Offshore wind resource in the Dutch North Sea 2022: Developing a long-term measurement campaign and understanding wind conditions

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Energy & Materials Transition
www.tno.nl
+31 88 866 50 65
info@tno.nl

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Offshore wind resource in the Dutch North Sea 2022: Developing a long-term measurement campaign and understanding wind conditions

Author(s)	E.T.G Bot J.A. Vitulli C.B.H. Eeckels J.P. Verhoef
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Summary

The Netherlands has set clear ambitions to accelerate the energy transition. By 2050 all energy used in the country shall come from sustainable sources and offshore wind energy plays a vital role in the transition to a carbon-free energy supply. The government has defined a roadmap for the Dutch offshore wind portfolio aiming to add 4.5 GW by 2023 in a first phase, to further expand to 21.5 GW by 2030 . The Netherlands is moving ahead with yearly tendering rounds for upcoming development areas. To further meet the revised European frameworks for 2050, in May 2022 the Netherlands has signed the Esbjerg Offshore Wind Declaration and in April 2023 the Ostend declaration, together with other European countries to reach offshore wind capacity of about 120 GW by 2030 in the North Seas and at least 300MW by 2050.

TNO performs for The Dutch Ministry of Economic Affairs and Climate Policy measurement campaigns in the North Sea since 2014 at different strategically chosen locations. Currently, the locations of the measurements are Lichteiland Goeree platform (LEG), Europlatform (EPL) and Wintershall Noordzee B.V. platform K13a, under the program “Wind op Zee”. Besides the currently available locations TNO also hosts data from previous locations like offshore Meteorological Mast IJmuiden (MMIJ) and the offshore Meteorological Mast OWEZ (Offshore Wind Farm Egmond aan Zee).

This report presents a series of analyses that provide insight into the correlations, long-term wind speed predictions, and other use cases that leverage both the on-site LiDAR data across the LEG, EPL, and K13a platforms in the Dutch North Sea for the period 2014-2022, and different reanalysis and modelled data from wind atlases, namely DOWA, KNW, and ERA5.

A correlation factor of 0.867 was deduced for LEG when comparing LiDAR measurement at the platform locations to KNW atlas. This indicates that the relation between the wind atlas and measurements is reasonably strong. Similarly, results have been observed with the DOWA wind atlas at 0.876. For the EPL and K13a platforms, similar (reasonably strong) correlations with the DOWA and KNW atlases were observed.

While cross comparing the three platform locations to each other, it was observed that LiDAR measurements at a distance of 30 km or less from the location of interest will provide more accurate results in comparison to the wind atlases. LEG and EPL have a correlation factor of 0.9, slight higher than the 0.87 factor observed between atlases. However, local data from the wind atlases will provide more accurate results than measurements at (much) larger distances, as observed with a correlation factor of 0.63 between K13a and LEG.

In a first attempt to establishing a long term correction to the measured data, ERA5 was used in the MCP analysis in order to obtain a 20 year representation of each platform location. The deduced long term wind speeds at 115-116 m height was 9.55 m/s, 9.53 m/s, and 9.89 m/s for LEG, EPL, and K13a respectively. These values deviate between 0.1% to 0.3% from the average wind speed obtained from the 6-7 year period of measurements.

Finally an investigation into the wake impacts of the recently operational Borssele wind farm was performed. By separating the data into 2 periods (before and after the construction) and plotting the ratio of wind speed at EPL and LEG directional, the maximum impact of Borssele was found to be 9.0% for LEG at 240° wind direction, and 11% for EPL at 210° wind direction. The estimated total impact on the average wind speed for all sectors is estimated as 0.30% or 0.029 m/s for both platforms.

Contents

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

1.1 Offshore wind energy deployment

The Netherlands has set clear ambitions to accelerate the energy transition. By 2050, all energy used in the country shall come from sustainable sources and offshore wind energy plays a vital role in the transition to a carbon-free energy supply. [1]

The Dutch government has defined a roadmap for offshore wind aiming to reach 4.5 GW by 2023 in a first phase, followed by deploying a further 21 GW by 2030 [2]. To achieve this, the government has planned to open new areas for offshore wind farm development to accommodate these ambitions and targets (**Figure 1.1**). In May 2022 the Netherlands has signed the Esbjerg Offshore Wind Declaration [3] and in April 2023 the Ostend declaration, together with other European countries to reach offshore wind capacity of about 120 GW by 2030 in the North Seas and at least 300MW by 2050 [4].

Together with European initiatives and legislation to become the first carbon neutral continent by 2050, the North Sea has become a center for industrial exploration for offshore wind, and is key for future transformation of the industry. With over 70% of existing and planned European offshore wind farms are expected to be located in this area.

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

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

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

This report gives insight in the wind conditions at different platforms in the North Sea, see Chapter 2 and 3. Chapter 4 gives a comparison of the measurement data with existing KNMI models, the correlation between measurements at the different locations and the establishment of long-term wind resource. Chapter 5 investigates the influence of wake impact of wind farm Borssele on the undisturbed measurements at platforms Lichteiland Goeree (LEG) and Europlatform (EPL).

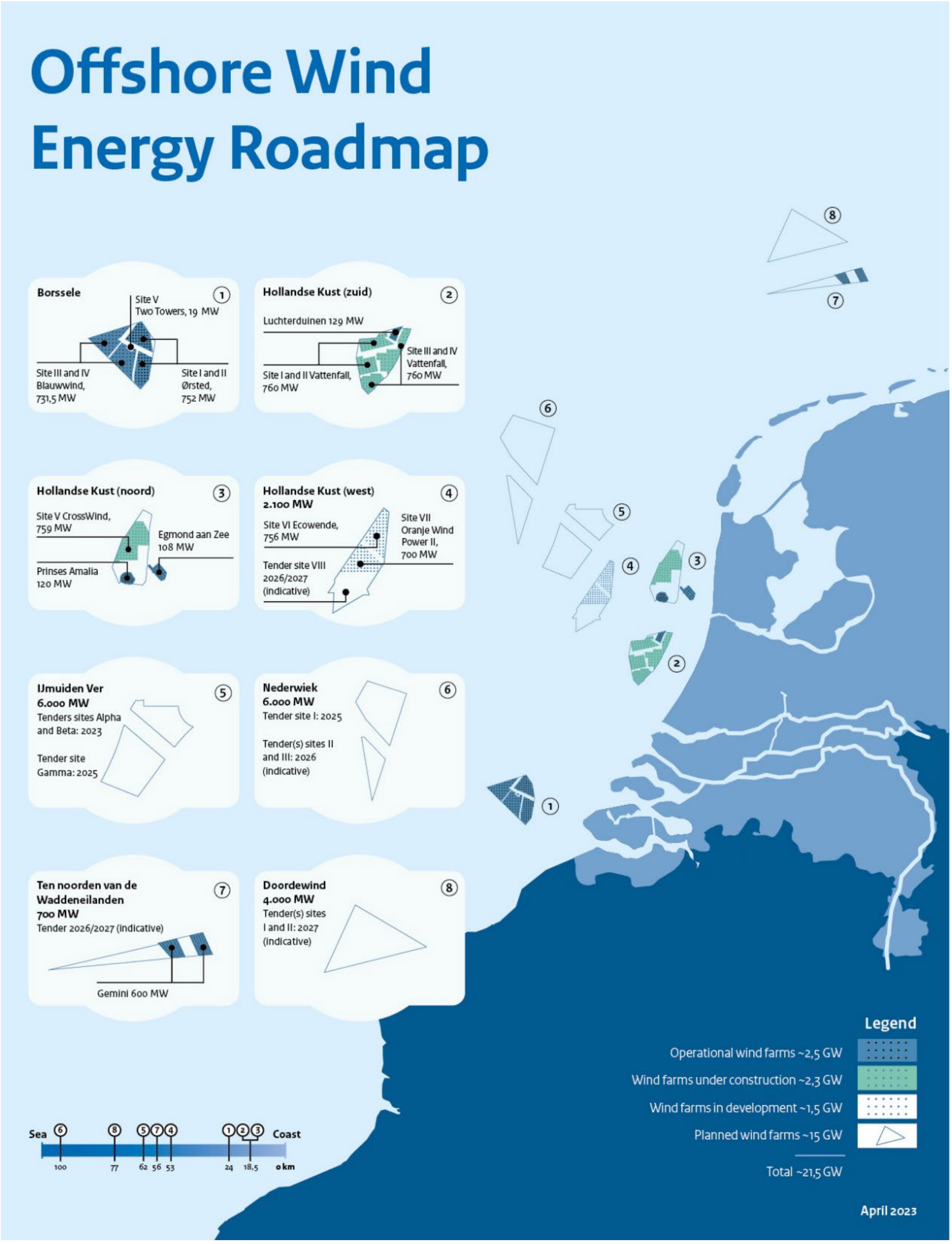


Figure 1.1 Locations of existing and planned wind farms with new designated zones for offshore wind farms to reach 21.5 GW over the Dutch North Sea by 2030, updated in April 2023 [2]

1.2 TNO leading role on offshore measurement campaigns

Before the introduction of LiDARs in offshore wind resource assessments, meteorological masts (met mast) have been widely used at TNO with examples such as the met mast at IJmuiden (MMIJ), and the met mast at the Egmond aan Zee Offshore Wind farm (OWEZ).

Onshore measurement campaigns are also part of the activities of TNO for more than 20 years, including independent ISO17025 accredited and IECRE approved 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 (14MW). During the measurement campaign, TNO is responsible for the entire life cycle: from selection of the instrumentation and planning the installation, to the purchase, validation, installation, and maintenance of the LiDAR, as also analyzing, reporting and dissemination of the data.

1.3 Complementary TNO activities in the North Sea

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

- A characterization of the precipitation levels over the entire Dutch North Sea based on wind climatology at different locations is carried out by TNO within the PROWESS project. This information is applied to develop a long term and high resolution predictive model with the aim of assessing future levels of wind turbine degradation due to leading edge erosion. The measurement campaign couples different sources such as radar, weather stations and disdrometers and is ongoing at several strategic location in the North Sea (Figure 1.2). The measurements and their characteristics will be correlated to levels of blade erosion assessed by inspection reports, and later implemented to maintenance and operational planning, strategies and decisions for the development of future wind farms. This could help further reduce the levelized cost of energy and extend the operational lifetime of turbines [4].

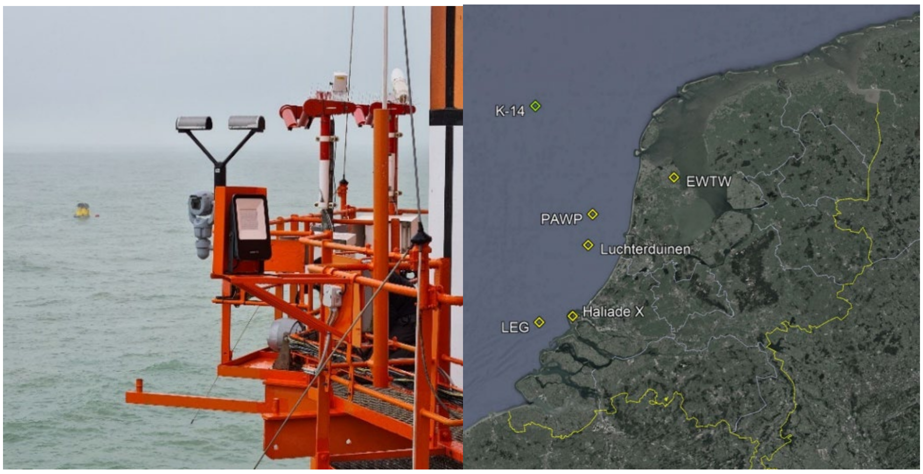


Figure 1.2 Disdrometer instrument installed at LEG platform (left), and the measurement campaign layout (right) for PROWESS project running form 2021 until 2023.

1.4 Open-access and public datasets

TNO has published annually reports on the wind conditions for each measurement campaign location since 2020. An overview of the most recent reports is given in Table 1.1.

Table 1.1 Overview of Wind Condition Reports per platform and measurement period

Report reference	Platform	Period
[5]	LEG platform	2014-2022
[6]	EPL platform	2016-2022
[7]	K13a platform	2016-2022

These reports are available at https://www.windopzee.net/en/.

The data measured in the "Wind op Zee" project are retrieved and post-processed before making the information publicly accessible through the web-service https://nimbus.windopzee.net/. Post-processed data are reported each month for verification purposes. Users can download the data after free registration.

To use "Wind op Zee" measured data in publications, further research or commercial purposes, users must acknowledge the use of the data as:

1. Citation of this report:
   Bot E.T.G., Vitulli J.A., Eeckels C.B.H., Verhoef J.P., Bergman G., van der Werff P.A., (2023) Offshore wind resource in the Dutch North Sea 2022: Developing a long-term measurement campaign and understanding wind conditions. TNO 2023 R10577.

The publication date at which the data have last been accessed must be indicated along the citations (e.g. Last accessed April 2023).

All measurement data is publicly accessible and is shared in .csv format. For each platform the measurement data can be retrieved via the website:
https://www.windopzee.net/meet-locaties/.

2 Measurement Campaign Across the Dutch North Sea

TNO has been performing offshore wind measurement campaigns at strategic locations in the North Sea since 2011 with the installation and data management of both a 100-meter met-mast and a co-located LiDAR situated 75 km west of IJmuiden. From 2014 onwards, TNO has further organized wind measurement campaigns with LiDARs on offshore platforms for the Dutch Ministry of Economic Affairs and Climate Policy. These campaigns are part of the “Wind op Zee” project to support the Dutch wind offshore roadmap. They consist of three longstanding locations: Lichteiland Goeree (LEG), Europlatform (EPL) and Wintershall platform K13a. Since March 15th 2023, a LiDAR has been deployed at a fourth platform, L2-FA-1, located north of the Wadden Islands, is operational (see **Figure 2.2**). An overview of the platforms is given in **Table 2.1** and **Figure 2.1**. For this report, the measurement data until the end of 2022 is considered, and therefore the data of L2-FA-1 is not yet included.

Table 2.1 Overview measurement platforms

Platform	Coordinates	Coordinates	Data start	Data end
EPL	51°59.8752’ N	3°16.4886’ E	May 2016	current
LEG	51°55.502’ N	3°40.106’ E	Oct 2014	current
K13a	53°13.0716’ N	3°13.110’ E	Nov 2016	current
L2-FA-1	53°57.6333’ N	4°29.7667' E	Mar 2023	current

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). The latter is not the main focus of TNO but we see an increasing interest in these data. These activities are coordinated by the weather meteorological agency (KNMI) and Rijkswaterstaat, the Dutch Ministry of Infrastructure and the Environment.

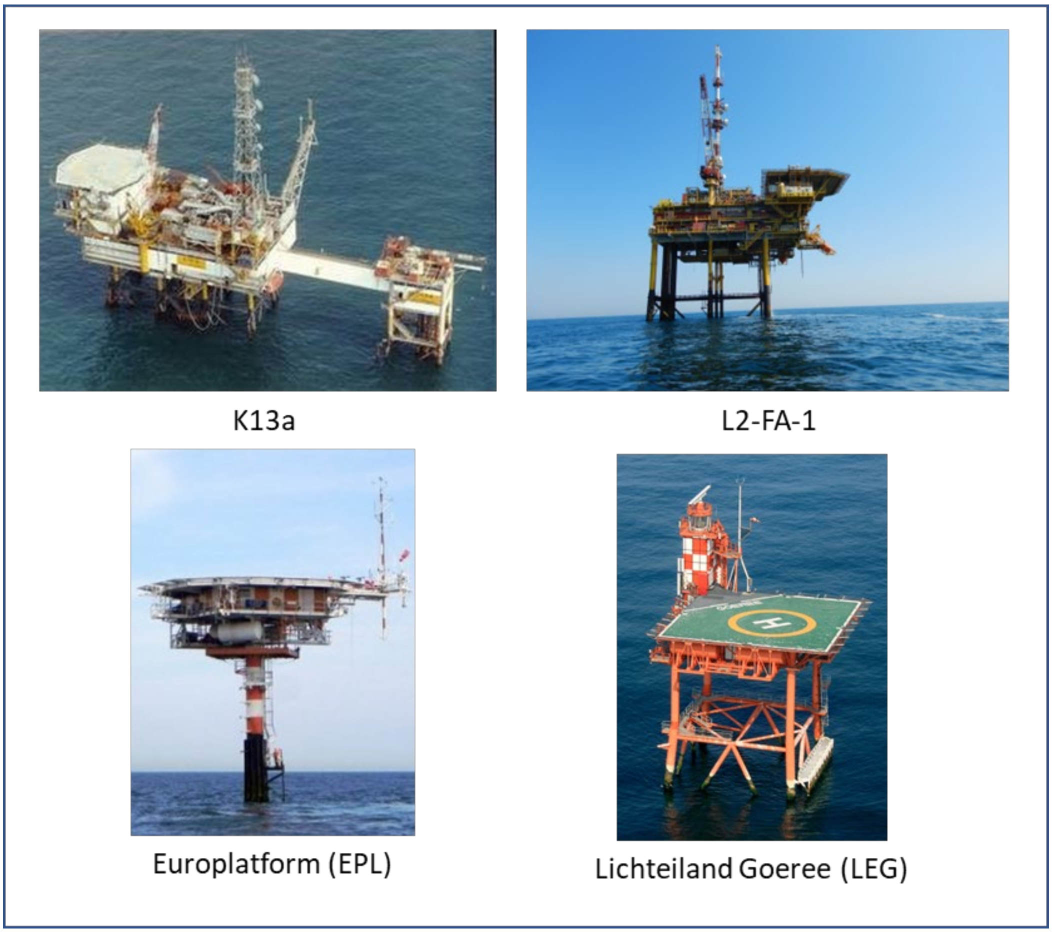


Figure 2.1 TNO offshore measurement platforms

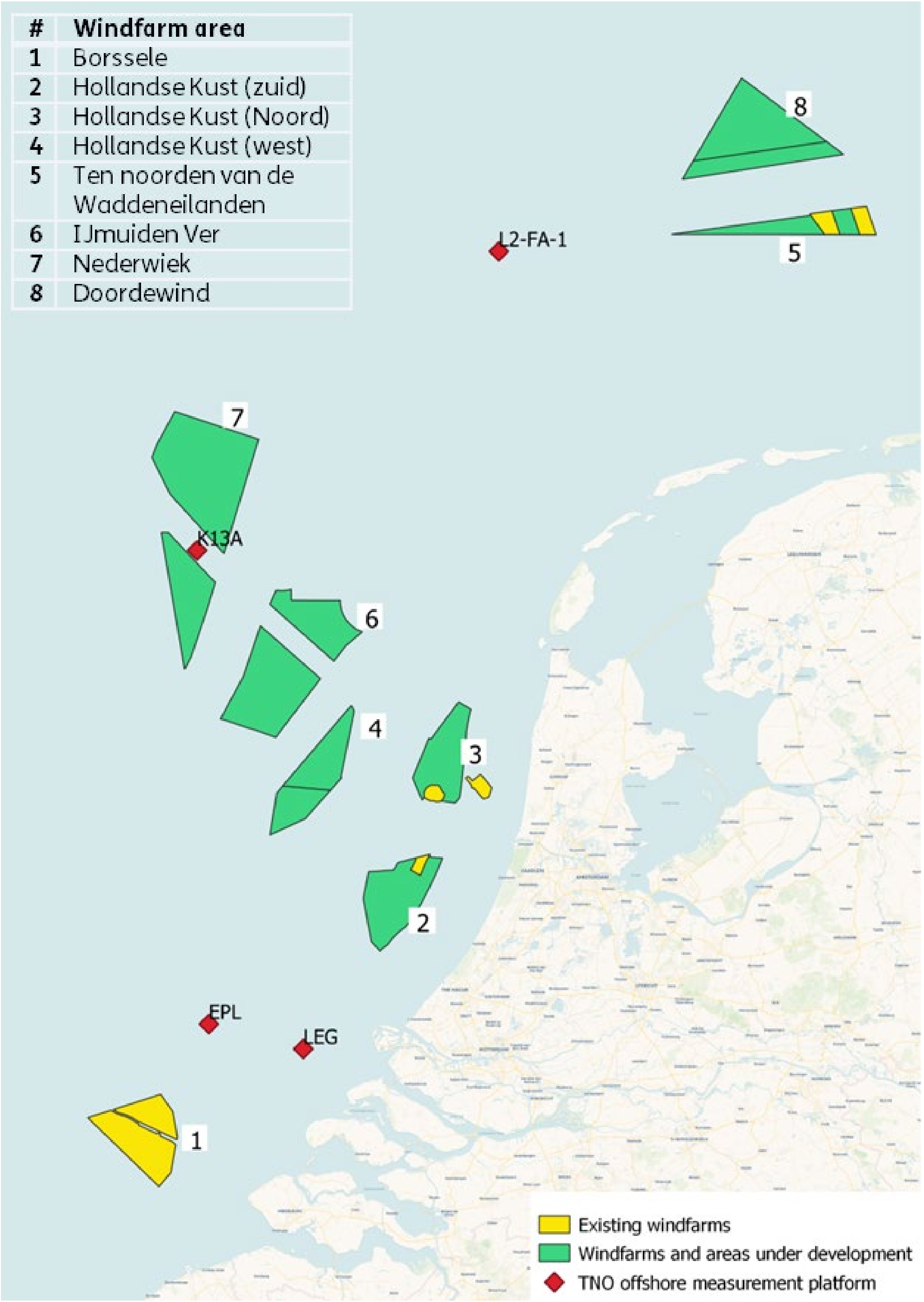


Figure 2.2 Illustration of TNO long-term offshore wind measurement campaign locations at Lichteiland Goeree (LEG), Europlatform (EPL) and Wintershall platform (K13a), and L2-FA-1, along with wind farm development zones in the Dutch North Sea

3 Wind conditions at the different platforms

In 2022 wind measurements have been performed at three different platforms (LEG, EPL and K13a) in the North Sea. In this chapter for each platform the wind conditions are evaluated over the past years (from the moment the measurements started) up to the end of 2022. The platform specific wind conditions have been summarized in the section below, the detailed evaluation for LEG can be found in [5], EPL in [6], and K13a in [7].

In 2022, a triplet of storms hit the Netherlands with the most severe and powerful one being Storm Eunice. Additional information on extreme weather conditions can be found in the reports mentioned above.

3.1 LEG

At the LEG platform, the wind analysis for the 2014-2022 period shows that the wind profiles are dominated by the regional climate, mainly by the positive phase effect of North Atlantic Oscillation (NAO). The prevailing wind direction is from the southwest with a mean direction ranging from 234° to 244° across the different sensor heights (62 m to 240 m). The average calculated wind speed ranges from 8.92 m/s at the lowest measured height of 62 m up to 10.21 m/s at 240 m, increasing gradually. In Table 3.2 average wind speed (ws) and direction (wd) at different heights for the 2014-2022 period at the LEG platform. **Figure 3.1** shows the associated wind roses. [5]

The Weibull distribution, which describes the shape of measured wind frequency distribution and inter-annual variability, shows typical offshore wind shape and scale parameters for the North Sea ($k = 2.103$ and $c = 10.880$ m/s at 140 m height). The wind speed frequency distribution is flatter and moderately skewed to the right at higher sensor heights, with more frequent wind speeds greater than 26 m/s. , see **Figure 3.2.** [5]

The resulting assessment of the shear profile shows an annualized range of 0.088 to 0.095 considering the entire data period between sequential sensor height pairs of the LiDAR. For the year 2022, the calculated day and night time shear was found to be approximately 0.08 [5].

Table 3.1 Average wind speed (Ws) and direction (Wd) at different heights for the 2014-2022 period at the LEG platform. [5]

H (m)	62	90	115	140	165	190	215	240
Ws - Mean	8.92	9.24	9.45	9.63	9.79	9.94	10.08	10.21
Ws - Max	33.02	34.38	35.23	36.08	82.61	37.5	37.91	38.27
Wd - Mean	234.5	235.6	236.3	237.3	238.5	239.8	241.4	243.9

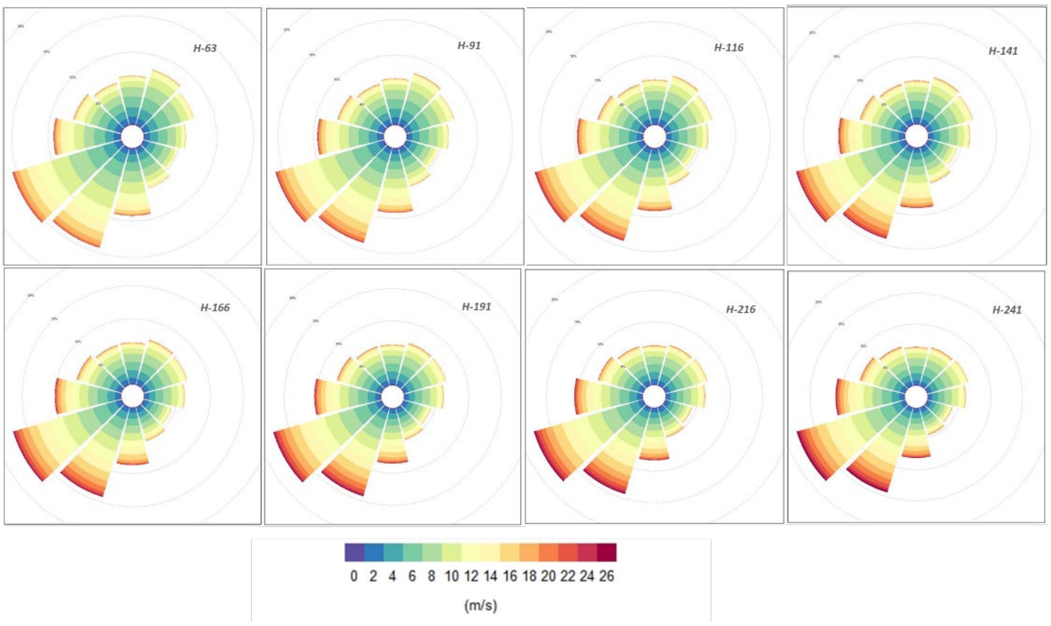
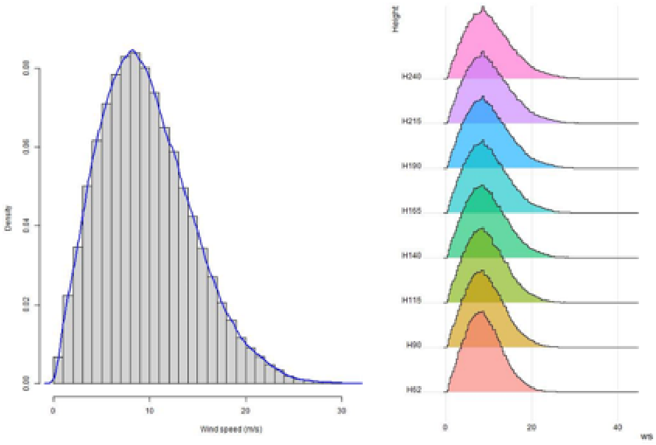


Figure 3.1 Wind roses at different heights showing the wind prevailing direction for the 2014 -2022 period [5]



Height (m)	Shape (k)	Scale (c)
62	2.220	10.078
90	2.174	10.438
115	2.134	10.673
140	2.103	10.880
165	2.078	11.071
190	2.060	11.249
215	2.046	11.425
240	2.040	11.598

Figure 3.2 Frequency distribution and Weibull curve fitting at 140 m height (left), frequency distributions at different heights for the measurement campaign (centre) with k and c parameters (table) at LEG for 2014-2022 **Note:** The years 2014, and 2015 were excluded due to incomplete years caused by the start of the campaign or to poor overall availability. [5]

3.2 EPL

At the EPL platform, the wind analysis for the 2016-2022 period shows that the wind profiles are dominated by the regional climate, mainly by the positive phase effect of North Atlantic Oscillation (NAO). The prevailing wind direction is from the southwest with a mean direction ranging from 228° to 237° across the different sensor heights (63 m to 291 m). The average calculated wind speed ranges from 9.05 m/s at the lowest measured height of 63 m up to 10.18 m/s at 291 m, increasing gradually. In **Table** 3.2 the average wind speed (ws) and direction (wd) at different heights at the EPL platform are presented and **Figure** 3.3 shows the associated wind roses. [6]

The Weibull distribution, which describes the shape of measured wind frequency distribution and inter-annual variability, shows typical offshore wind shape and scale parameters for the North Sea (2.052 and c = 10.945 m/s at the 141 m measurment height). The wind speed frequency distribution is flattened and moderately skewed right with higher heights, with more frequently occuring wind speeds greater than 26 m/s, see **Figure 3.4**. [6]

The resulting assessment of the shear profile shows an annualized range of 0.052 to 0.085 considering the entire data period between sequential sensor height pairs of the LiDAR. For the year 2022, the calculated day and night time shear was found to be approximately 0.08 and 0.07 respectively. [6]

Table 3.2 Average wind speed (Ws) and direction (Wd) at different heights for the 2016-2022 period at the EPL platform. [6]

H (m)	63	91	116	141	166	191	216	241	266	291
Ws – Mean	9.05	9.35	9.52	9.67	9.79	9.89	9.97	10.04	10.11	10.18
Ws – Max	39.07	39.16	38.56	38.17	39.22	36.86	42.47	47.06	56.89	44.28
Wd – Mean	227.7	228.5	229.3	230.4	231.5	232.7	234.0	235.0	235.8	236.6

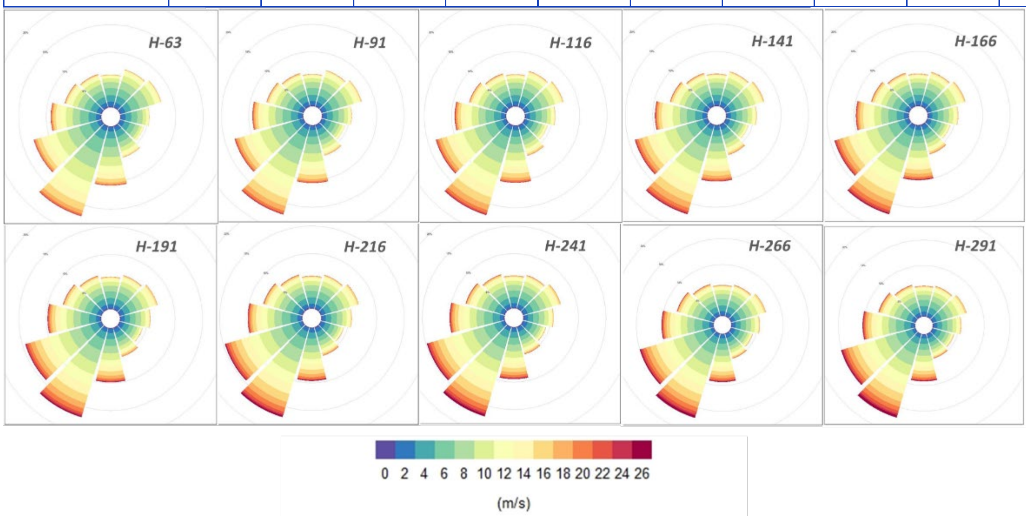
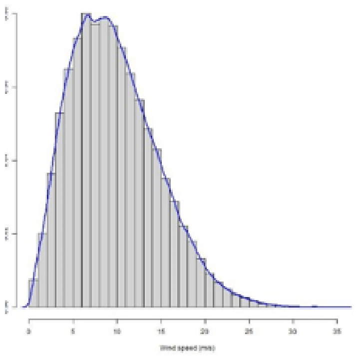
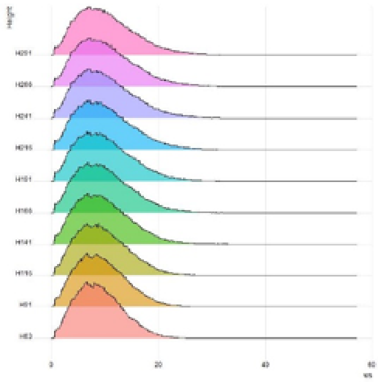


Figure 3.3 Wind roses at different heights showing the wind prevailing direction for the 2016 -2022 period [6]





Height (m)	Shape (k)	Scale (c)
63	2.150	10.224
91	2.113	10.566
116	2.082	10.770
141	2.052	10.945
166	2.025	11.083
191	2.003	11.200
216	1.984	11.301
241	1.968	11.392
266	1.959	11.486
291	1.949	11.578

Figure 3.4 Frequency distribution and Weibull curve fitting at 141 m height (left), frequency distributions at different heights for the measurement campaign (centre) with k and c parameters (table) at EPL for 2016-2022. **Note:** The years 2016, 2018 and 2019 were excluded due to incomplete years caused by the start of the campaign or to poor overall availability [6]

3.3 K13A

At the K13a platform, the wind analysis for the 2016-2022 period shows that the wind profiles are dominated by the regional climate, mainly by the positive phase effect of North Atlantic Oscillation (NAO). The prevailing wind direction is from the southwest with a mean direction ranging from 241° to 251° across the different sensor heights (63 m to 291 m). The average calculated wind speed ranges from 9.29 m/s at the lowest measured height of 63 m up to 10.44 m/s at 291 m, increasing gradually. In Table 3.3 the average wind speed (ws) and direction (wd) at different heights at the EPL platform are presented and Figure 3.5 shows the associated wind roses. [7]

The Weibull distribution, indicating wind regimes and inter-annual variability, shows wind speed distributions with typical offshore wind k, and c parameters (k = 2.155 and c = 11.389 m/s at 141 m height). The wind speed frequency distribution is flattened and moderately skewed right with higher heights, with more frequent wind speeds greater than 26 m/s, see **Figure** 3.6 [7].

The resulting assessment of the shear profile shows an annualized range of 0.026 to 0.111 considering the entire data period between sequential sensor height pairs of the LiDAR. For the year 2022, the calculated day and night time shear is not properly represented by the fitted shear exponent, indicating shear relaxation between heights [7].

Table 3.3 Average wind speed (Ws) and direction (Wd) at different heights for the 2016-2022 period at the K13a platform. [7]

H (m)	63	91	116	141	166	191	216	241	266	291
Ws - Mean	9.29	9.68	9.92	10.08	10.19	10.28	10.34	10.38	10.42	10.44
Ws - Max	32.41	34.02	34.88	35.77	36.43	36.84	37.27	37.67	38.00	38.09
Wd - Mean	241.2	243.0	244.3	245.4	246.4	247.5	248.5	249.4	250.1	250.8

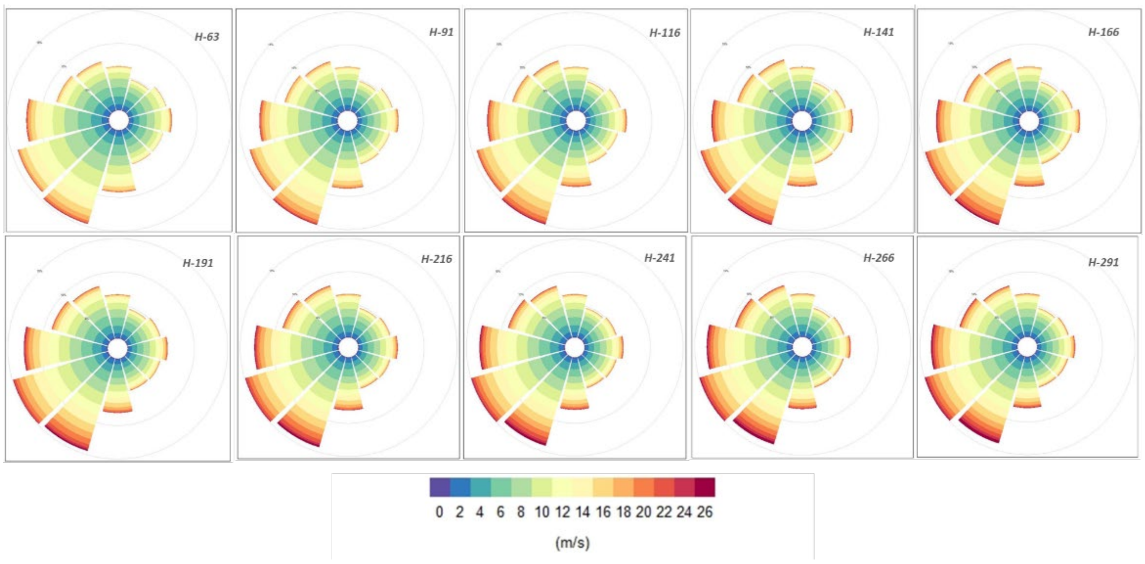
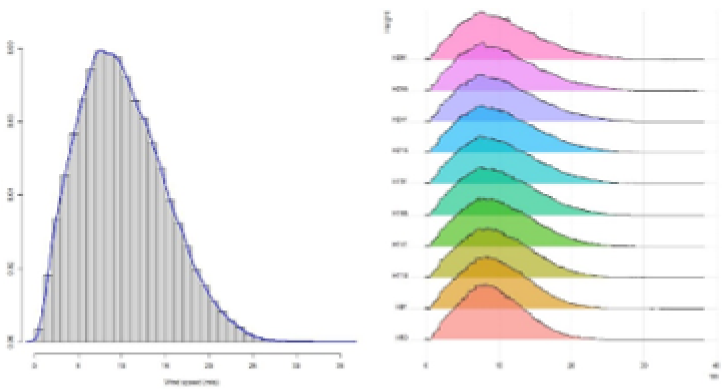


Figure 3.5 Wind roses at different heights showing the wind prevailing direction for the 2016 -2022 period. [7]



Height (m)	Shape (k)	Scale (c)
63	2.263	10.510
91	2.238	10.943
116	2.195	11.207
141	2.155	11.389
166	2.120	11.519
191	2.089	11.615
216	2.063	11.686
241	2.040	11.736
266	2.022	11.777
291	2.010	11.806

Figure 3.6 Frequency distribution and Weibull curve fitting at 141 m height (left), frequency distributions at different heights for the measurement campaign (centre) with k and c parameters (table) at K13a for 2016-2022. [7]

4 Comparison to other measurement locations

4.1 Comparison of LiDAR measurements and KNMI wind atlases

For the platforms LEG, EPL and K13a, LiDAR measurements have been correlated to data from two KNMI wind atlases. The KNMI North Sea Wind (KNW) atlas contains climatological and hourly undisturbed wind data, based on 40 years (1979-2019) of re-analyses data with an accuracy of 0.2 m/s at wind turbine hub height offshore. The Dutch Offshore Wind Atlas (DOWA) contains 10 years (2008-2017) wind climatology for the North Sea, with a better hourly correlation than the KNW-atlas.

For each platform a year of data has been selected with high availability in the LiDAR measurements that coincides with available data from the wind atlases, and for varying heights that are relevant for wind energy.

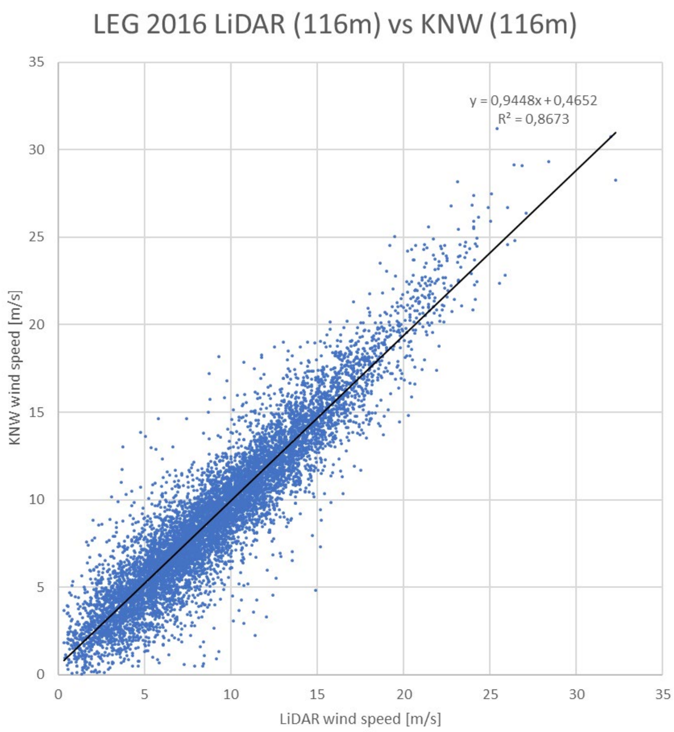


Figure 4.1: Correlation plot of LiDAR data from LEG at 115 m height with data from the KNMI wind atlas KNW for the year 2016.

Figure 4.1 shows the correlation plot of LiDAR measurements of LEG at 115 m height for the year 2016 with data from KNW. With a correlation factor of 0.867 the relation between the wind atlas and measurements is reasonably strong. Similar results have been observed with the DOWA wind atlas in **Figure 4.2**.

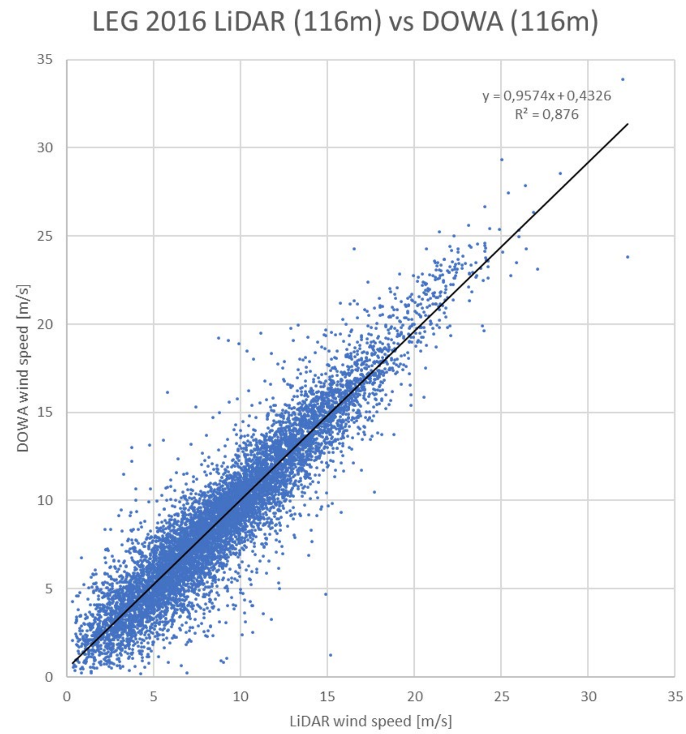


Figure 4.2: Correlation plot of LiDAR data from LEG at 115 m height with data from the KNMI wind atlas DOWA for the year 2016.

Also for the EPL platform at 166 m height and the K13a platform at 116 m height, reasonably strong correlation with the wind atlases are found with correlation coefficients of approximately 0.87, see **Figure 4.3** up to **Figure 4.6**. These results show that the quality of the correlation between wind atlas and LiDAR data is similar for different heights and different years (2016 and 2017).

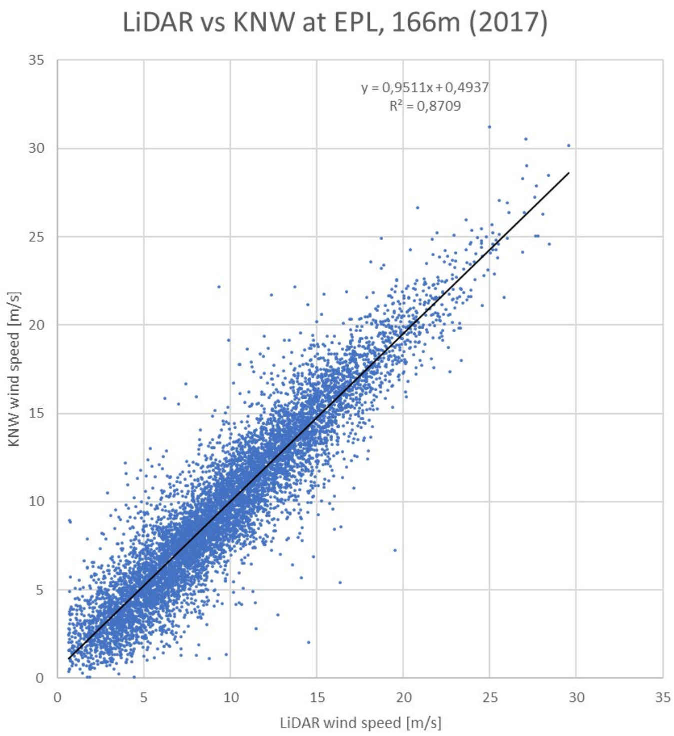


Figure 4.3: Correlation plot of LiDAR data from EPL at 166 m height with data from the KNMI wind atlas KNW for the year 2017.

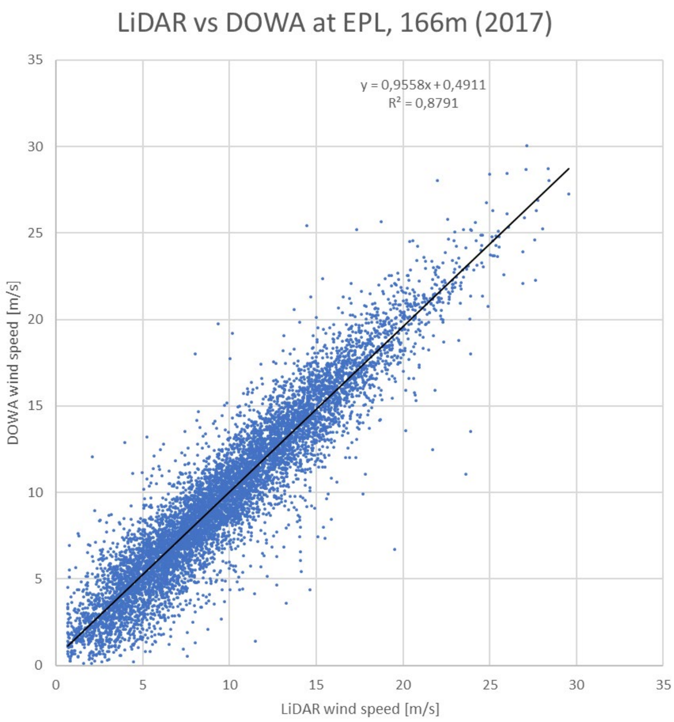


Figure 4.4: Correlation plot of LiDAR data from EPL at 166 m height with data from the KNMI wind atlas DOWA for the year 2017.

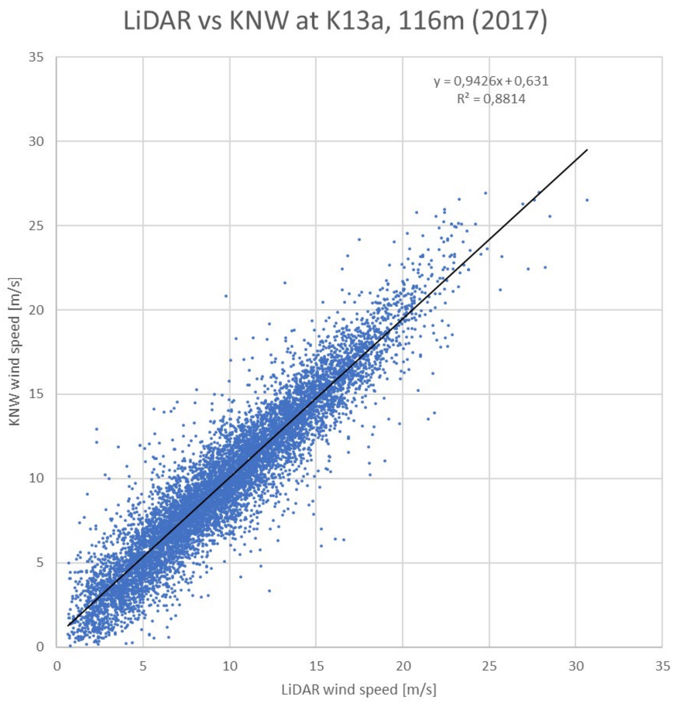


Figure 4.5: Correlation plot of LiDAR data from K13a at 116 m height with data from the KNMI wind atlas KNW for the year 2017.

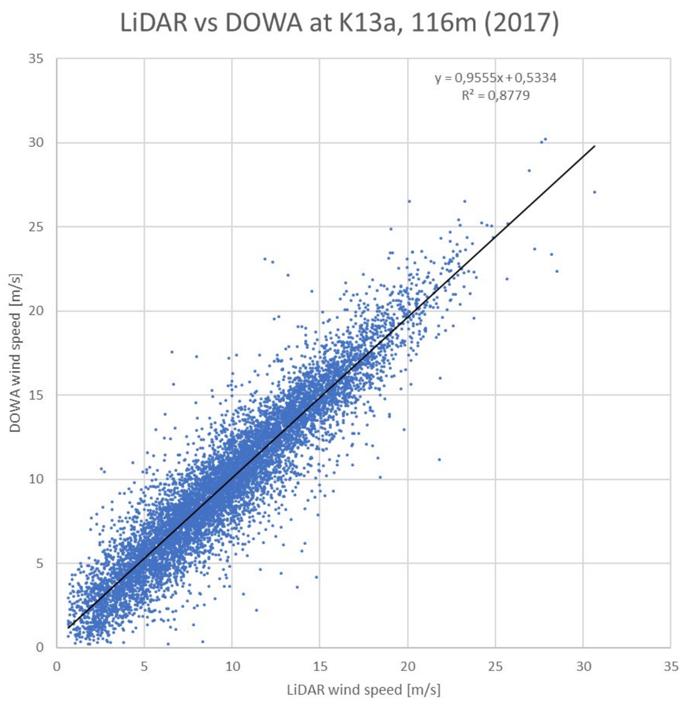


Figure 4.6: Correlation plot of LiDAR data from K13a at 116 m height with data from the KNMI wind atlas DOWA for the year 2017.

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

In order to quantify the quality of the correlation between the wind atlases of KNMI and the LiDAR measurements, these results have been compared with mutual correlations between LiDAR measurements of these platforms.

For the period 2016 – 2022, the correlation of the LiDAR data from LEG and EPL is plotted in **Figure 4.7**. The correlation coefficient for these platforms is 0.90, which shows that the correlation between the measurements of these platforms is much stronger in comparison with the correlation between LiDAR measurements and the wind atlases in the previous section. This suggests that LiDAR measurements at a distance of 30 km or less from the location of interest will provide more accurate results in comparison with the wind atlases. However, local data from the wind atlases will provide more accurate results than measurements at (much) larger distances, as can be seen from the correlation of the LiDAR data from K13a and EPL in **Figure 4.8**, where a correlation coefficient of only 0.63 is found. The distance between these platforms is approximately 135 km.

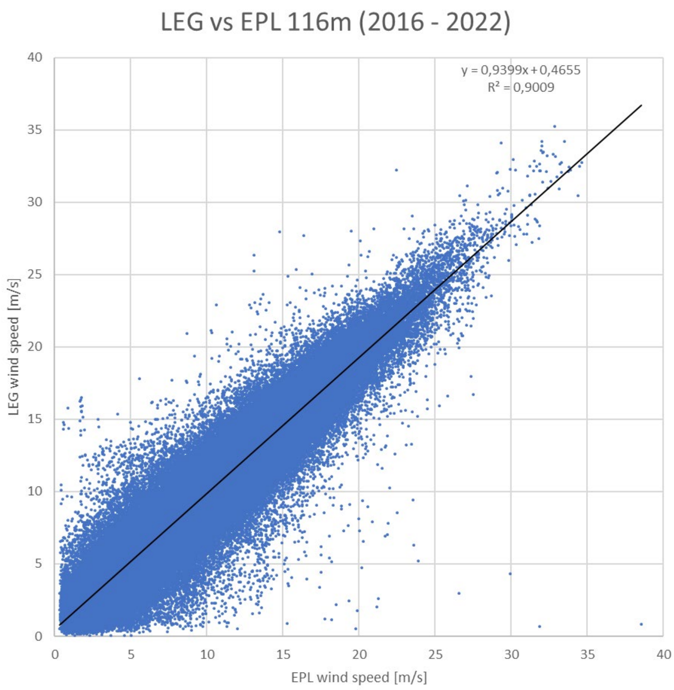


Figure 4.7: Correlation plot of LiDAR data between LEG and EPL platforms for the period 2016-2022.

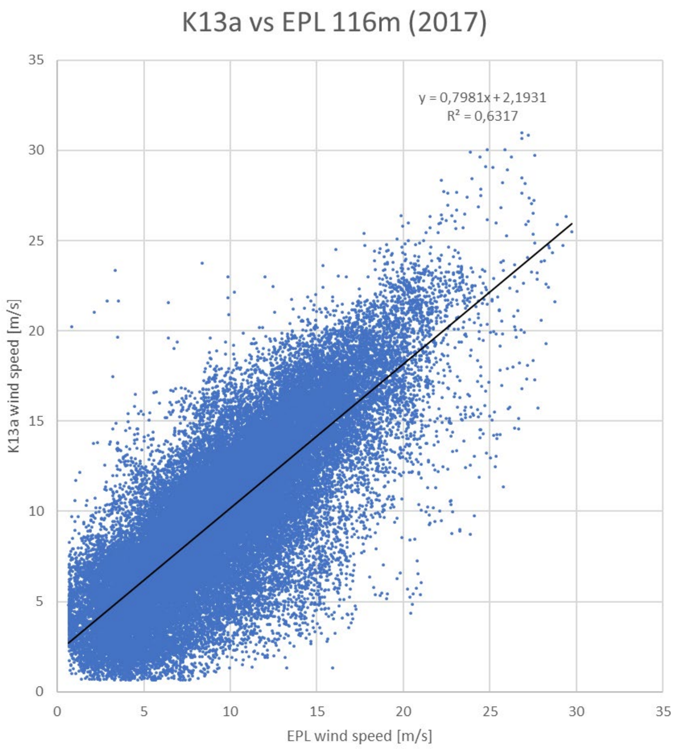


Figure 4.8: Correlation plot of LiDAR data between K13a and EPL platforms for the year 2017.

4.3 Establishment of long term wind resource

In this section, long-term wind data (2000-2022) at 100 m height from ERA5 is used with LiDAR data (2016-2022) at 116 m height from the three platforms to assess the long term wind resource for these location using Measure-Correlate-Predict (MCP) methodology. ERA5 is the fifth generation European Centre for Medium range Weather Forecast (ECMWF) reanalysis for the global climate and weather, providing hourly estimates of the wind data. Two-parameter correction based on linear regression has been applied, since this method leads to the highest accuracy of the average wind speed compared with single-factor correction.

For the LEG platform, correcting the long term wind speed from ERA5 data with MCP based on LiDAR data of the year 2016, results in a corrected long term wind speed of 9.494 m/s at 115 m height. The average corrected long term wind speed based on MCP applied over the years 2016 – 2022 is 9.437 m/s with a correlation coefficient of 0.870, see **Table 4.1**. The long term wind speed is 0.14% lower than the measured average wind speed in the 2014-2022 period, see Table 3.1. The standard deviation over these 7 years is 0.076 m/s resulting in a standard error of 0.0289 m/s. Using 1.96 times the standard error to calculate the 95% confidence interval of the long term wind speed at 115 m height results in 9.437 ± 0.057 m/s.

Table 4.1: Long term wind speed at LEG based on ERA5 using MCP methodology

Year	R^2	Corrected long term wind speed [m/s]
2016	0.864	9.494
2017	0.864	9.581
2018	0.855	9.468
2019	0.875	9.398
2020	0.892	9.398
2021	0.869	9.335
2022	0.873	9.386
Average	0.870	9.437

For the EPL platform, the average corrected long term wind speed based on MCP applied over the years 2016 – 2022 at 116 m height is 9.530 m/s with a correlation coefficient of 0.874, see **Table 4.2**. The long term wind speed is 0.1% higher than the measured average wind speed in the 2016-2022 period, see **Table** 3.2. The standard deviation of the yearly samples is 0.131 m/s, resulting in a 95% confidence interval of 9.530 ± 0.097 m/s.

Table 4.2: Long term wind speed at EPL based on ERA5 using MCP methodology

Year	R^2	Corrected long term wind speed [m/s]
2016	0.858	9.690
2017	0.869	9.727
2018	0.866	9.552
2019	0.891	9.485
2020	0.899	9.485
2021	0.858	9.317
2022	0.879	9.457
Average	0.874	9.530

For the K13a platform, the average corrected long term wind speed over the years 2017 – 2022 at 116 m height is 9.89 m/s with a correlation coefficient of 0.912, see **Table 4.3**. Because the measurements started at the end of 2016, the year 2016 is not considered here. The long term wind speed is 0.30% lower than the measured average wind speed in the 2016-2022 period, see **Table** 3.3. The standard deviation of the yearly samples is 0.058 m/s, resulting in a 95% confidence interval of 9.890 ± 0.046 m/s.

Table 4.3: Long term wind speed at K13a based on ERA5 using MCP methodology

Year	R^2	Corrected long term wind speed [m/s]
2017	0.918	9.802
2018	0.910	9.998
2019	0.914	9.879
2020	0.927	9.868
2021	0.914	9.896
2022	0.892	9.899
Average	0.912	9.890

Instead of ERA5, it is also possible to use more accurate wind atlases from KNMI: the 40 years (1979-2019) KNW-atlas or the 10 years (2008-2017) Dutch Offshore Wind Atlas (DOWA) KNMI wind atlases KNW or DOWA. However, because direct correlation between these atlases with measurements is limited or not possible at all, using these wind atlases requires a three-step MCP approach:

- Determine correlation factor between ERA5 (100 m) with LiDAR (116 m)
- Apply the correction factor on ERA5 time series that matches the time period of the wind atlas and calculated the average wind speed for this period.
- Correct the time series of the wind atlas to match the average wind speed in the previous step.

This method will not lead to different long term wind speeds (since these are corrected by the correlation factor) but would result in more accurate wind direction distributions and thus a more accurate wind rose.

5 Wake impact investigation of Borssele

5.1 Borssele offshore wind farm zone

In this section an analysis is presented on the wake effects from offshore wind farm Borssele at the platforms EPL and LEG. **Figure 5.1** shows the location of these platforms with respect to the Borssele wind farm zone. Several Belgian wind farms are located south of the Borssele wind farm zone.

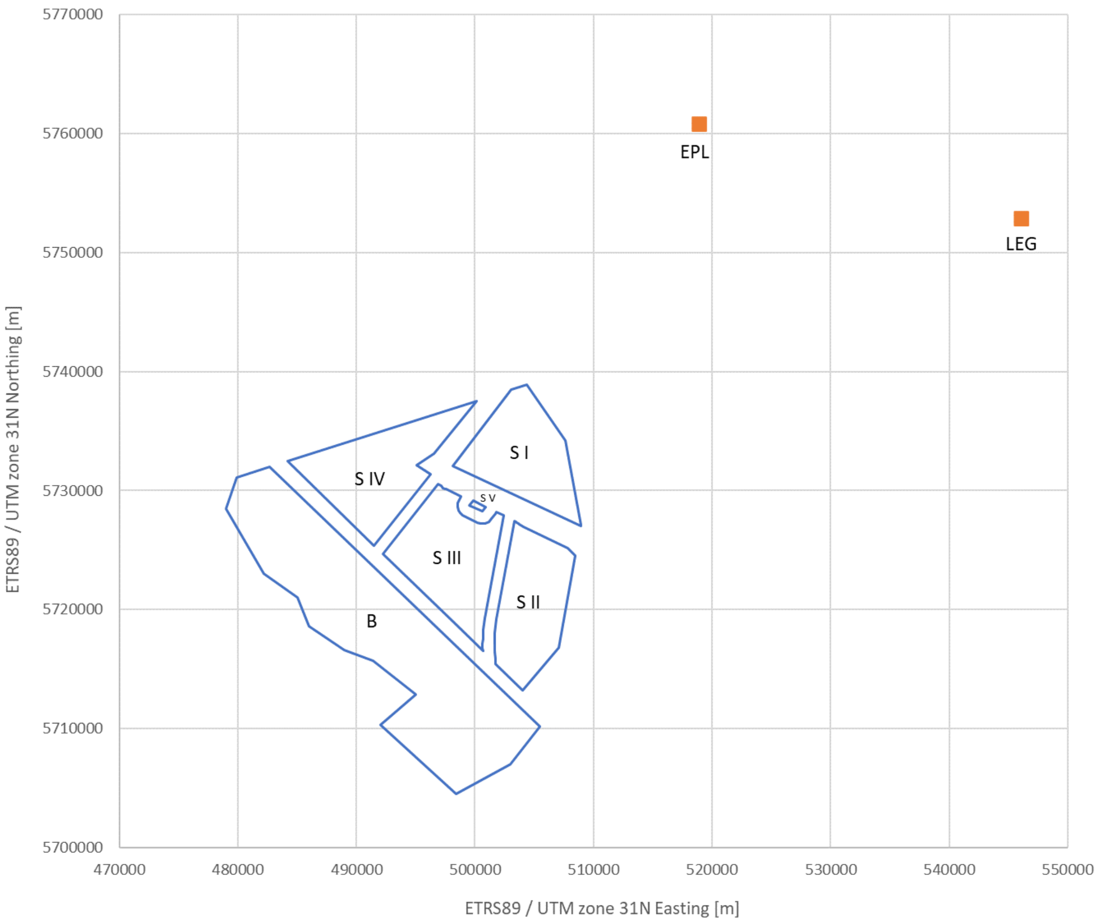


Figure 5.1: Map of the sites of Borssele offshore wind farm zone (S I, S II, S III, S IV and S V), the location of the Belgium wind farms (B) and the platforms EPL and LEG.

The distance between platform EPL and the Borssele wind farm is 26.7 km and the distance to the nearest Belgian wind turbine is 46.2 km. For LEG, the distance to the Borssele wind farm is 43.2 km and the distance to the nearest Belgian wind turbine is 60.0 km.

Site I & II of the Borssele wind farm became operational in April 2020 with a total energy production of 752 MW (installed capacity). Site III and IV became fully operational in January 2021 with a total energy production of 731.5 MW, see **Figure 5.2** for the time line of the wind farms becoming fully operational. For the analysis of wake effects from Borssele, the wind measurements are divided in two periods: the first period from January 2016 until March 2020 where only Belgian wind farms were partly in operation with a total energy production of 1556 MW, and the second period from January 2021 and December 2022 where the Borssele wind farm sites I-IV were fully operational. Site V is an innovation site with negligible wake effects outsite the Borssele wind farm zone.

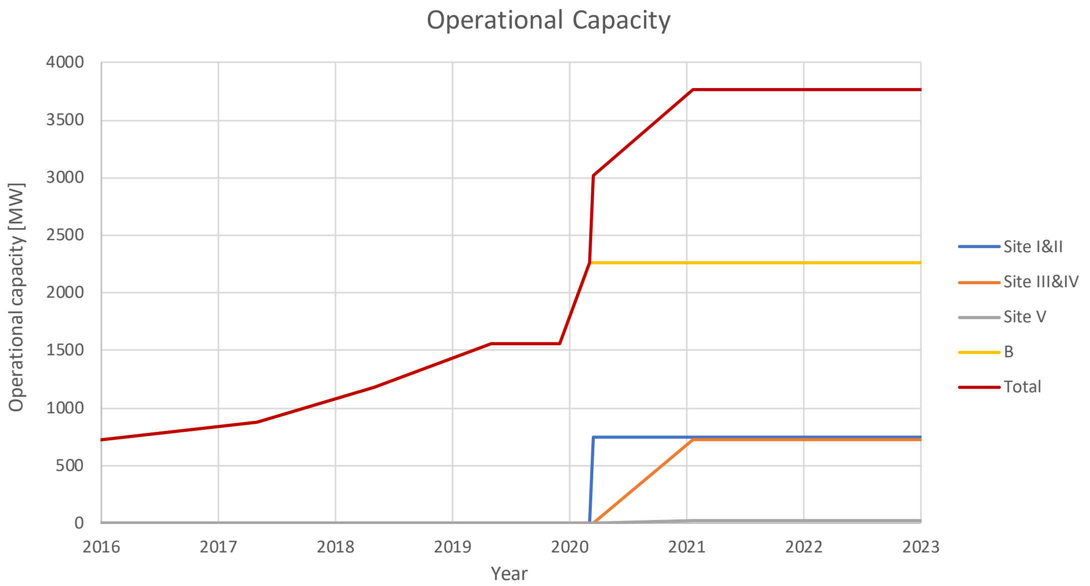


Figure 5.2: Time line of the installed and fully operational capacity at and near the Borssele offshore wind farm zone.

5.2 Wake impact at LEG and EPL

For the wake impact analysis of the Borssele offshore wind farm at the platforms LEG and EPL, LiDAR data from these platforms has been used at 115-116 m height. To increase the accuracy of the results, some filtering has been applied on the dataset:

- To ensure reliable wind directions from the LiDAR data, the maximum difference between EPL and LEG wind directions is ±25°.
- Only wind speed data is selected between 5.5 and 12.5 m/s to ensure strong wake effects, i.e. when all turbines are operating at high thrust values. At higher wind speeds the wind turbines operate at low thrust values and at full power where wake losses from neighbouring wind farms do not occur.

Wind speed reductions from the Borssele wind farm at the platforms can be determined by plotting the ratio of the measured wind speeds as a function of the wind direction. **Figure 5.3** shows this ratio of the measured wind speeds between EPL and LEG for the two periods. For comparison, results from a wake simulation with FarmFlow [8] are also included. This wake model solves the steady-state Navier-Stokes equations in parabolic form (by eliminating the stream-wise second order viscous terms) in combination with a k-epsilon turbulence model.

In the plot two sectors are indicated where only one of the two platforms is in the wake region of the Borssele wind farm zone. EPL is in the wake sector of the Borssele wind farm between

195° and 225°, and LEG between 225° and 255°. In perfect agreement of these sectors, the wake simulations show a minimum ratio of 0.89 around 210° and a maximum ratio of 1.09 around 242°. Data from the LiDAR measurements show approximately the same ratios for the period 2021-2022, however with a shift of the wind direction with approximately 6.5°. For the period 2016-2020 where only some Belgian wind farms were operational, the minimum and maximum ratios are 0.98 and 1.02 approximately, see the blue line in the sectors 185-225° and 225-255° respectively. The average effect of the Borssele wind farm for the whole sector for both LEG and EPL is estimated at 4.5%.

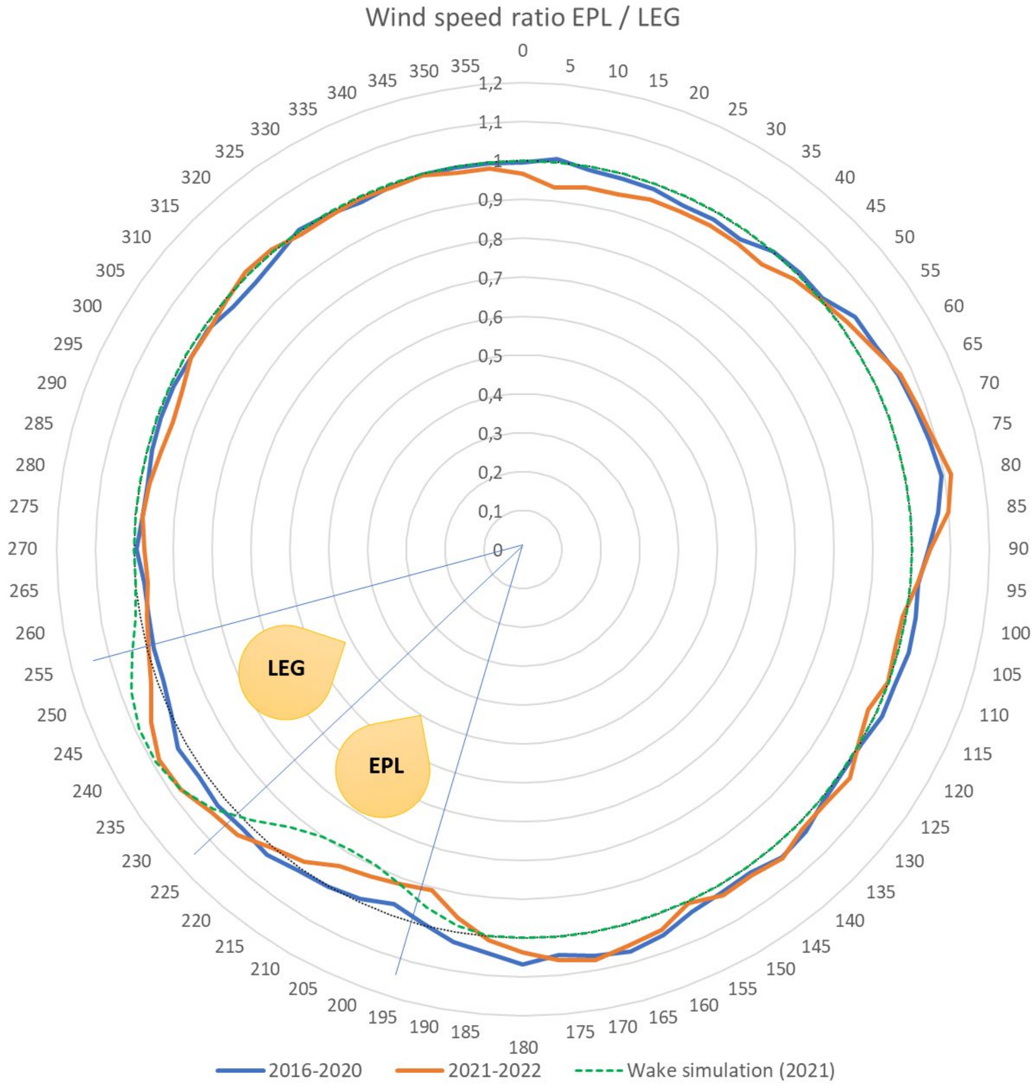


Figure 5.3: Wind speed ratios between data from the platforms EPL and LEG for wind speeds between 5.5 and 12.5 m/s in the period 2016-2020 and 2021-2022. Results from a wake simulations are added for comparison.

The frequency for wind from the Borssele sector at LEG is 17.2% and for EPL 13.0% according to the wind roses in Chapter 3. According to the Weibull distributions, the frequency of wind between 5.5 and 12.5 m/s in these sectors is 51%. This all leads to a total reduction of the average wind speed by wakes from the Borssele wind farms at the platforms LEG and EPL of 4.5% · 13% · 51% = 0.30% or 0.029 m/s.

Apart from these wake sectors, two sectors with positive ratios are visible for all periods: between 60° and 95° and between 160° and 185° the wind speeds measured at EPL is 7% to 10% higher than at LEG. It is not clear what causes this effect. A comparison with data from KNMI wind atlases KNW and DOWA (see Figure 5.4) shows a somewhat similar effect at the 60-95° sector with DOWA wind data only. However, the DOWA data also shows a positive ratio of 1.07, on average, in a very large sector between 130° and 230°, while KNW shows no difference in wind speeds (i.e. ratio = 1.0) between the location of the platforms.

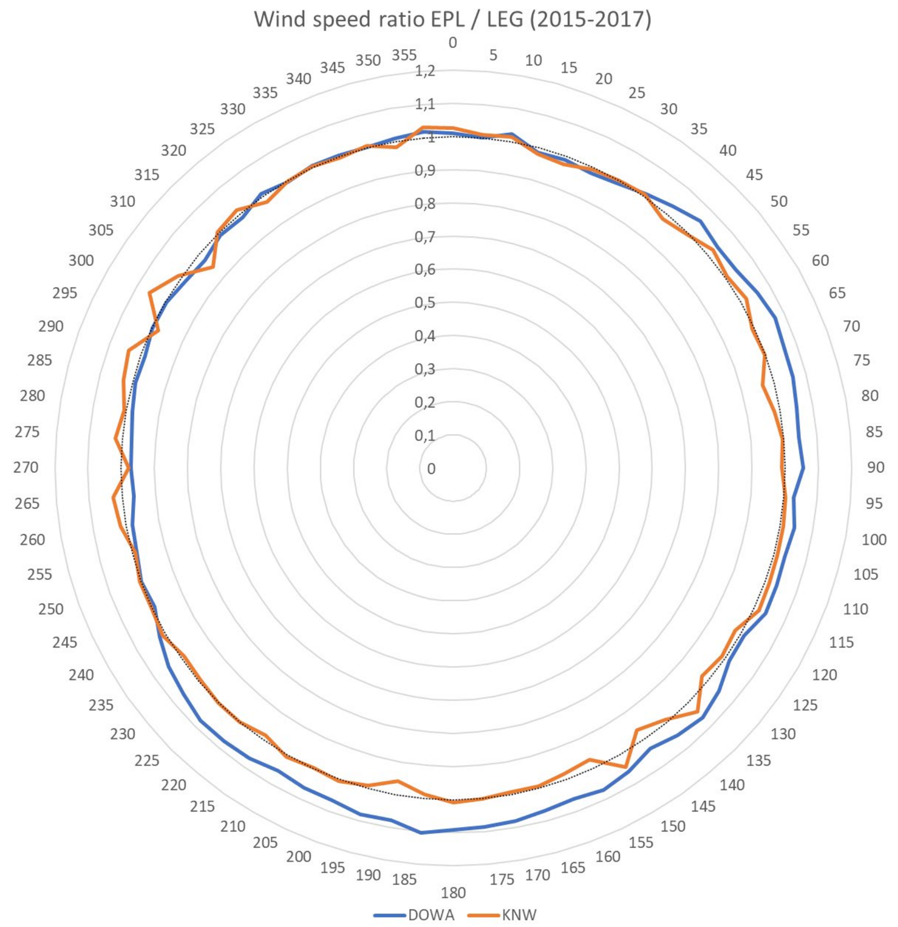


Figure 5.4: Wind speed ratios between the locations of the two platforms EPL and LEG for the period 2015–2017, determined from the DOWA and KNW atlas.

6 Conclusions and recommendations

TNO performs for The Dutch Ministry of Economic Affairs and Climate Policy measurement campaigns in the North Sea since 2014 at different strategically chosen locations. Currently, the locations of the measurements are Lichteiland Goeree platform (LEG), Europlatform (EPL) and Wintershall Noordzee B.V. platform K13a, under the program "Wind op Zee".

This report presents a series of analyses that provides insight into the correlations, long-term wind speed predictions, and other use cases that leverage both the on-site LiDAR data across the LEG, EPL, and K13a platforms in the Dutch North Sea for the period 2014-2022, and different reanalysis and modelled data from wind atlases, namely DOWA, KNW, and ERA5.

A correlation factor of 0.867 was deduced for LEG when comparing LiDAR measurement at the platform locations to KNW atlas. This indicates that the relation between the wind atlas and measurements is reasonably strong. Similarly, results have been observed with the DOWA wind atlas at 0.876. For the EPL and K13a platforms, similar (reasonably strong) correlations with the DOWA and KNW atlases were observed.

While cross comparing the three platform locations to each other, it was observed that LiDAR measurements at a distance of 30 km or less from the location of interest will provide more accurate results in comparison to the wind atlases. LEG and EPL have a correlation factor of 0.9, slightly higher than the 0.87 factor observed between atlases. However, local data from the wind atlases will provide more accurate results than measurements at (much) larger distances, as observed with a correlation factor of 0.63 between K13a and EPL, which are approximately 135km apart.

In a first attempt to establishing a long term correction to the measured data, ERA5 was used in the MCP analysis in order to obtain a 20 year representation of the location. The deduced long term wind speeds at 115-116 m height was 9.55 m/s, 9.53 m/s, and 9.89 m/s for LEG, EPL, and K13a respectively. These values deviate between 0.1% to 0.3% from the average wind speed obtained from the 6-7 year period of measurements..

Finally, an investigation into the wake impacts of the recently operational Borssele wind farm was performed. By separating the data into 2 periods (before and after the construction) and plotting the ratio of wind speed at EPL and LEG directional, the maximum impact of Borssele was found to be 9.0% for LEG at 240° wind direction, and 11% for EPL at 210° wind direction. The estimated total impact on the average wind speed for all sectors is estimated as 0.30% or 0.029 m/s for both platforms.

Overall this work can be further improved upon by considering:

- MCP investigations with other long term sources, or by applying multi-step approaches.
- Establishing new measurement locations near K13a for improved correlations and MCP analysis, and in general establishing a larger network of measurement locations that are reasonably spaced.

- Relaunch of DOWA with missing data from 2018 and beyond can enhance MCP analysis and improve understanding of wind farm performance in clustered wind farms.
- When more wind farms become operational at the North sea, these measurements can generate further insight in wake effects and serve as input for models such as DOWA.

7 Acknowledgements

The measurement campaigns at the offshore measurement platforms LEG, EPL, and K13a are carried out on the authority of the Ministry of Economic Affairs and Climate Policy of The Netherlands.

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