox meetings among the teams to agree on the alignment of the preparation at the platform.
- TNO employees have valid GWO climbing 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. Continuous quality assurance and control techniques are applied during the measurement campaign. Data measured are classified into two categories:

- **System availability**, independent to the height such as internal temperature and humidity of the LiDAR, bearing, tilt angle and battery voltage.
- **Signal availability** at different heights such as wind speed and direction, horizontal and vertical and the standard deviation of wind, temperature, relative humidity and pressure (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 starting the data collection from the 31st May 2016 at 00 UTC (Universal Time Coordinates). This report includes a period until the 31st of December 2020 at 23:50 hr. UTC although the campaign will run at least until 2030.

Table 2 List of variables measured in the LiDAR during the experimental campaign. Where EPL 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.

Signal name	Meaning	Unit
EPL_batvoltage	Battery Voltage	V
EPL_tempmax	Maximum temperature inside the LiDAR	deg C
EPL_tempmin	Minimum temperature inside the LiDAR	deg C
EPL_tempcpu	CPU temperature inside the LiDAR	deg C
EPL_humpod	Relative Humidity inside the LiDAR	%
EPL_bearing	LiDAR Bearing	Deg
EPL_tilt	LiDAR tilt angle	Deg
EPL_tair	Air temperature at LiDAR position	Deg
EPL_pair	Air Pressure at LiDAR position	hPa
EPL_rh	Relative humidity at LiDAR position	%
EPL_wsmet	Wind speed measured by LiDAR meteo station	m/s
EPL_wdmet	Wind direction measured by LiDAR meteo station	Deg
EPL_rain	Precipitation measured by the LiDAR meteo station	%
EPL_HXXX_npts	Measuring points	
EPL_HXXX_missed	Missed points	
EPL_HXXX_npackets	Packets in fit	
EPL_HXXX_wd	Wind direction	Deg
EPL_HXXX_wshor_av	Horizontal wind speed average	m/s
EPL_HXXX_Wshor_sd	Horizontal wind speed standard deviation	m/s
EPL_HXXX_Wshor_min	Horizontal wind speed minimum	m/s
EPL_HXXX_Wshor_max	Horizontal wind speed maximum	m/s
EPL_HXXX_Ws_ver	Vertical wind speed average	m/s
EPL_HXXX_spvar	Spatial variation	
EPL_HXXX_cs	CS	
EPL_HXXX_bs	Back Scatter	
EPL_HXXX_hconf	Horizontal confidence	

The ZX 300 does not determine the direction of the Doppler shift in the received series and there is a 180° ambiguity in the wind direction. Therefore, the attached met station with wind speed and direction measurements (EPL_wsmet and EPL_wdmet, Table 2) is used to correct the 180° offset (See Annex A for more specifications). The overall system availability and the overall data availability for the whole campaign is evaluated following [8], based on the Offshore Wind Accelerator roadmap [11].

As indicated in Figure 4 and Table 3 (and Annex A); in contrast with the LEG measurements, the data availability with the ZX 300M at the K13a and the ZX 300 at EPL platforms is independent of the height. The LiDAR provides data at all heights for the full period analysed. The estimation of the measured availability follows the approach by [9]. Furthermore, Table 3 shows a lower availability of the signal for the last three years, despite the yellow colour which defines an availability lower than 90%, the signal measured has enough availability to let the LiDAR operating. The lower availability is related to the LiDAR characteristics of the wiper.

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 (%)	H191 (%)	H 216 (%)	H 241 (%)	H 266 (%)	H291 (%)
2016	90.8	90.8	90.8	90.8	90.8	90.8	90.9	90.9	90.2	91.0
2017	92.0	92.0	92.0	92.0	92.0	92.0	92.0	92.0	92.0	92.0
2018	78.8	78.8	78.8	78.8	78.8	78.8	78.8	78.8	78.8	78.8
2019	56.8	56.8	56.8	56.8	56.8	56.8	56.8	56.8	56.8	56.8
2020	68.5	71.2	72.5	72.5	72.5	74.0	67.8	76.4	64.5	61.2

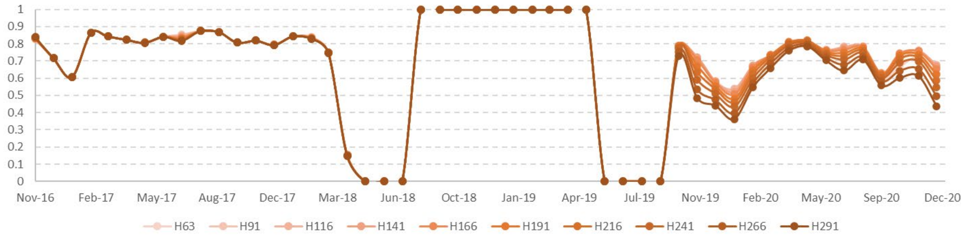


Figure 4 Monthly averages of the data available (%) measured by the ZX 300 LiDAR by height at the EPL platform.

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.

There are complementary reports with data verification comparing with other measurements. In particular, [12] examines the wind speed and direction measurements campaigns during 2012-2018 at eight offshore measurement locations distributed throughout the North Sea, including the EPL, with the aim of better understanding the wind conditions over the North Sea. The chapter 4.3 of this report includes the data measured comparison with the KNMI observations.

4 Wind conditions at EPL platform

This section provides an overview of the weather conditions during the campaign at the EPL platform for the entire period 2016-2020 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 EPL 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 2016-2020

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 [13], [14].

At the EPL platform, the weather analysis for 2016-2020 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 193° to 198° and the lower and upper quartiles range from 129° to 261° 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 2016-2020 period at the EPL platform.

H (m)	63	91	116	141	166	191	216	241	266	291
Ws - Min	0.42	0.32	0.33	0.34	0.32	0.31	0.31	0.32	0.31	0.31
Ws – 1st quartile	6.08	6.18	6.24	6.27	6.28	6.30	6.33	6.35	6.37	6.41
Ws - Median	9.01	9.26	9.38	9.46	9.52	9.56	9.59	9..60	9.62	9.64
Ws - Mean	**9.37**	**9.66**	**9.84**	**9.98**	**10.10**	**10.19**	**10.27**	**10.33**	**10.39**	**10.44**
Ws - 3rd quartile	12.24	12.71	12.99	13.20	13.37	13.48	13.59	13.66	13.72	13.76
Ws -98 p	19.38	20.13	20.72	21.30	21.86	22.38	22.80	23.13	23.44	23.68
Ws - Max	39.07	39.16	38.56	38.17	39.22	36.28	42.47	47.06	56.89	44.28
Wd - 1st quartile	129	132	134	136	136	137	138	138	139	139
Wd - Median	208	210	210	211	212	213	214	215	215	216
Wd - Mean	**193**	**194**	**195**	**195**	**196**	**196**	**197**	**197**	**198**	**198**
Wd - 3rd quartile	255	256	257	257	258	258	259	259	260	261

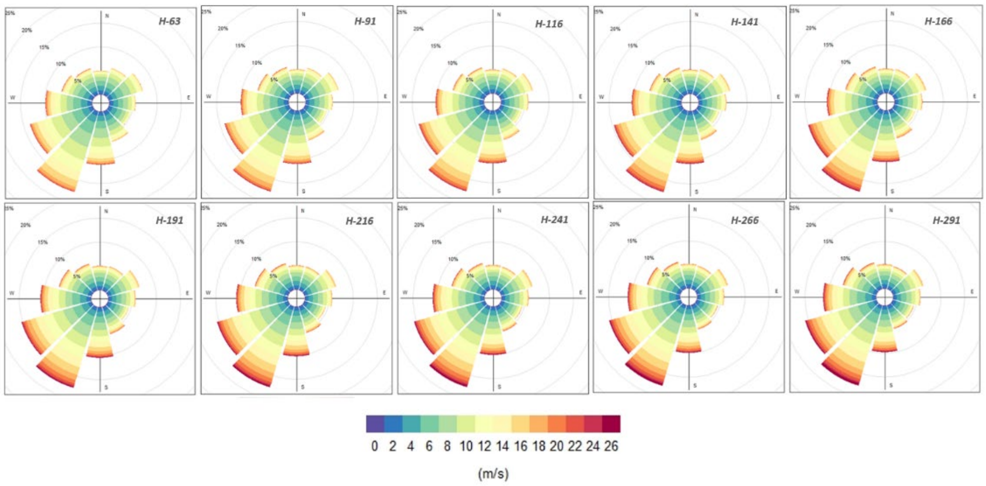
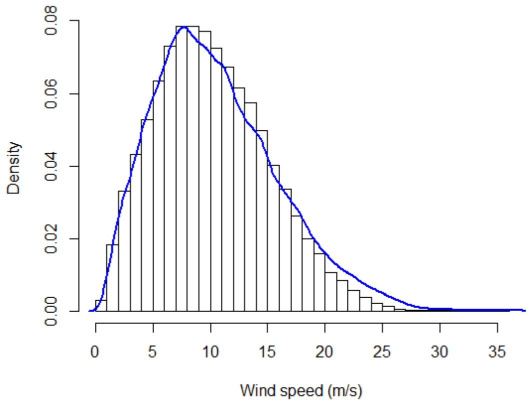


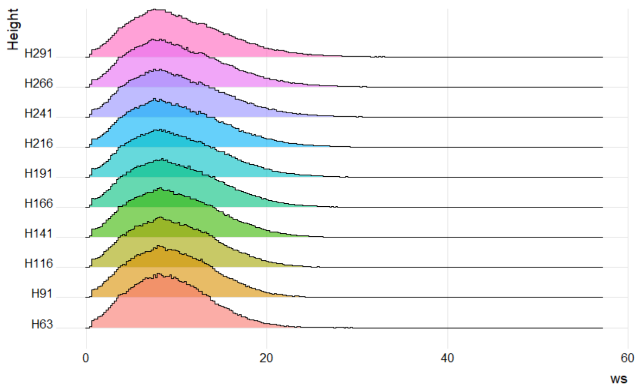
Figure 5 Wind roses at different heights showing the wind prevailing direction for the 2016 -2020 period.

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:

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

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 EPL, during the period 2016-2020, the Weibull distribution show that k = 2.129 and c = 11.271 m/s at 141 m height (Figure 6a). The Figure 6b indicates how the distribution is flattening and moderately skewed right with higher heights including the k and c parameters for each height. For the 2016-2020 period at 141 m height, the k parameter is similar to the k at LEG and K13a platforms.





Height (m)	Shape (k)	Scale (c)
63	2.238	10.575
91	2.200	10.908
116	2.163	11.109
141	2.129	11.271
166	2.097	11.400
191	2.071	11.507
216	2.049	11.598
241	2.030	11.671
266	2.019	11.734
291	2.009	11.788

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 EPL for 2016-2020.

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 [15].

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 EPL platform, the offshore wind speeds vary within margins of about 0.5 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 [12], [16] 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.

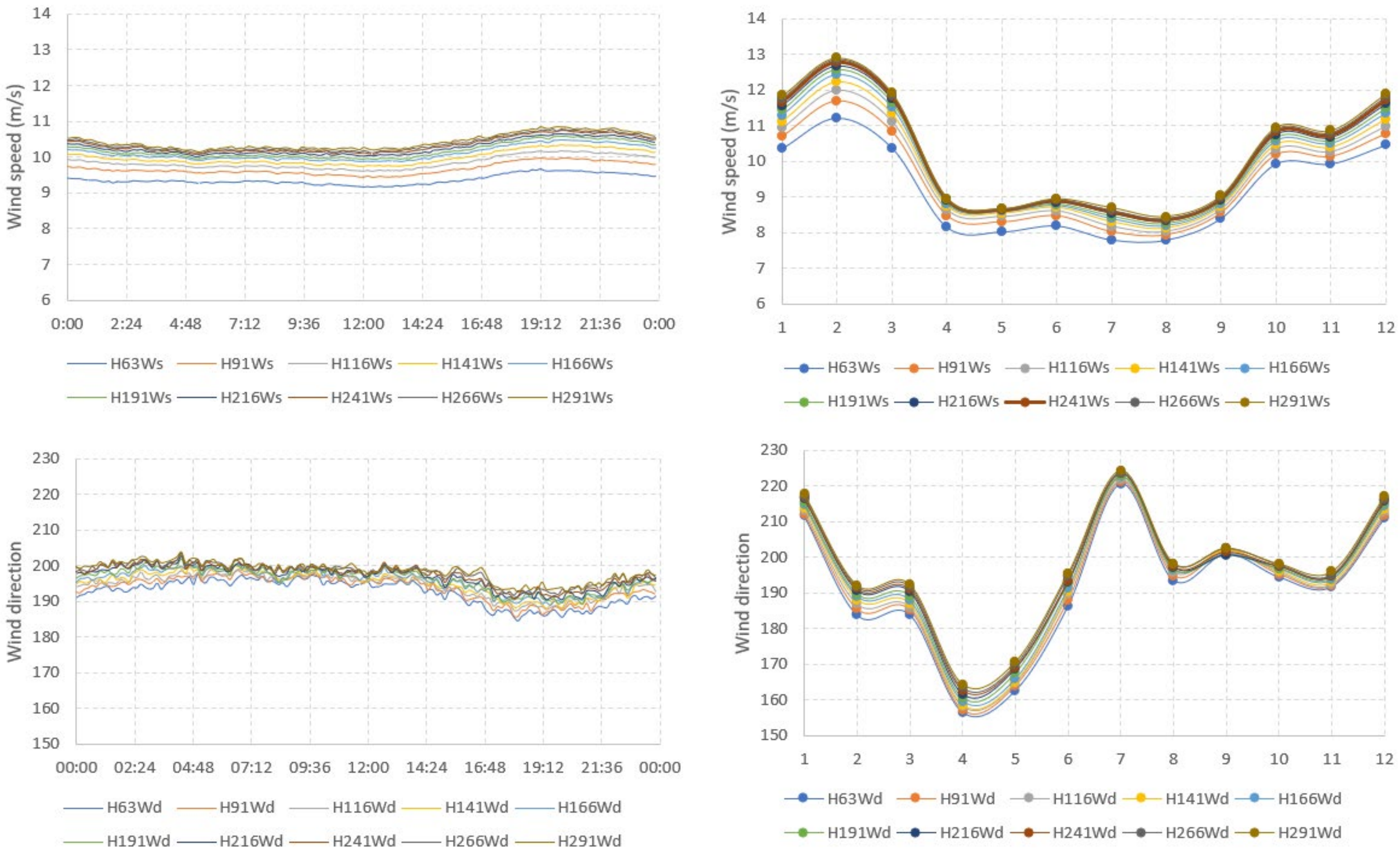


Figure 7(right) Monthly wind speed and direction averages and (left) daily cycle averages at different heights for the 2016-2020 period.

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).

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 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 LEG and K13a platform, indicating that the main influence comes from the regional patterns. The annex B includes additional annual wind analysis and statistics for the EPL platform.

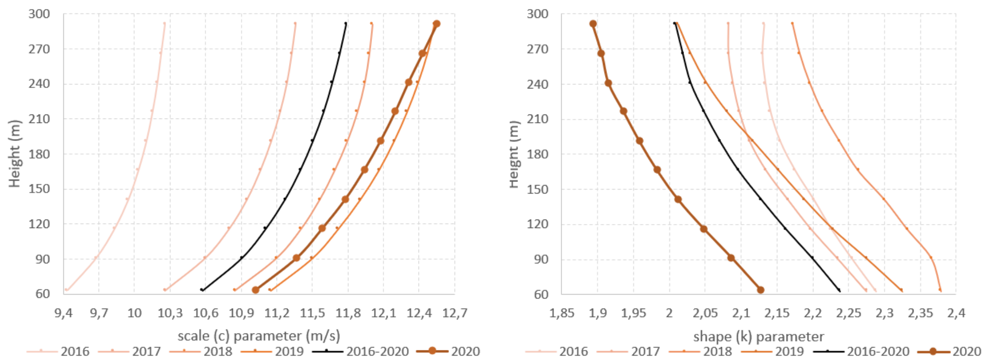


Figure 8 Annual Weibull (left) scale and (right) shape parameters at different heights at the EPL platform from 2016 to 2020.

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

H141 (m)	2016	2017	2018	2019	2020
Ws (m/s)- Min	0.675	0.675	0.661	0.452	0.344
Ws (m/s)– 1st q	5.938	6.097	6.754	6.840	6.312
Ws (m/s)-Median	8.952	9.241	9.852	9.968	9.955
Ws (m/s)- Mean	**9.426**	**9.697**	**10.246**	**10.543**	**10.448**
Ws (m/s)- 3rd q	12.464	12.918	13.410	13.845	13.962
Ws (m/s)– Max	31.854	30.164	38.174	29.100	33.232
Wd (°)- 1st q	139.6	156.7	121.7	139.0	126.9
Wd (°) Median	215.9	220.7	195.6	206.7	209.8
Wd (°)- Mean	199.4	206.2	187.1	197.3	190.0
Wd (°)- 3rd q	263.3	268.9	250.5	262.5	250.2

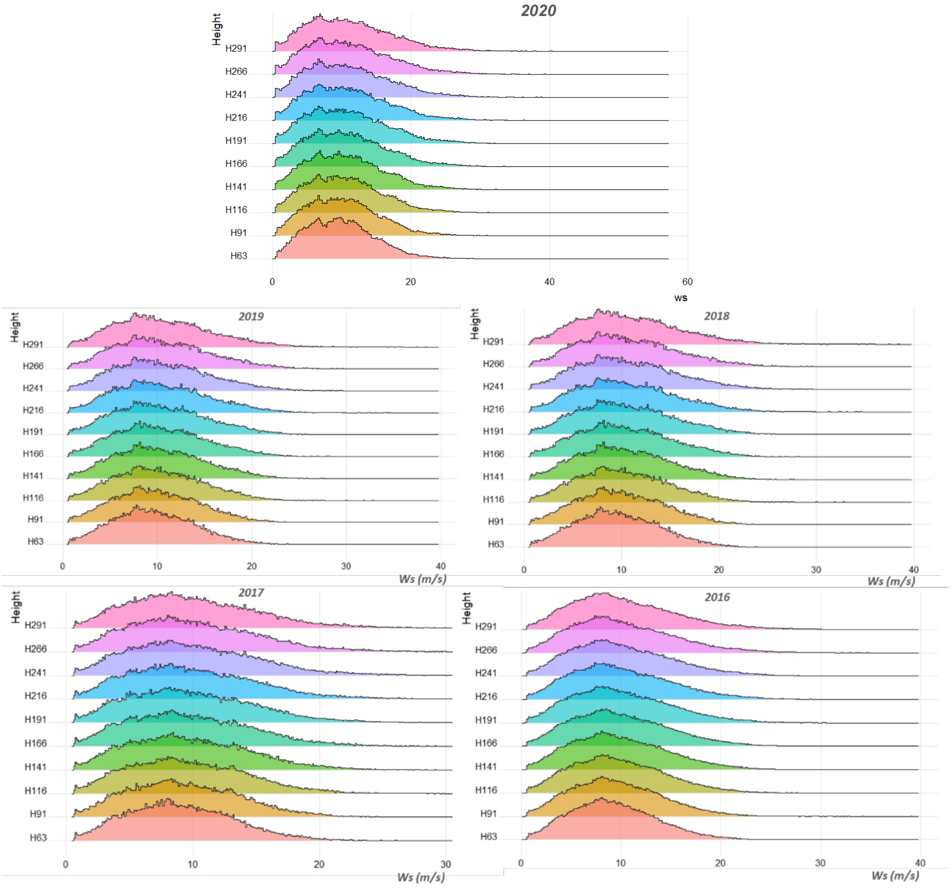


Figure 9 Annual Weibull distributions at different heights at the EPL platform for the 2016-2020 period.

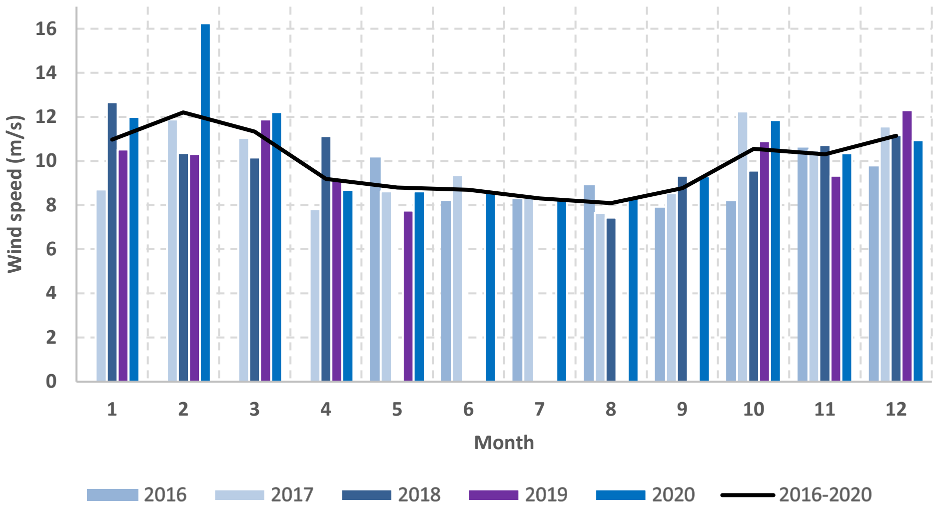


Figure 10 Annual wind speed (m/s) monthly averages bars at 141 m height and 2016-2020 monthly average (black line).

4.3 Comparison of LiDAR and KNMI measurements

The comparison of the two data measurements of the LiDAR and KNMI met mast at EPL 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 29.1 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 EPL platform, for 2016-2020.

Ws (m/s)	KNMI (29.1 m)	LiDAR (63 m)
Mean	7.89	9.36
Max.	27.53	39.06
Min.	0.00	0.00
Std dev.	3.87	4.55
Wd (°)	KNMI (29.1 m)	LiDAR (63 m)
Mean	188.88	192.66
Min.	0.00	0.00
Std dev.	94.24	90.30

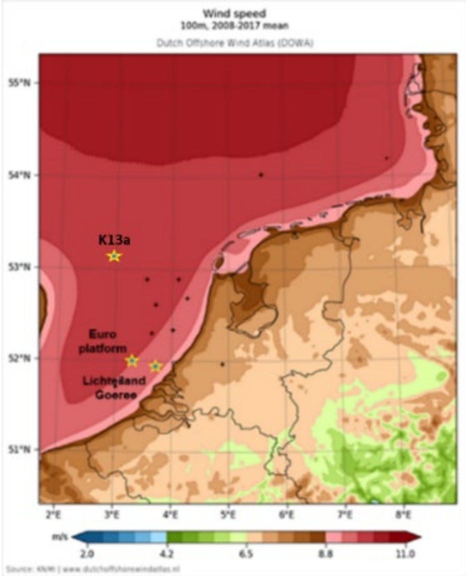
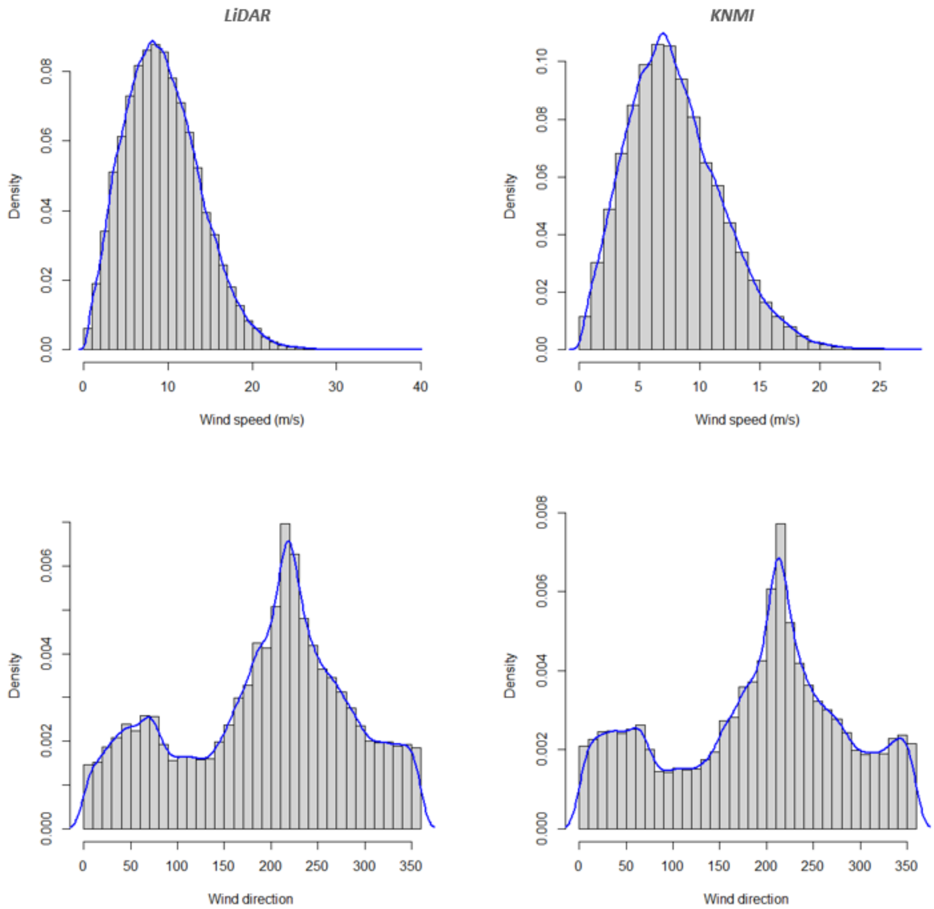
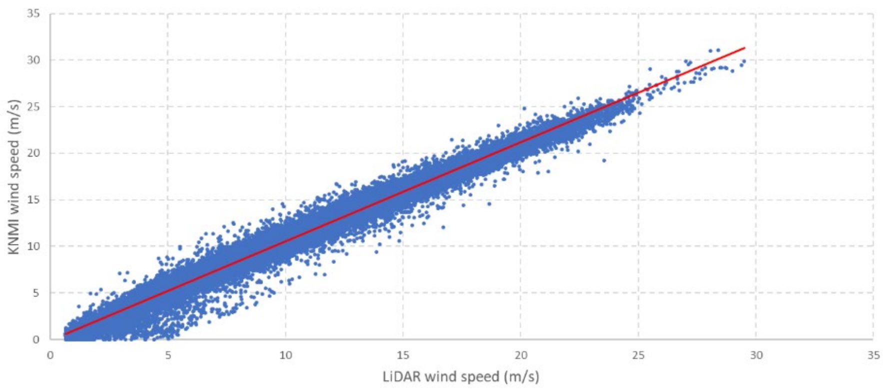


Figure 11 100 m mean wind speed between 2008-2017 provided by the Dutch Offshore Wind Atlas.



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 29.1 m height measurements at the EPL 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 2016-2020 and (bottom) time series 2020 between LiDAR (blue) and KNMI (orange) measurements at the EPL platform.

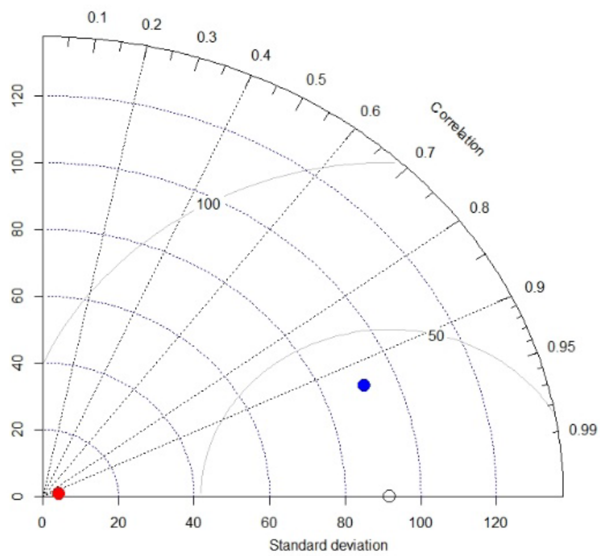


Figure 14 Taylor diagram for wind speed (red) and wind direction (blue) for KNMI as reference and LiDAR at the EPL platform. X and Y axis represent the Standard deviation, white marker represent normalized standard deviation with RMSE ~ 0 and correlation =1.

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. This analysis does not include data beyond 200 m height at LEG.

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).

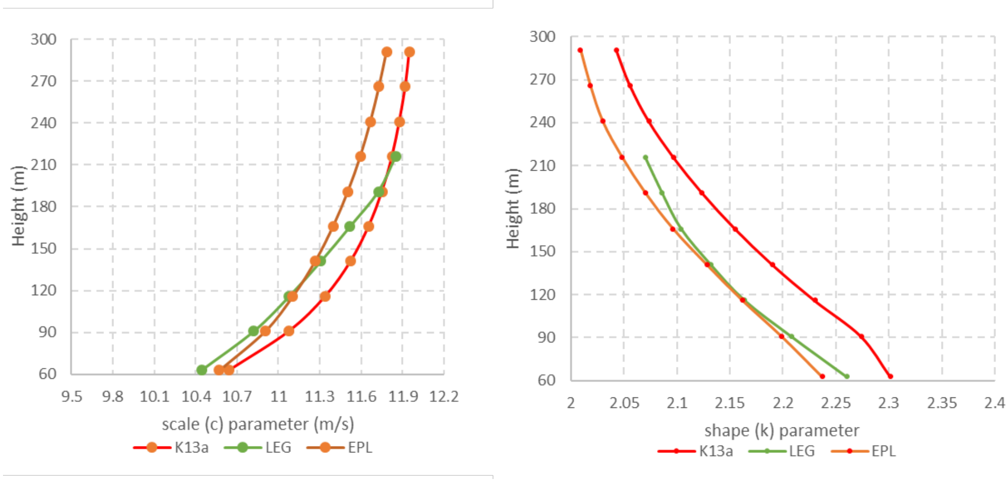


Figure 15 (left) Weibull distribution c and (right) k parameters for all heights at K13a, EPL and LEG over averaged 2016-2020 period.

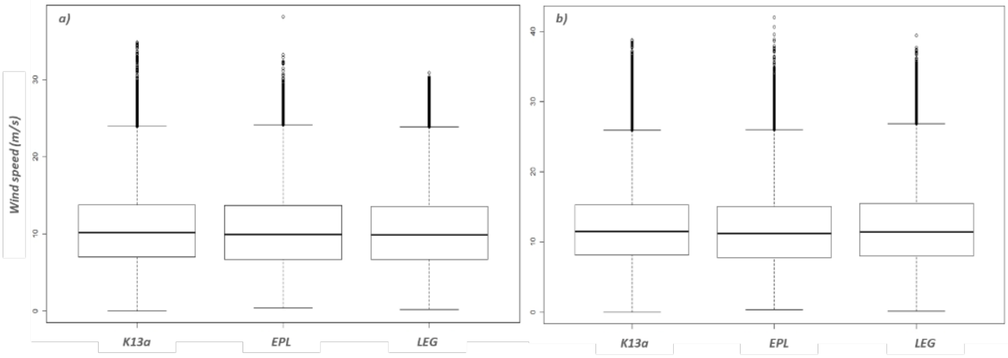


Figure 16 Boxplots of the (left) averaged and (right) maximum wind speed at 141m height at the K13a, EPL and LEG platforms for 2016-2020 period.

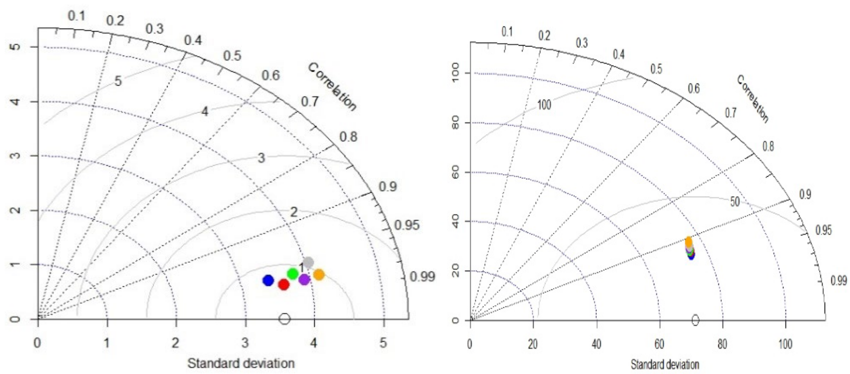


Figure 17 Taylor diagrams for (left) wind speed (m/s) and b) wind directions (boxplots of the (left) averaged and (right) maximum wind speed at 141m height at the, EPL platform for 2016-2020 period. (blue = 63m, red = 91m, green = 116 m, purple = 141 m, grey = 166 m , yellow = 191).

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 EPL 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 EPL 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 the16th 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.

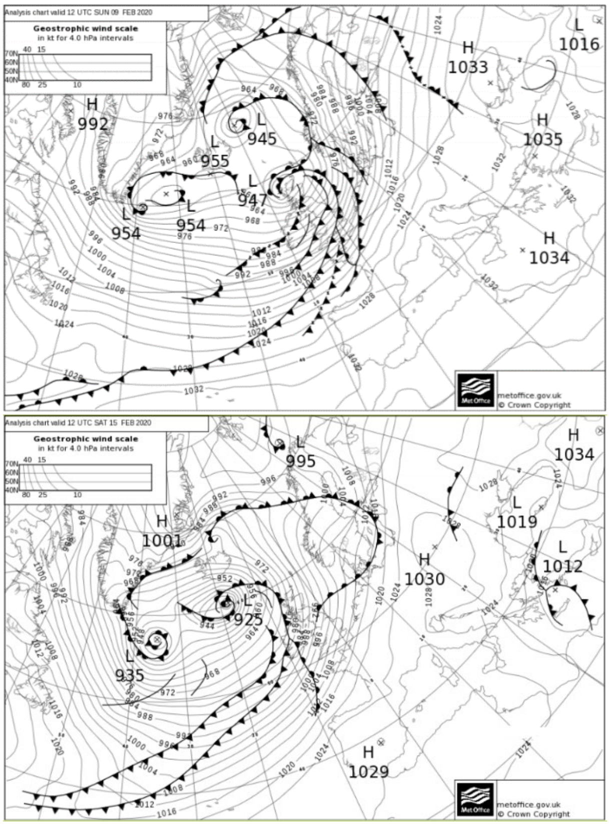


Figure 18 Analysis chart over the North Sea UK and Dutch coast on the a) 9th and b) 16th of February 2020. [image extracted from the Met Office, UK, copyright Met Office / NASA/ NOAA].

- 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 2019[1]. 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

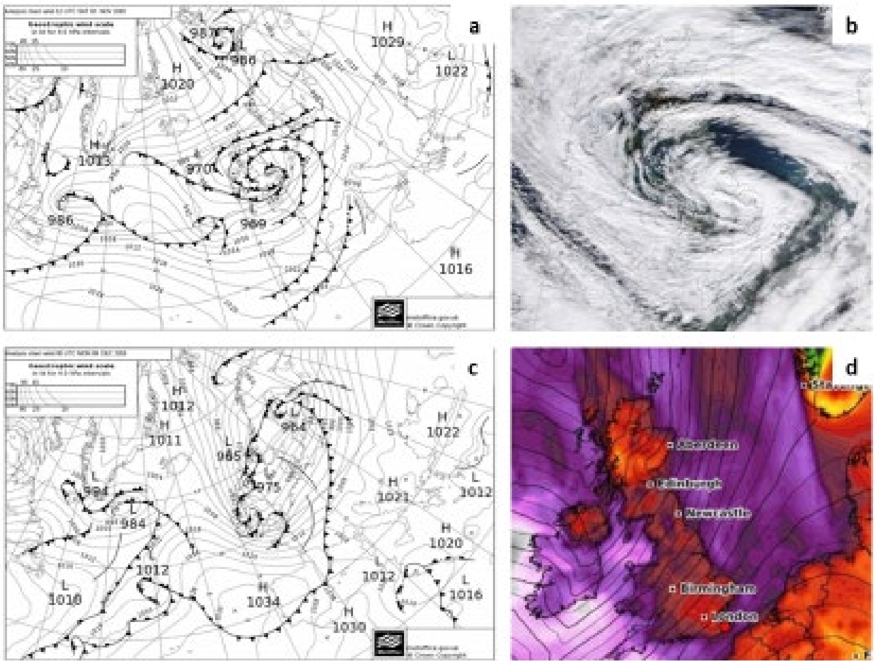


Figure 19 Analysis chart (a) and satellite image (b) over the North Sea UK and Dutch coast on the 2nd of November 2016. c) Isobars and d) zooming out the isobars over UK and The Netherlands representing the Atiyah storm on the 8th of December 2019 [image extracted from the Met Office, UK, copyright Met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

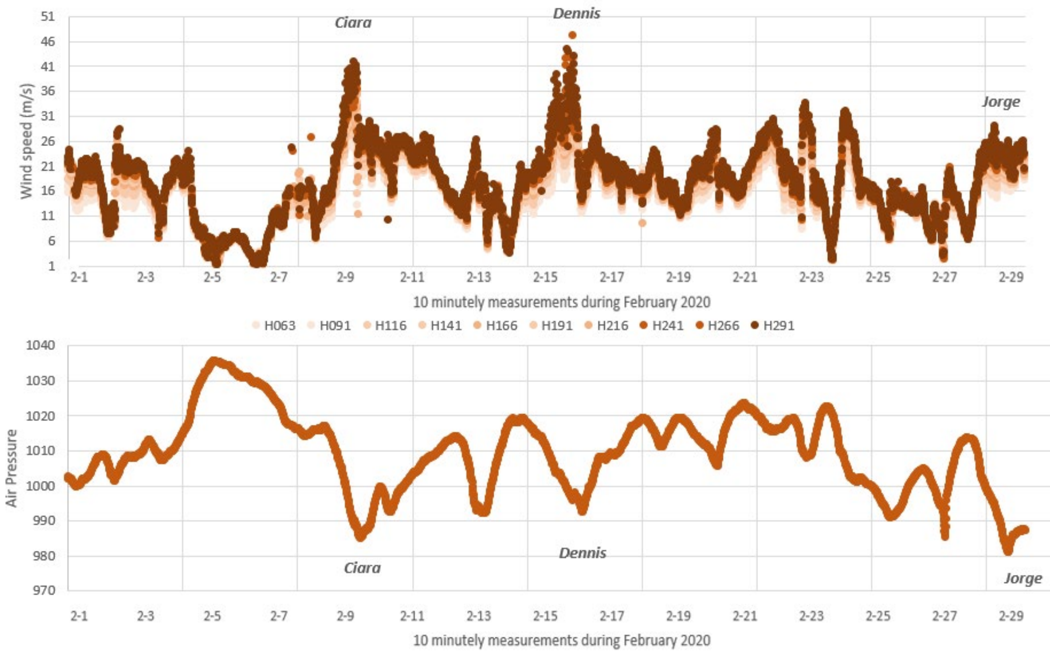


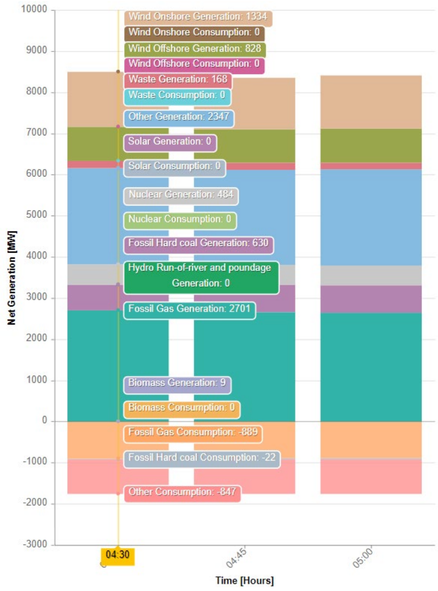
Figure 20 (Top) Wind speed (m/s) at different heights and (bottom) air pressure (hPa) measured at EPL during February 2020.

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 20 (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)

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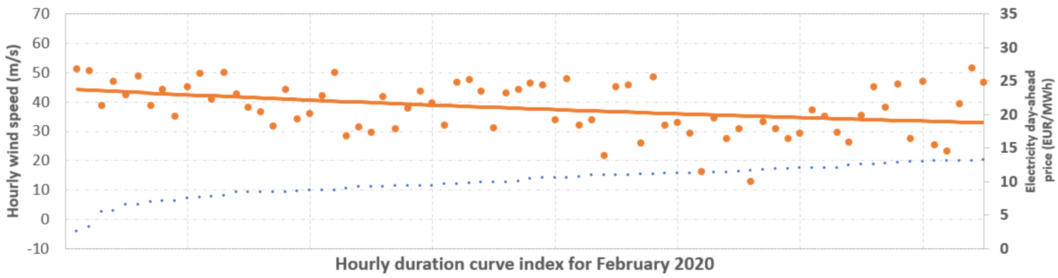

c)

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 [17] 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 [18] 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.

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 [19], [20].

- 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**.

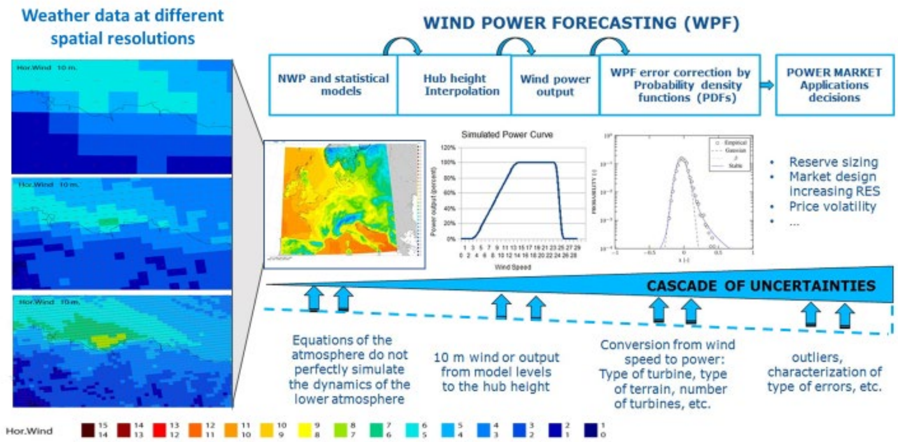

Figure 22 The need of accurate wind resource data and to increase the spatial resolution in power system modelling for more accurate power market applications and decisions.

6 Conclusions

Within the Dutch project *'Wind op Zee' 2021*, 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 (EPL) 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 EPL platform where a ZX 300 LiDAR has been deployed, providing high quality data. The data are publicly available to be used for further purposes (www.windopzee.net).

At the EPL platform, the wind analysis for the 2016-2020 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 193° to 198° and the lower and upper quartiles range from 129° to 261° 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 = 2.129 and c = 11.271 m/s at 141 m height).

The wind speed bell distribution is flattener and moderately skewed right with higher heights, with more frequent wind speeds >26 m/s. 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 35 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 EPL is carried out on the authority of the Ministry of Economic Affairs and Climate Policy of The Netherlands.

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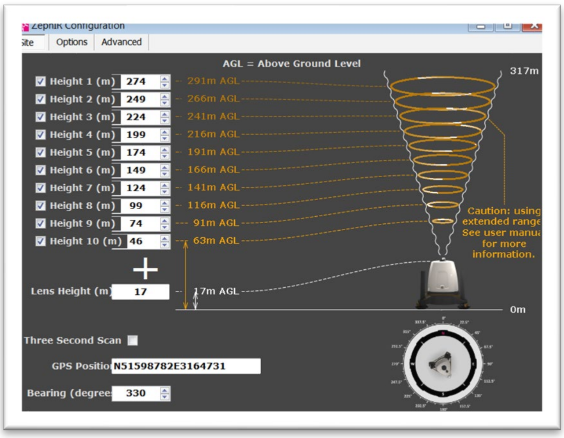
A LiDAR specifications

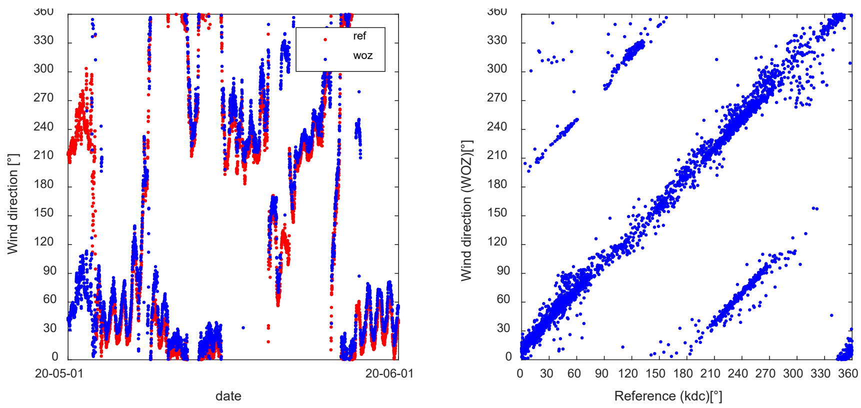
ZX 300 settings and configuration

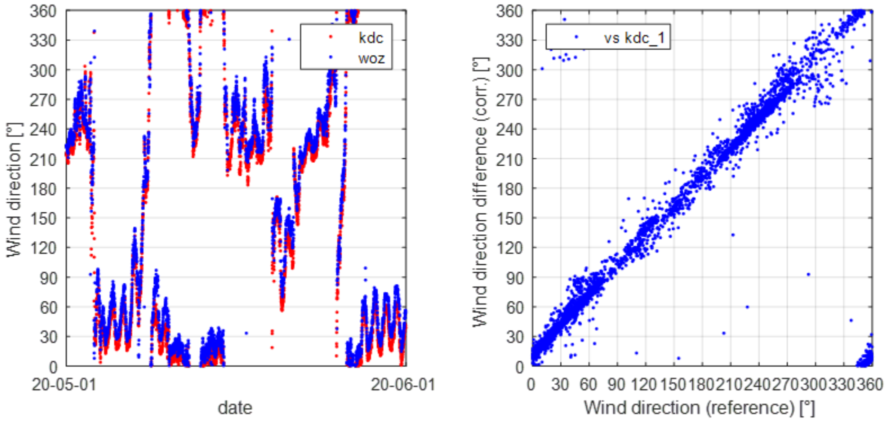
TNO is accredited for remote sensing device calibration (ISO 17025). The LiDAR is upfront verified against Meteorological Mast 4, in accordance with *IEC 61400-12-1:2017*. The validation is performed by checking Key Performance Indicators (KPIs) [9]. The figure below shows an example of screen setting of the LiDAR configuration and adjustments.



Data correction – 180 degrees offset

As abovementioned, The ZX 300 does not determine the direction of the Doppler shift in the received series and there is a 180◦ ambiguity in the wind direction. Therefore, the attached met station with wind speed and direction measurements (EPL_wsmet and EPL_wdmet, Table 2) is used to correct the 180◦ offset. Firstly, the difference of the two wind direction timeseries are considering; then, the solitary spikes from this difference in signal are removed and; identification of the periods where the LiDAR wind direction is reversed. The figures below show the wind direction time series (left figures) and the comparisons (right figures) from the LiDAR at EPL and from the KNMI met mast; before (top) and after (bottom) applying the correction methodology.





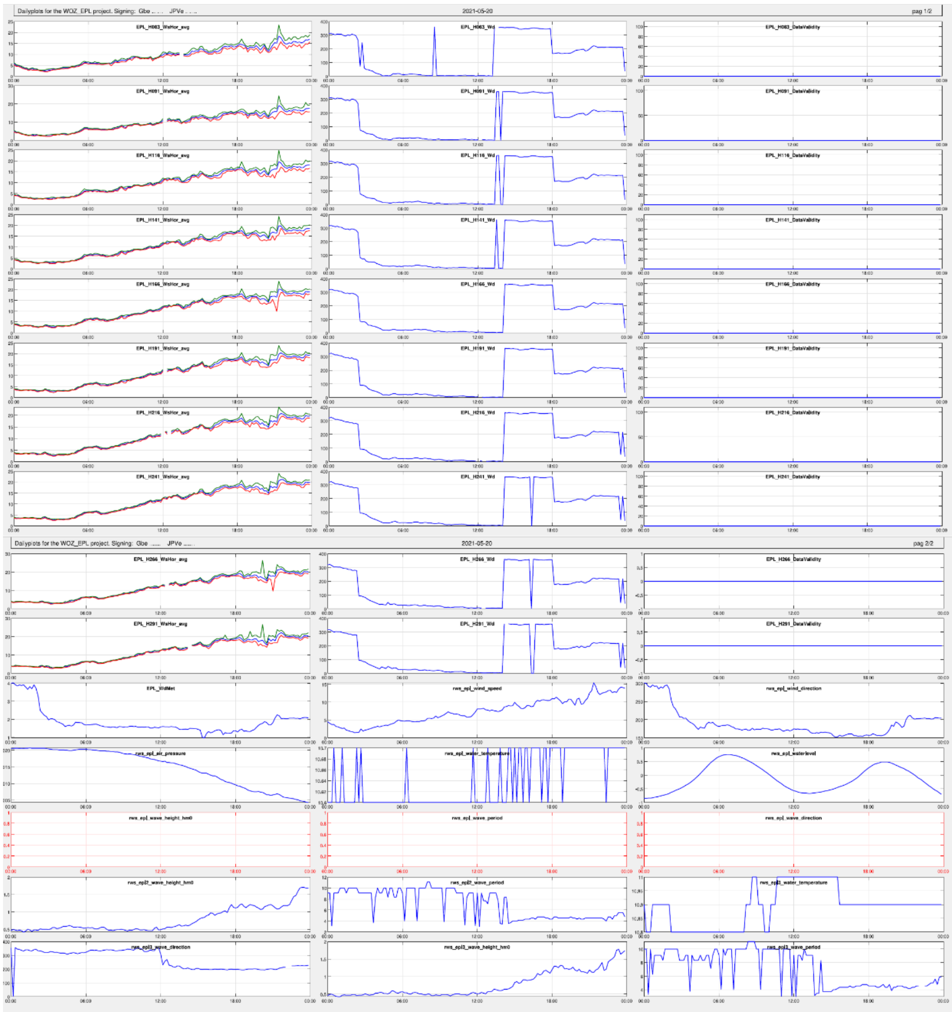
Data availability

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

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

Where max($n_{packets}$) is the maximum value for the number of packets metric observed in the entire data set and it depends on the type of the LiDAR.

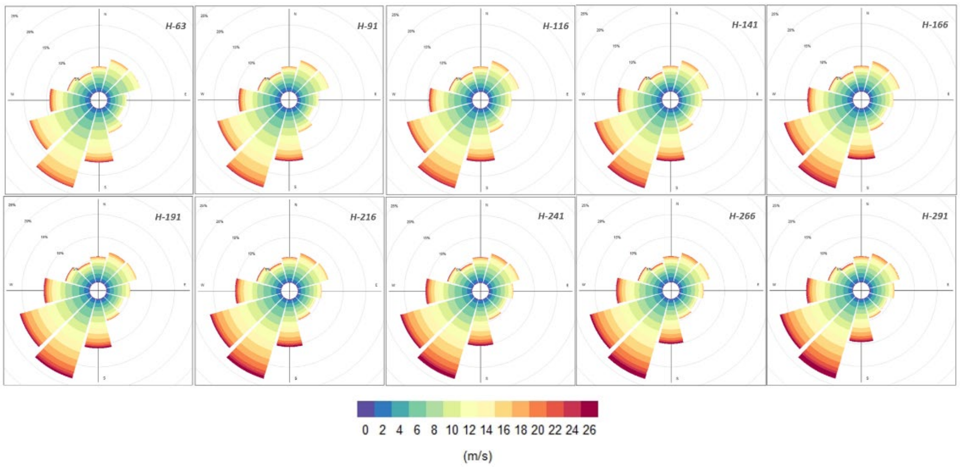
Example of Daily Plot

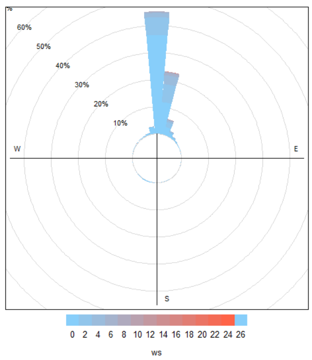


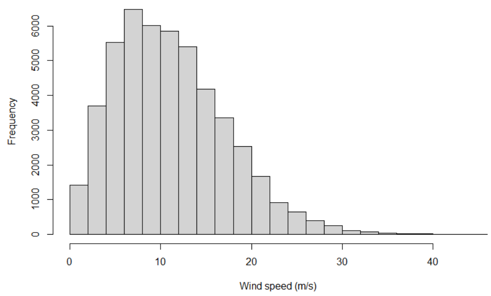
B Annual weather conditions during the campaign at EPL

This section contains visual and statistical descriptive summary about the annual weather conditions for 2016-2020 at EPL. The annual prevailing wind direction recorded was South-West, at different heights, as indicated by the wind roses (a) and distribution function (c). Although the predominant wind direction is South-West, with lower heights, the North component is stronger. The wind rose chart (b) shows the difference on wind speed and direction between heights of 291m and 63 m indicating the mean difference of wind direction between lowest and highest height measured.

B.1 2020

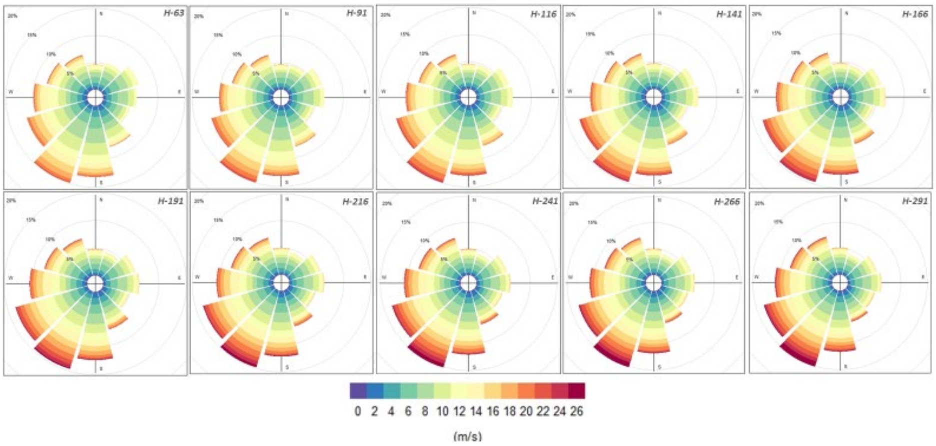


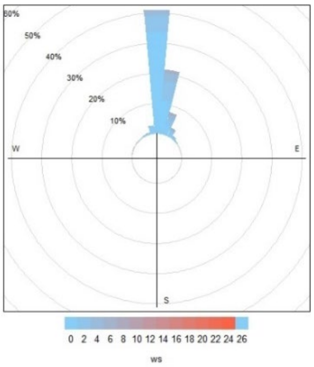


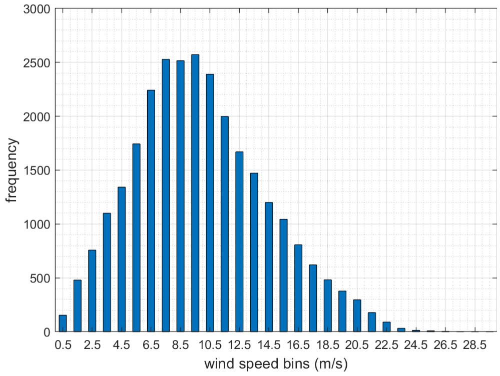


H (m)	63	91	116	141	166	191	216	241	266	291
Ws - Min	0.416	0.322	0.331	0.341	0.318	0.313	0.307	0.315	0.308	0.310
Ws – 1st q	6.082	6.210	6.273	6.312	6.328	6.345	6.373	6.388	6.446	6.471
Ws - Median	9.453	9.720	9.839	9.955	10.046	10.116	10.181	10.228	10.301	10.389
Ws - Mean	9.764	10.080	10.273	10.447	10.590	10.715	10.827	10.927	11.036	11.146
Ws - 3rd q	12.865	13.366	13.684	13.961	14.187	14.361	14.513	14.639	14.773	14.938
Ws – Max	28.985	30.887	31.850	33.232	34.124	36.276	42.470	47.058	56.893	44.280
Wd - 1st q	123.0	125.6	127.1	126.9	127.6	126.5	126.5	126.3	126.2	125.7
Wd - Median	207.5	208.3	208.9	209.8	210.8	211.7	212.6	213.3	214.1	214.7
Wd - Mean	188.1	188.9	189.5	190.0	190.8	191.1	191.6	192.0	192.2	192.4
Wd - 3rd q	248.8	249.3	249.7	250.1	251.0	251.4	251.9	252.2	252.3	252.5

B.2 2019

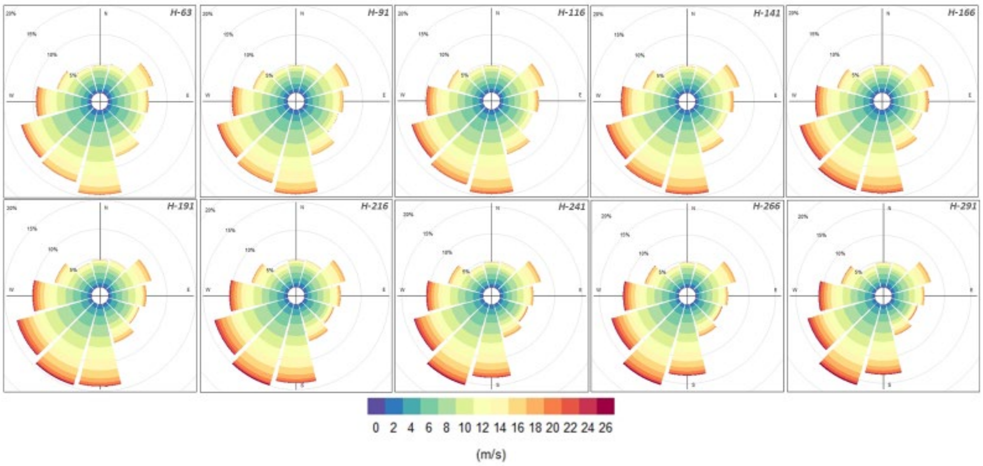


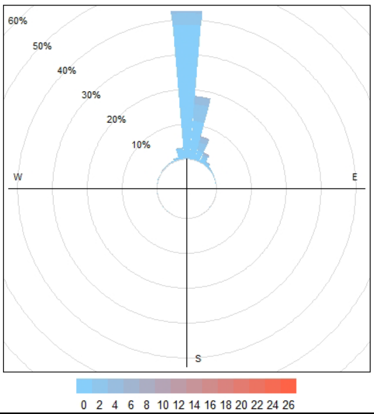


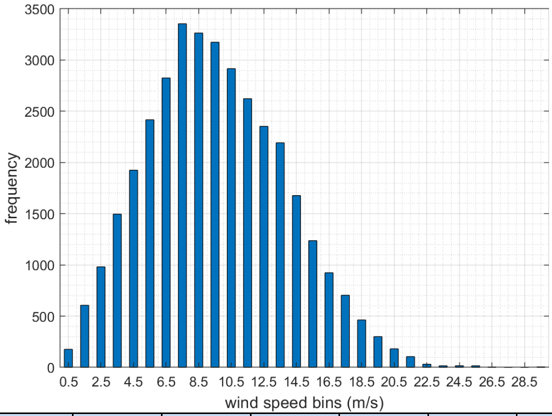


H (m)	63	91	116	141	166	191	216	241	266	291
Ws - Min	0.472	0.413	0.381	0.452	0.426	0.319	0.320	0.363	0.370	0.335
Ws – 1st q	6.685	6.768	6.820	6.840	6.868	6.878	6.872	6.868	6.878	6.877
Ws - Median	9.441	9.729	9.865	9.968	10.039	10.085	10.072	10.097	10.118	10.135
Ws - Mean	9.883	10.194	10.383	10.543	10.679	10.791	10.887	10.969	11.037	11.090
Ws - 3rd q	12.752	13.235	13.563	13.845	14.055	14.242	14.399	14.521	14.601	14.662
Ws – Max	27.000	28.300	28.500	29.100	29.600	31.600	34.100	34.600	34.400	34.900
Wd - 1st q	134.0	136.4	137.7	139.0	140.5	141.7	142.6	143.1	143.5	143.6
Wd - Median	202.6	204.2	205.4	206.7	208.1	209.6	210.6	211.4	212.2	213.1
Wd - Mean	194.3	195.5	196.4	197.3	198.3	199.3	200.1	200.6	201.4	202.1
Wd - 3rd q	260.9	261.5	262.1	262.5	263.2	264.4	265.1	266.2	267.4	268.2

B.3 2018

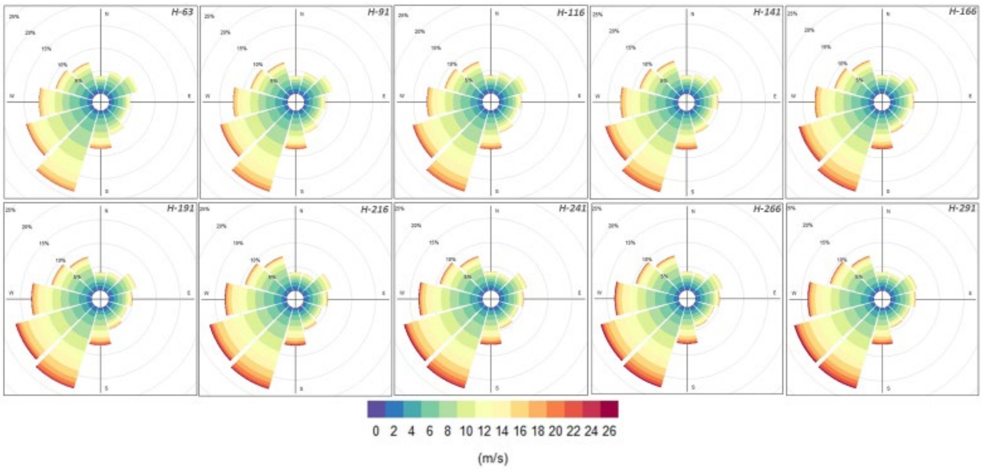


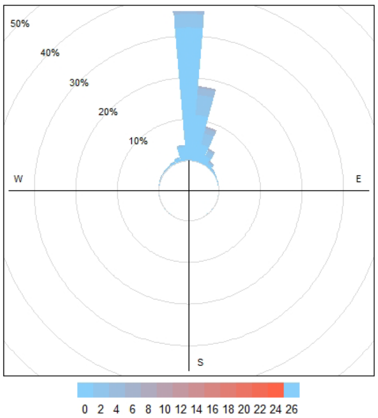


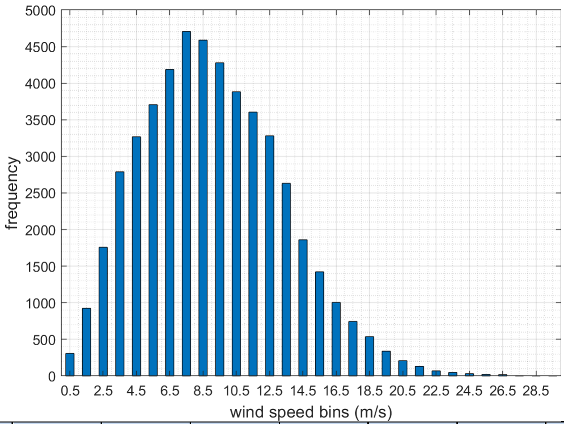


H (m)	63	91	116	141	166	191	216	241	266	291
Ws - Min	0.658	0.661	0.662	0.661	0.664	0.669	0.669	0.667	0.663	0.661
Ws – 1st q	6.497	6.659	6.713	6.754	6.780	6.795	6.820	6.821	6.838	6.842
Ws - Median	9.319	9.608	9.766	9.852	9.905	9.960	9.988	10.008	10.006	10.009
Ws - Mean	9.621	9.931	10.110	10.246	10354	10.446	10.519	10.572	10.605	10.628
Ws - 3rd q	12.526	13.011	13.241	13.410	13.541	13.662	13.757	13.821	13.844	13.872
Ws – Max	39.066	39.156	38.559	38.174	39.251	35.442	38.869	38.414	39.557	38.480
Wd - 1st q	116.1	119.3	120.6	121.7	121.7	121.4	122.1	123.5	124.6	124.2
Wd - Median	190.7	192.5	194.2	195.6	196.8	198.0	199.1	200.6	201.7	202.5
Wd - Mean	184.7	185.6	186.7	187.1	187.2	187.6	187.9	188.5	189.1	189.2
Wd - 3rd q	248.6	249.4	250.2	250.5	250.5	250.9	251.4	251.9	252.5	252.8

B.4 2017

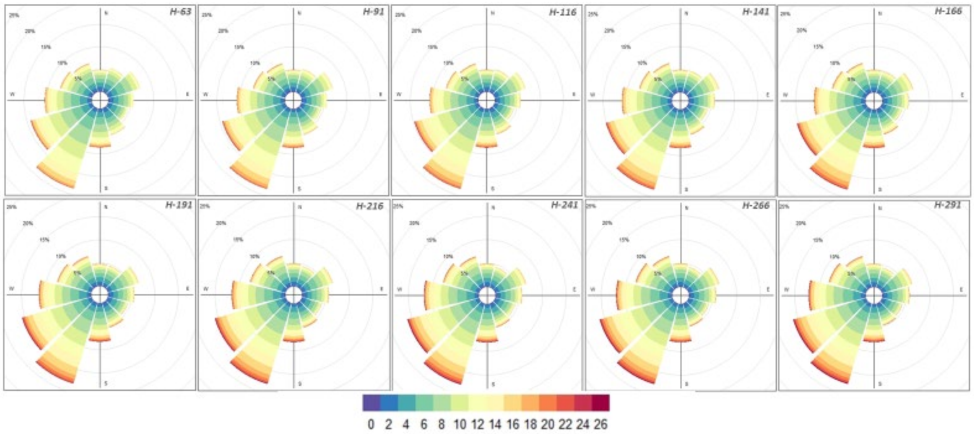


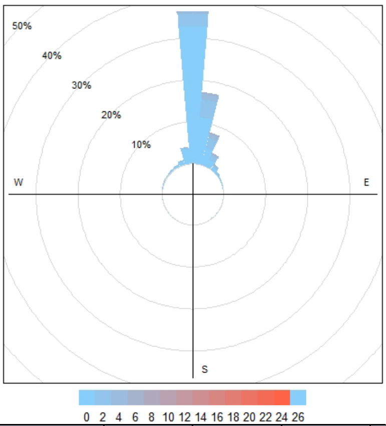


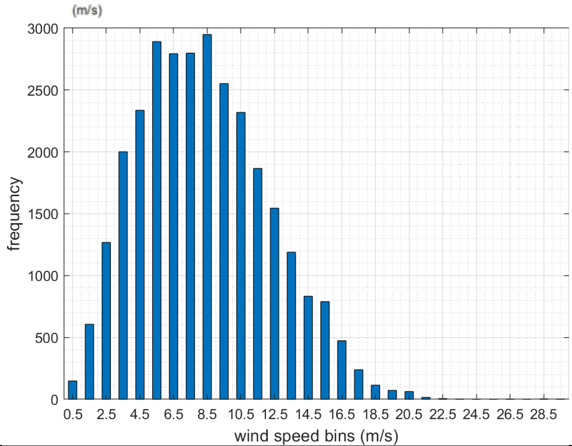


H (m)	**63**	**91**	**116**	**141**	**166**	**191**	**216**	**241**	**266**	**291**
Ws - Min	0.671	0.673	0.668	0.675	0.678	0.678	0.647	0.677	0.678	0.678
Ws – 1st q	5.947	6.033	6.069	6.097	6.118	6.151	6.181	6.218	6.238	6.281
Ws - Median	8.732	9.016	9.155	9.241	9.301	9.342	9.353	9.381	9.400	9.396
Ws - Mean	9.089	9.389	9.566	9.697	9.796	9.876	9.942	9.992	10.026	10.054
Ws - 3rd q	11.907	12.439	12.720	12.918	13.055	13.135	13.205	13.244	13.267	13.263
Ws – Max	28.572	29.424	29.759	30.164	30.079	30.355	30.668	30.852	31.715	31.938
Wd - 1st q	150.8	152.9	155.1	156.7	158.1	16014	161.7	163.2	165.1	166.1
Wd - Median	217.6	218.6	219.8	220.7	221.5	222.28	223.2	223.95	224.7	225.2
Wd - Mean	203.1	204.3	205.3	206.2	206.9	207.9	208.9	209.6	210.5	210.9
Wd - 3rd q	266.8	267.7	268.3	268.9	269.5	270.44	271.2	271.8	272.6	273.1

B.5 2016



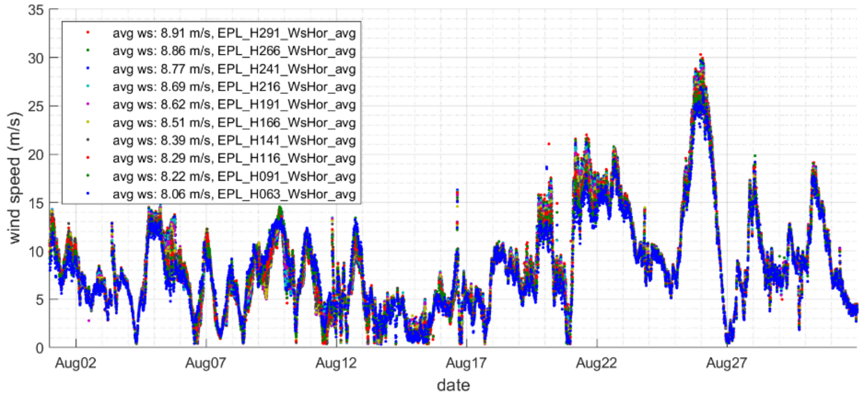


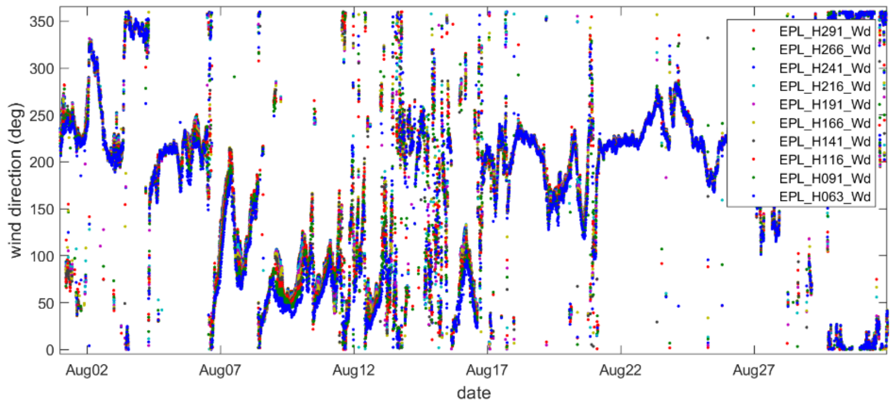


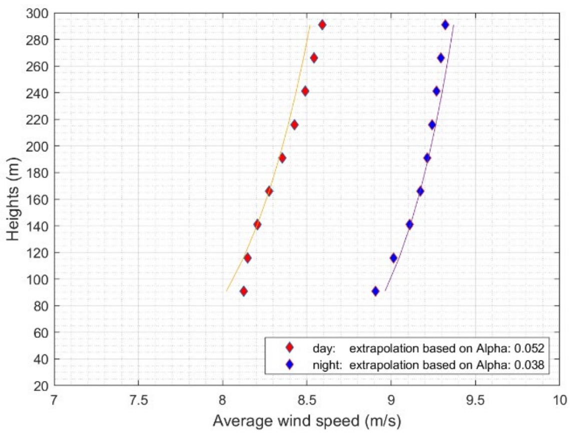
H (m)	63	91	116	141	166	191	216	241	266	291
Ws - Min	0.669	0.673	0.668	0.675	0.678	0.678	0.647	0.675	0.676	0.678
Ws – 1st q	5.770	5.859	5.895	5.938	5.960	5.993	6.023	6.053	6.082	6.127
Ws - Median	8.527	8.759	8.874	8.952	8.987	9.020	9.030	9.034	9.033	9.048
Ws - Mean	8.876	9.145	9.307	9.426	9.516	9.588	9.646	9.692	9.724	9.753
Ws - 3rd q	11.595	12.043	12.301	12.464	12.593	12.672	12.742	12.771	12.785	12.785
Ws – Max	30.475	31.225	32.339	31.854	31.808	31.895	32.476	32.030	32.636	33.029
Wd - 1st q	133.2	135.7	138.3	139.6	140.9	142.8	144.2	144.7	145.7	146.9
Wd - Median	213.4	214.3	215.0	215.9	216.5	217.2	217.9	218.6	219.2	219.6
Wd - Mean	196.5	197.7	198.7	199.4	199.6	200.9	201.6	202.1	202.9	203.4
Wd - 3rd q	260.8	261.9	262.7	263.3	263.5	264.6	265.3	265.9	266.9	267.4

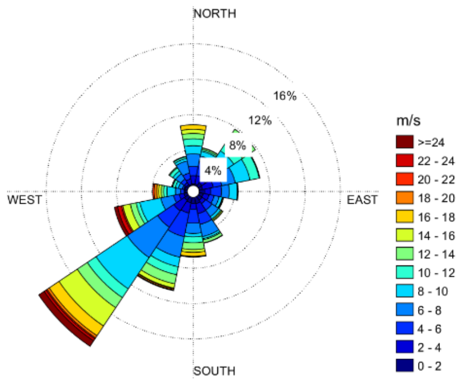
C Weather conditions analyses during the monthly reporting

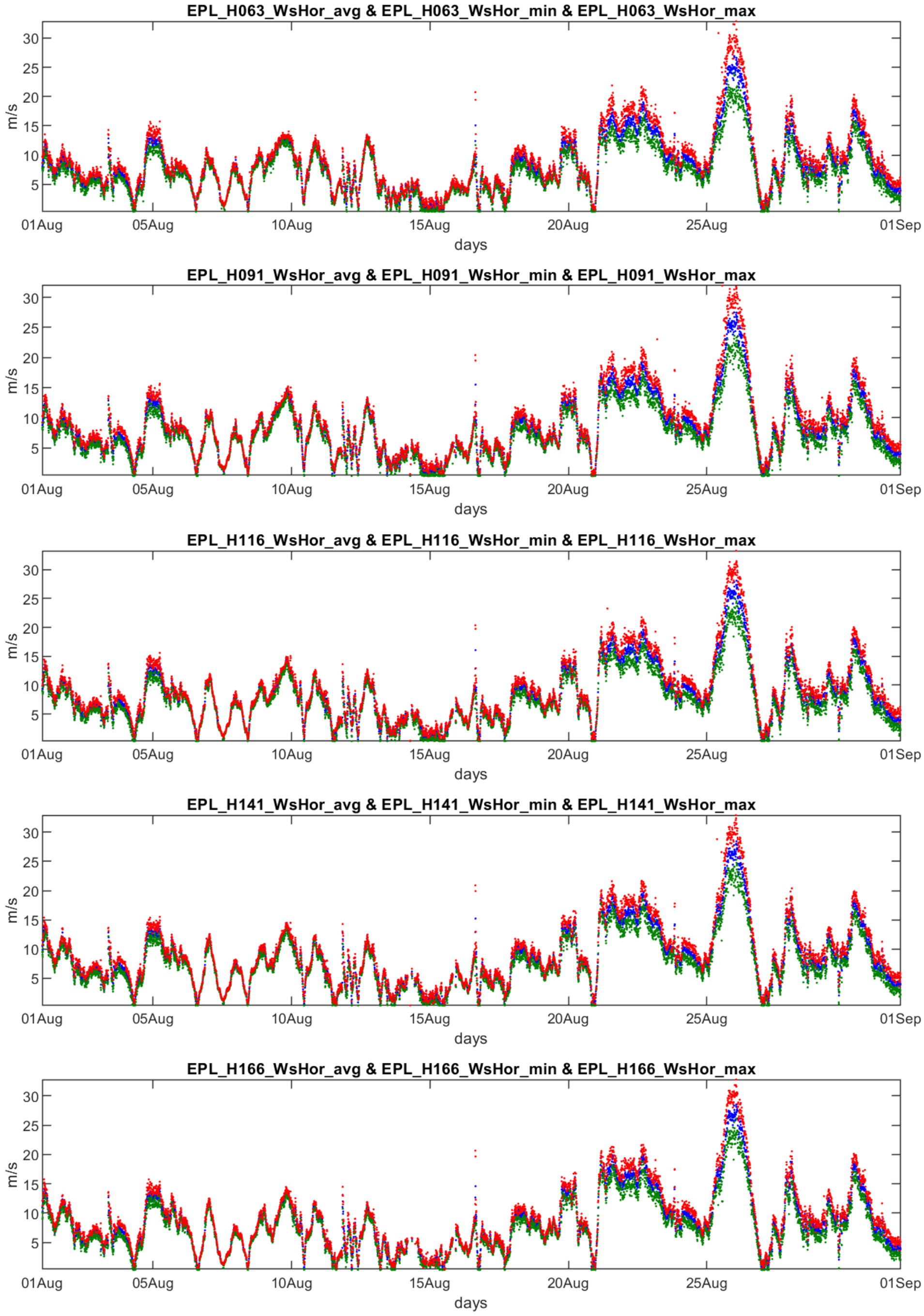
Weather conditions were analysed through different signalling figures including wind speed and direction signals, wind shears and dominant winds. Maximum, minimum and mean wind speed and directions time series were also analysed each month. The figures below show visual examples of the monthly reporting in August 2020 as an example, wind speed (a) and direction (b) signals; (c) wind shear and (d) wind rose at the EPL platform. Similar plots for the rest of months in the reporting period are available as well.



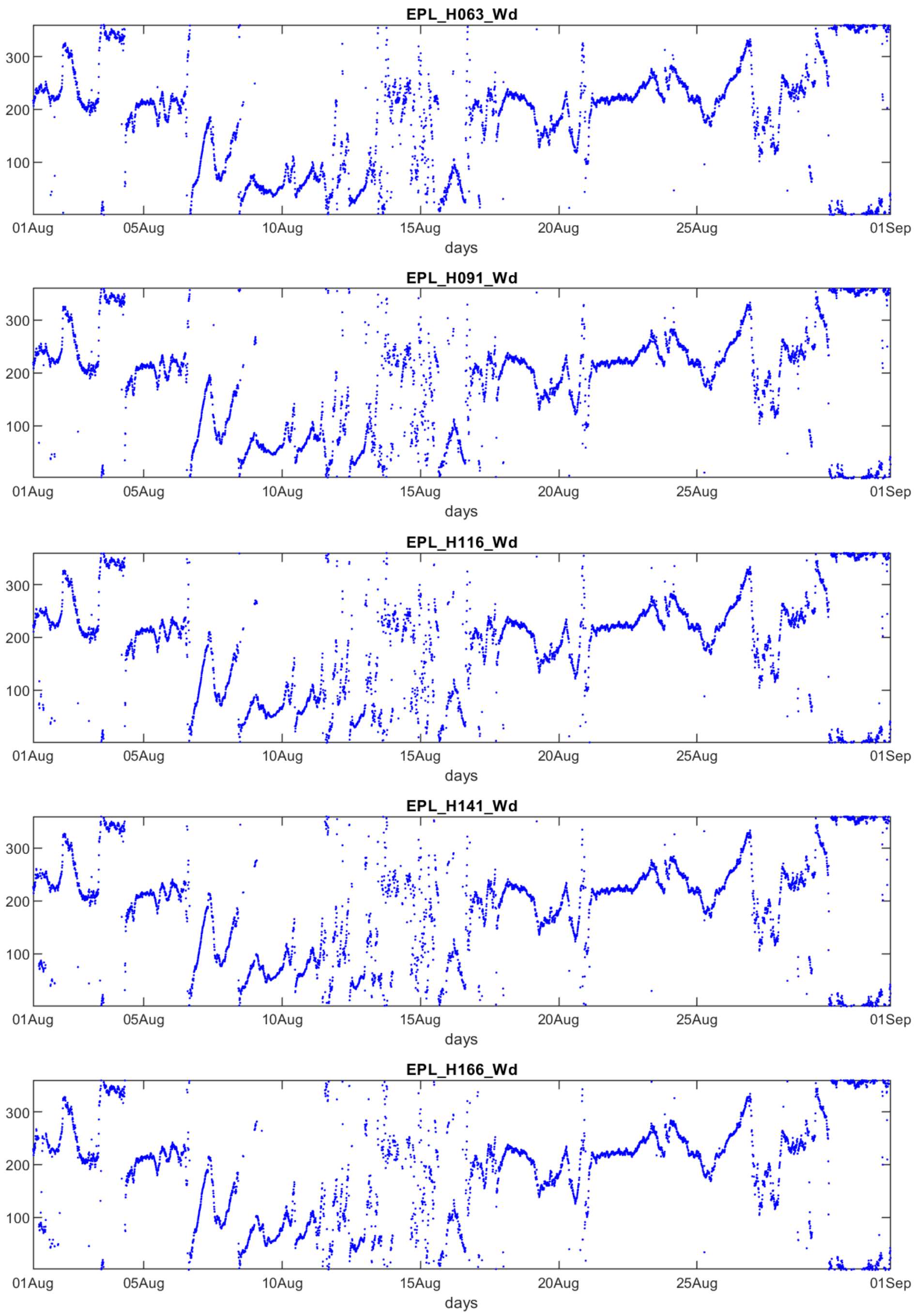








legend: [blue]: signal 1, [green]: signal 2, [red]: signal 3



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