Long-term measurement campaign and understanding wind conditions, 2023

Offshore wind resource at the North Sea

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TNO Wind Energy is accredited conform ISO / IEC 17025 and accepted as RETL under IECRE WE.

- Power performance measurements conform to IEC 61400-12-1, MEASNET Power Performance measurement procedure, FGW TR2, FGW TR5
- NTF/NPC measurements conform to IEC 61400-12-2
- Mechanical loads measurements conform to IEC 61400-13
- Meteorological measurements (wind speed, wind direction, temperature, air pressure and relative humidity) conform to IEC 61400-50-1
- Verification of ground-based or nacelle-mounted Remote Sensing Devices conform to IEC 61400-50-2
- Verification of Floating Lidar Systems conform to IEC 61400-50-2 and IEA Recommended Practices 18

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 as a first phase, to further expand to 21 GW by 2030. The Netherlands is moving ahead with almost yearly tendering rounds for upcoming development areas. New developments have been started for the search areas IJmuiden Ver and Nederwiek Wind Farm Zone.

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 meteorological 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 Climate Policy and Green Growth. These campaigns are part of the Wind op Zee project to support the Dutch wind offshore roadmap. They consist of three long-standing locations: Lichteiland Goeree (LEG), Europlatform (EPL) and Wintershall platform K13-A. Since March 2023 a lidar has been deployed for wind measurements at a fourth platform, L2-FA-1, located north of the Frisian Islands. TNO is accredited for performing these measurements in accordance with IEC 61400-50-2.

This report presents a series of analyses that provide insight into the correlations of measurement data and wind atlas data ERA5, evolution of long term wind resource at the different location in the Dutch North Sea, wake impact of Borssele wind farm observed on measurement data and a summary of wind resource characteristics for each measurement location over the measurement period (2014-2023).

The correlations plots of the lidar measurements at the platforms show a correlation of 0.85 for LEG and EPL with ERA5 data at 100 m height. At K13-A and L2-FA-1 a higher correlation of 0.93 with ERA5 at 100 m height is determined.

The long term wind speed at 100 m height varies between c = 9.36 m/s at LEG up to c = 10.02 m/s at L2-FA-1. These values are based on ERA5 data over the period 1970 until 2023 and corrected based on the correlation data.

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Abbreviations

EPL	Europlatform
LEG	Lichteiland Goeree
WRA	wind resource assessment

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 government has defined a roadmap for the Dutch offshore wind portfolio to reach 21 GW by 2030 [2][1]. The intermediate milestone of reaching 4.5 GW by 2023 has been reached with an installed capacity of 4.7 GW in the Dutch part of the North Sea. The Netherlands is moving ahead with almost yearly tendering rounds for upcoming development areas such as IJmuiden Ver and Nederwiek Wind Farm Zone [1].

To reach such ambitious realization of operational offshore wind farms in the Dutch part of the North Sea, importance must be given to both spatial planning, and characterization of this precious, valuable and variable resource in order to ensure profitability and an overall sound business case.

One crucial requirement to evaluate the financing of an offshore wind farm is the wind resource assessment (WRA) of a given site. Accurate long-term offshore wind measurements allow for improved WRAs which reduce uncertainties and increase the financial success of these projects. This increases the trust between interested stakeholders including developers, consultants, the financial community, the government and policymakers. At the same time it allows the selection and identification of strategic locations.

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 meteorological 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 Ministry of Climate Policy and Green Growth. 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 K13-A. Since March 2023 a lidar has been deployed for wind measurements at a fourth platform, L2-FA-1, located north of the Frisian Islands (figure 1.1). TNO is accredited for performing these measurements in accordance with IEC 61400-50-2 [3].

1.2 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. 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

[1] On 14 May 2024, an updated planning was published indicating a new end date to 2032.

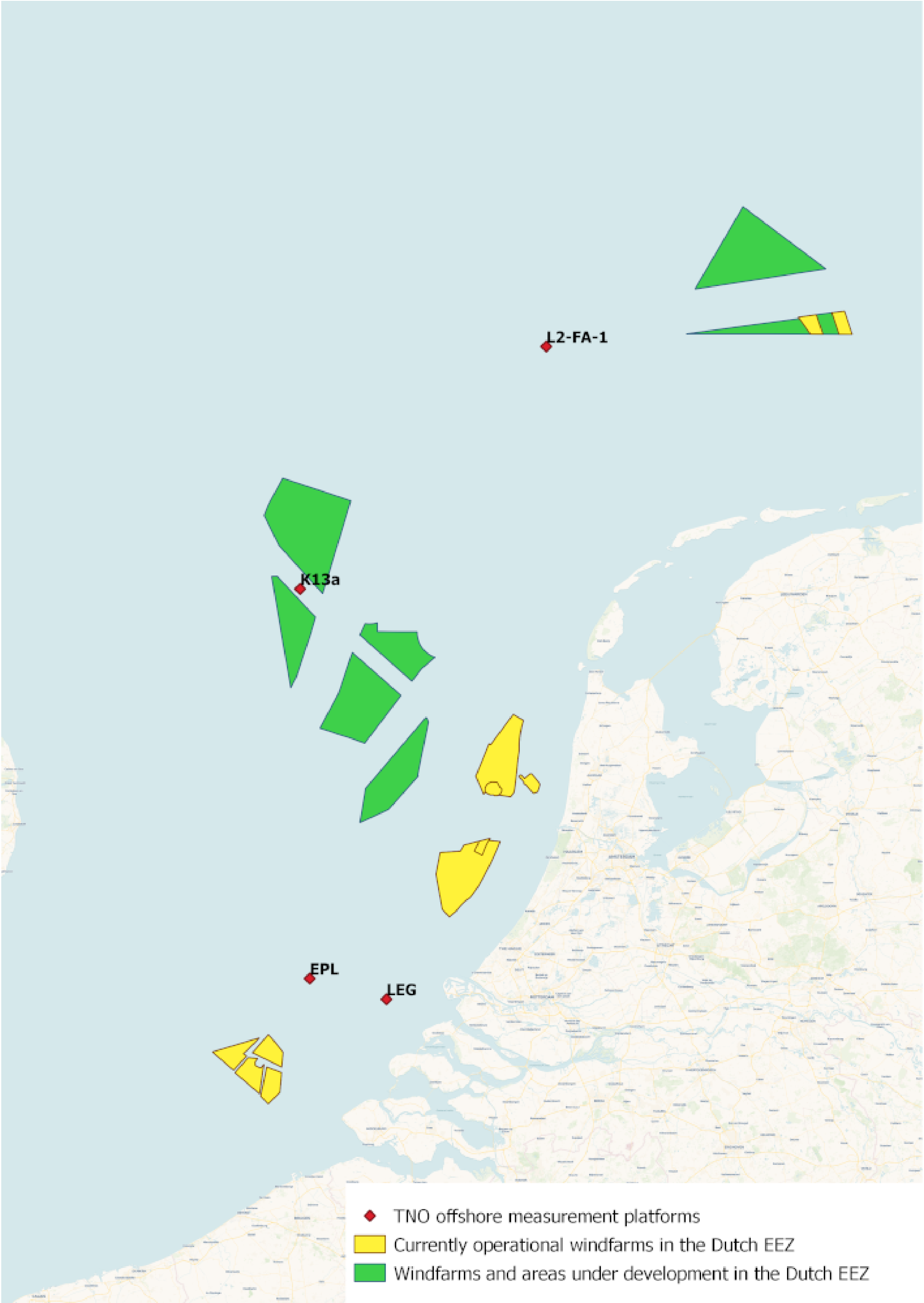


Figure 1.1: TNO long-term offshore wind measurement campaign locations at Lichteiland Goeree (LEG), Europlatform (EPL), Wintershall platform K13-A (K13a) and L2-FA-1, along with wind farm development zones in the Dutch North Sea.

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, see figure 1.2. The measurements and their characteristics will be correlated to levels of blade erosion assessed by inspection reports. As a next step, these findings will be implemented for maintenance and operational planning, strategies and decisions for the development of future wind farms. This can help further reduce the levelized cost of energy and extend the operational lifetime of wind turbines.

1.3 Open-access and public datasets

Since 2020 TNO has published annual reports on the wind conditions for all the measurement locations. Latest reports are available at offshorewind-measurements.tno.nl and an overview is given in table 1.1.

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

Report reference	Platform	Period
TNO 2024 R11674	LEG platform	2014 – 2023
TNO 2024 R11675	EPL platform	2016 – 2023
TNO 2024 R11676	K13-A platform	2016 – 2023
TNO 2024 R11677	L2-FA-1 platform	Mar 2023 – Dec 2023

The data measured in the *Wind op Zee* project are retrieved and post-processed before making the information publicly accessible through the web-service 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 to this report:

```
author      = {Bot, E. T. G. and Eeckels, C. B. H. and  Verhoef, J. P. and Wouters, D. A. J.},
institution = {TNO},
title       = {Offshore wind resource in the Dutch North Sea},
subtitle    = {Long-term measurement campaign and understanding wind conditions, 2023},
number      = {TNO 2024 R11678},
date        = {2024-12-16}
```

The publication date at which the data have last been accessed must be indicated along the citations, e.g. “Last accessed December 2024”.

The data is shared in .csv format. For each platform the measurement data can be retrieved via the website: offshorewind-measurements.tno.nl/en/data/

Figure 1.2: Disdrometer instrument installed at LEG platform.

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 lidar 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 K13-A. Since March 15th 2023, a lidar has been deployed at a fourth platform, NAM platform L2-FA-1, located north of the Frisian Islands. An overview of the platforms is given in table 2.1 and figure 2.1.

Table 2.1: Overview measurement platforms

Platform	Coordinates		Start date	End date
LEG	51°55.502′ N	3°40.106′ E	Oct 2014	Current
EPL	51°59.8752′N	3°16.4886′E	May 2016	Current
K13-A	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) over multiple years to give insight in the wind resource developments across the Dutch North Sea over time.

(a) L2-FA-1 (b) EPL

(c) K13-A (d) LEG

Figure 2.1: Lidar location on the platforms

3 Wind conditions at the different platforms

In 2023 wind measurements have been performed at four different platforms (LEG, EPL, K13-A and L2-FA-1) 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 2023. The platform specific wind conditions have been summarized in table 1.1.

3.1 LEG

The LEG platform is located about 30 km south-west from the coast of Hoek van Holland, see figure 1.1. The lidar at LEG is a Vaisala WindCube. At the LEG platform, the wind analysis for the 2014 - 2023 period shows that the wind profiles are dominated by the regional climate, mainly by the positive phase effect of the North Atlantic Oscillation. The prevailing wind direction is from the southwest. The average wind speed ranges from 9.05 m/s at the lowest measurement height of 62 m up to 10.56 m/s at 290 m. The Weibull distribution, which describes the probability distribution of the measured wind speeds, shows shape and scale parameters that are typical for the North Sea (k = 2.125 and c = 11.13 m/s at 140 m height). Table 3.1 and figures 3.1 and 3.5 present the conditions as they were observed at LEG.

3.2 EPL

The Europlatform (EPL) is located about 60 km from the coast of Hoek van Holland figure 1.1. The lidar at EPL is the ZX300 lidar. At the EPL platform, the wind analysis for the 2016 - 2023 period shows that the wind profiles are dominated by the regional climate, mainly by the positive phase effect of the North Atlantic Oscillation. The prevailing wind direction is from the southwest. The average wind speed ranges from 9.06 m/s at the lowest measurement height of 63 m up to 10.29 m/s at 291 m. The Weibull distribution, which describes the probability distribution of the measured wind speeds, shows shape and scale parameters that are typical for the North Sea (k = 2.081 and c = 11.01 m/s at 141 m height). Table 3.2 and figures 3.2 and 3.6 present the conditions as they were observed at EPL.

3.3 K13-A

The lidar offshore platform is located northwest of Den Helder, 101 km from the coast (see figure 1.1). The lidar at K13-A is the ZX300M lidar. At the K13-A platform, the wind analysis for the 2016 - 2023 period shows that the wind profiles are dominated by the regional climate, mainly by the positive phase effect of the North Atlantic Oscillation. The prevailing wind direction is from the southwest. The average wind speed ranges from 9.35 m/s at the lowest measurement height of 63 m up to 10.64 m/s at 291 m. The Weibull distribution, which describes the probability distribution of the measured wind speeds, shows shape and scale parameters that are typical for the North Sea (k = 2.189 and c = 11.51 m/s at 141 m height). Table 3.3 and figures 3.3 and 3.7 present the conditions as they were observed at K13-A.

3.4 L2-FA-1

The lidar offshore platform is owned by NAM B.V. and located north of the Frisian Islands, 80 km from the coast (figure 1.1). The lidar at L2-FA-1 is the ZX300M lidar. At the L2-FA-1 platform, the wind analysis for the period March 2023 – December 2023 shows that the wind profiles are dominated by the regional climate, mainly by the positive phase effect of the North Atlantic Oscillation. The prevailing wind direction is from the southwest. The average wind speed ranges from 9.30 m/s at the lowest measurement height of 63 m up to 10.99 m/s at 291 m. The Weibull distribution, which describes the probability distribution of the measured wind speeds, shows shape and scale parameters that are typical for the North Sea (k = 2.111 and c = 11.34 m/s at 141 m height). Table 3.4 and figures 3.4 and 3.8 present the conditions as they were observed at L2-FA-1.

Table 3.1: Wind speed and wind direction statistics LEG. The four quartiles of the wind speed distribution are listed, alongside the MoMM wind speed and wind direction. 'N' is the number of valid 10-minute average wind speed samples for each height.

Height	Wind speed						Wind direction
	N	Q_1	median	Q_3	maximum	MoMM	MoMM
m	#	m/s	m/s	m/s	m/s	m/s	°
62	404 173	6.00	8.82	11.95	33.02	9.05	235.6
90	401 943	6.09	9.06	12.41	33.46	9.33	235.5
115	399 345	6.13	9.20	12.68	34.21	9.52	235.4
140	394 836	6.21	9.35	12.95	34.99	9.71	235.8
165	385 459	6.30	9.50	13.20	36.97	9.88	236.7
190	367 833	6.39	9.63	13.43	37.50	10.04	238.5
215	339 802	6.49	9.76	13.64	37.91	10.19	241.2
240	300 931	6.61	9.93	13.87	38.27	10.34	244.3
265	205 283	6.62	10.03	14.11	38.30	10.47	245.2
290	174 162	6.62	10.13	14.29	38.62	10.56	248.3

Table 3.2: Wind speed and wind direction statistics EPL. The four quartiles of the wind speed distribution are listed, alongside the MoMM wind speed and wind direction. 'N' is the number of valid 10-minute average wind speed samples for each height.

Height	Wind speed						Wind direction
	N	Q_1	median	Q_3	maximum	MoMM	MoMM
m	#	m/s	m/s	m/s	m/s	m/s	°
63	300 577	5.78	8.65	11.93	33.05	9.06	229.7
91	300 941	5.90	8.90	12.39	33.92	9.36	229.2
116	300 740	5.97	9.04	12.66	34.63	9.56	229.3
141	298 567	6.03	9.16	12.88	35.46	9.73	229.6
166	296 826	6.07	9.26	13.06	36.05	9.87	230.1
191	294 133	6.11	9.34	13.22	36.86	9.99	230.5
216	290 789	6.16	9.40	13.36	37.86	10.10	230.9
241	285 430	6.21	9.46	13.47	38.94	10.20	231.5
266	277 974	6.23	9.49	13.57	40.37	10.28	231.8
291	269 663	6.19	9.44	13.56	41.12	10.29	232.6

Table 3.3: Wind speed and wind direction statistics K13-A. The four quartiles of the wind speed distribution are listed, alongside the MoMM wind speed and wind direction. 'N' is the number of valid 10-minute average wind speed samples for each height.

Height	Wind speed						Wind direction
	N	Q_1	median	Q_3	maximum	MoMM	MoMM
m	#	m/s	m/s	m/s	m/s	m/s	°
63	344 191	6.22	9.01	12.19	32.41	9.35	235.9
91	343 458	6.39	9.38	12.79	34.02	9.75	237.0
116	343 160	6.46	9.56	13.16	34.88	9.99	237.7
141	341 871	6.49	9.68	13.43	35.77	10.16	238.7
166	339 916	6.51	9.77	13.62	36.43	10.30	239.6
191	338 446	6.53	9.82	13.75	36.84	10.40	240.7
216	336 950	6.54	9.86	13.86	37.27	10.48	241.9
241	335 068	6.55	9.88	13.93	37.67	10.54	243.1
266	332 792	6.56	9.90	13.99	38.00	10.60	243.9
291	329 724	6.57	9.92	14.04	38.09	10.64	244.7

Table 3.4: Wind speed and wind direction statistics L2-FA-1. The four quartiles of the wind speed distribution are listed, alongside the MoMM wind speed and wind direction. 'N' is the number of valid 10-minute average wind speed samples for each height.

Height	Wind speed						Wind direction
	N	Q_1	median	Q_3	maximum	MoMM	MoMM
m	#	m/s	m/s	m/s	m/s	m/s	°
63	42 002	5.97	8.80	12.02	29.01	9.30	234.4
91	41 531	6.13	9.17	12.61	30.62	9.71	233.6
116	40 985	6.22	9.34	12.99	30.95	9.97	233.6
141	40 697	6.29	9.46	13.23	31.12	10.17	234.4
166	39 923	6.37	9.60	13.46	31.49	10.37	235.1
191	39 592	6.41	9.67	13.62	31.59	10.51	236.1
216	39 081	6.45	9.75	13.79	31.89	10.63	237.0
241	38 307	6.48	9.83	13.95	31.93	10.75	237.5
266	37 522	6.54	9.92	14.09	32.08	10.87	238.0
291	36 374	6.55	10.03	14.28	32.31	10.99	238.3

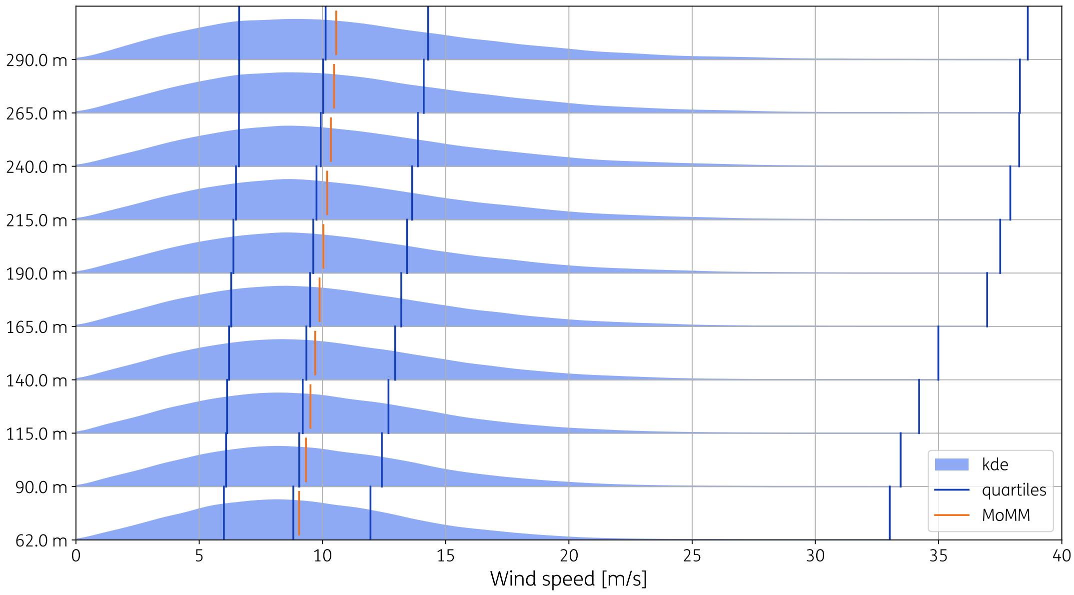


Figure 3.1: Wind speed distributions LEG. The kde is shown with blue markers for the quartiles (Q_1, median, Q_3 and maximum) and an orange marker for the MoMM, as listed in table 3.1.

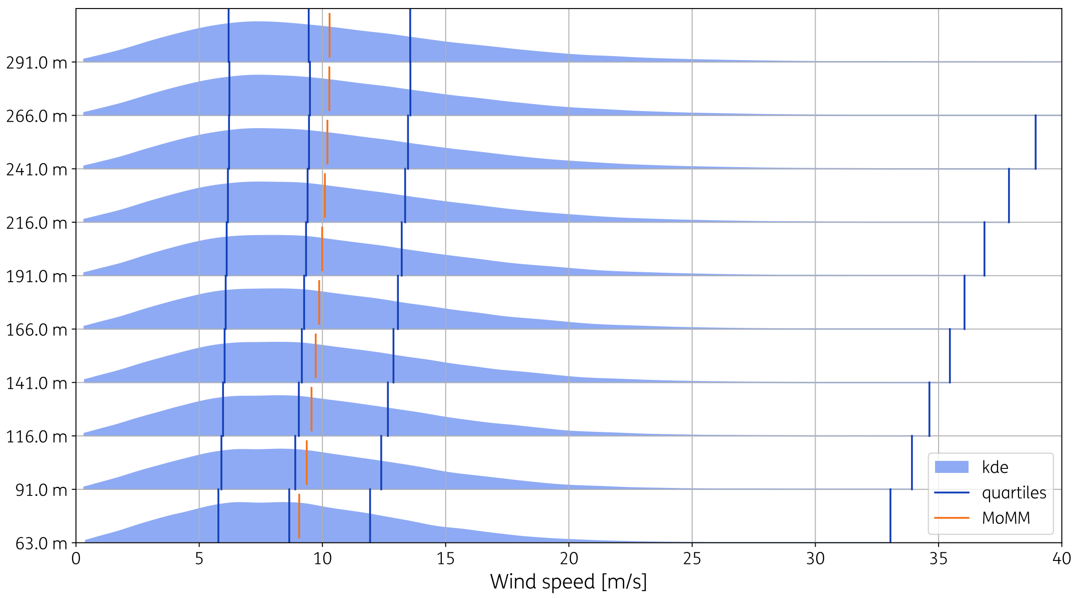


Figure 3.2: Wind speed distributions EPL. The kde is shown with blue markers for the quartiles (Q_1, median, Q_3 and maximum) and an orange marker for the MoMM, as listed in table 3.2.

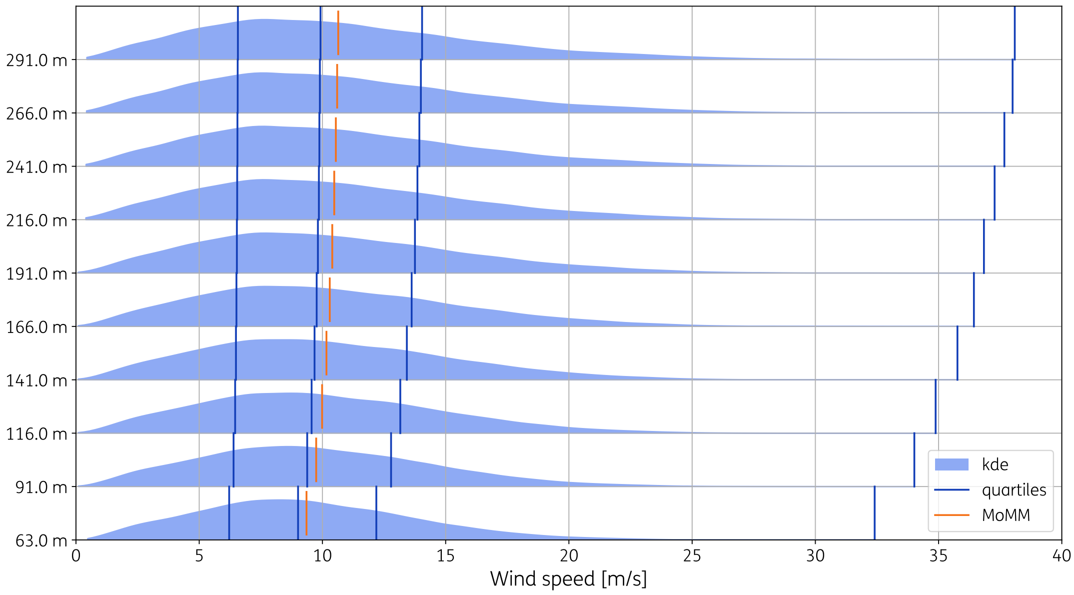


Figure 3.3: Wind speed distributions K13-A. The kde is shown with blue markers for the quartiles (Q_1, median, Q_3 and maximum) and an orange marker for the MoMM, as listed in table 3.3.

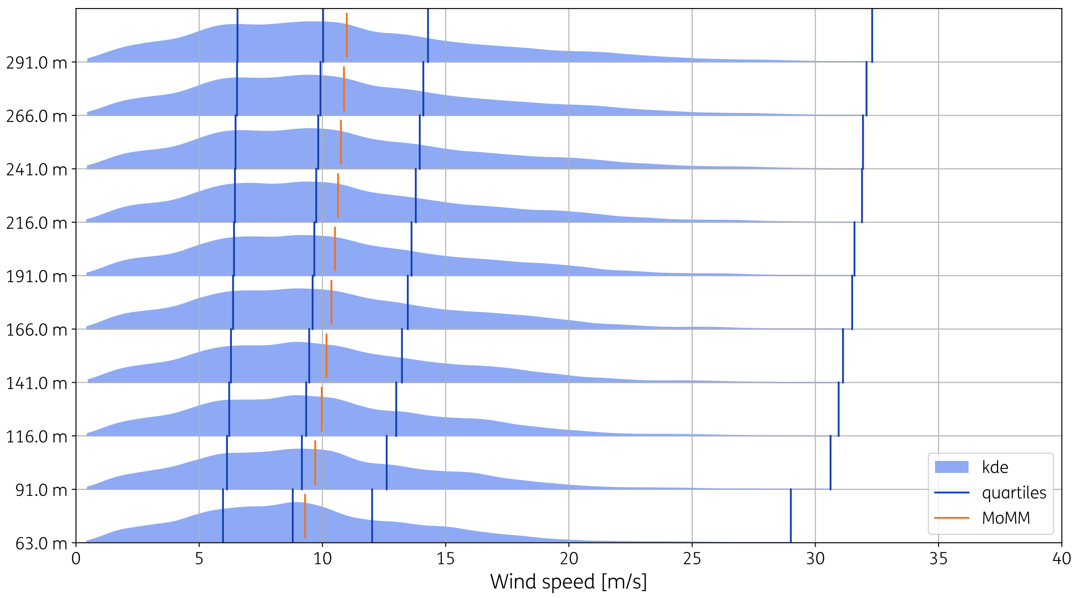


Figure 3.4: Wind speed distributions L2-FA-1. The kde is shown with blue markers for the quartiles (Q_1, median, Q_3 and maximum) and an orange marker for the MoMM, as listed in table 3.4.

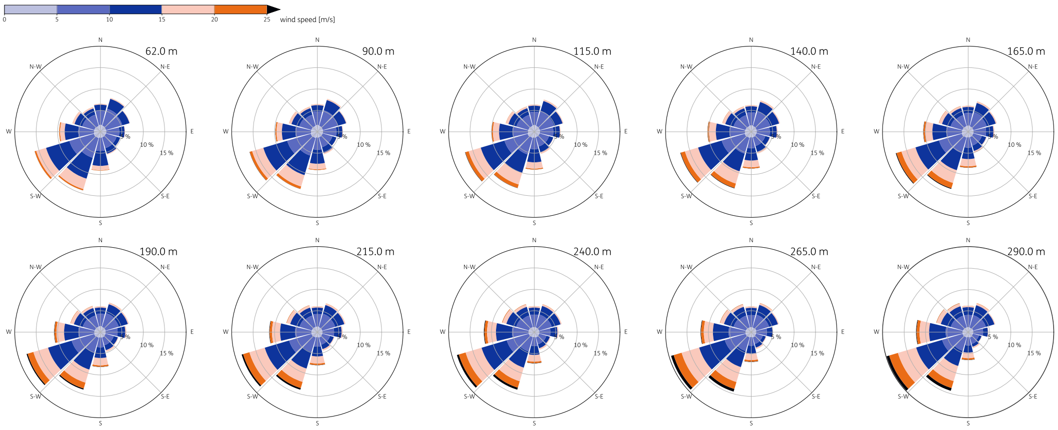


Figure 3.5: LEG windrose

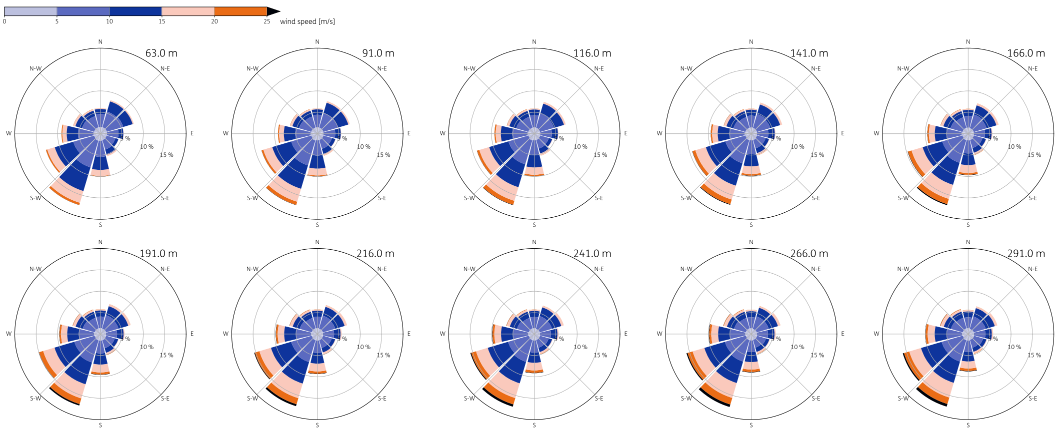


Figure 3.6: EPL windrose

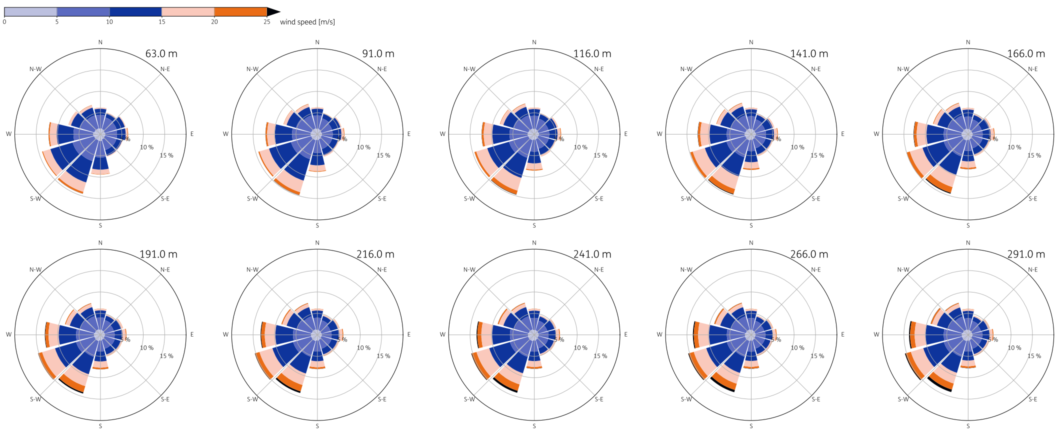


Figure 3.7: K13-A windrose

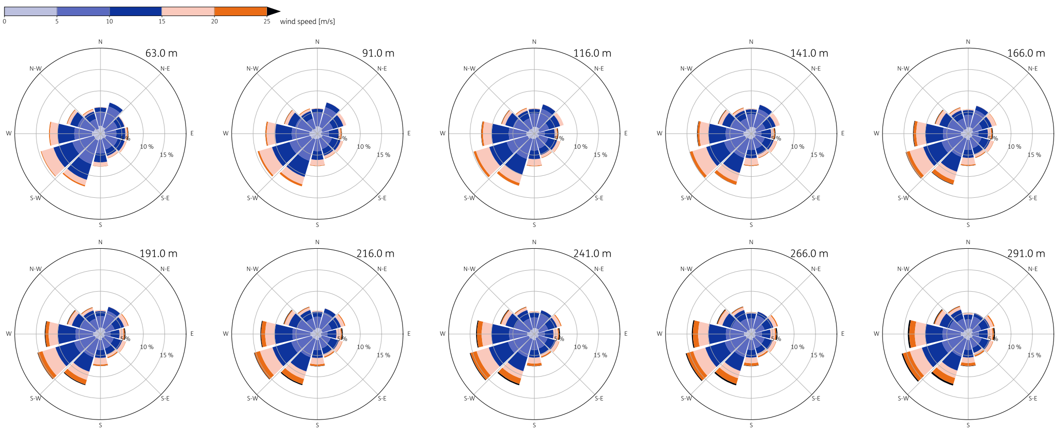


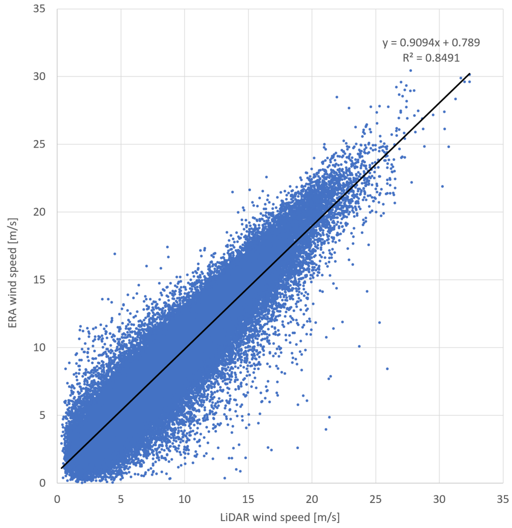
Figure 3.8: L2-FA-1 windrose

4 Comparison to other data sources

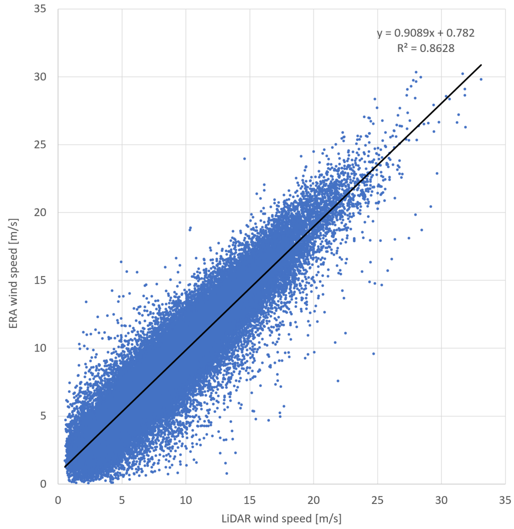
4.1 Comparison of lidar measurements and ERA5 hourly data

For the LEG, EPL, K13-A and L2-FA-1 platforms, lidar measurements have been correlated to hourly data from ERA5 at 100 m height. 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. For each platform, all available lidar data has been interpolated to 100 m height and synchronized with ERA5 data.

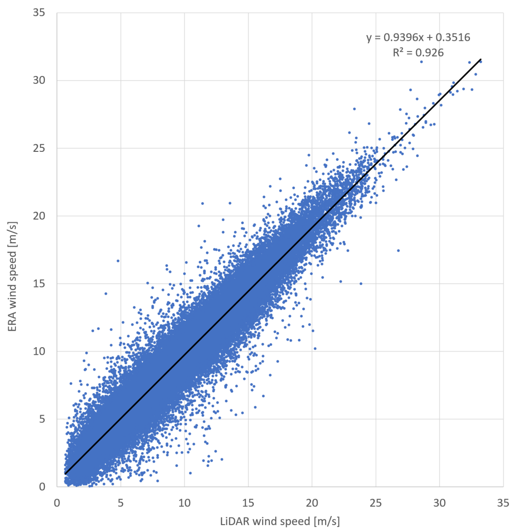
Figure 4.1(a) shows the correlation plot of lidar measurements at the LEG platform, interpolated to 100 m height for the period 2014-2023, with data from ERA5 for the same height. With a correlation factor of 0.849, the ERA5 data is reasonably accurate. Figure 4.1(b) shows similar results for lidar measurements at the EPL platform for the period 2016-2023, resulting in a correlation coefficient of 0.863. For the K13-A platform located at much larger distance from the coast, the ERA5 data is more accurate with a correlation coefficient of 0.926 for the period 2016-2023, see figure 4.1(c). Also for the L2-FA-1 platform, with similar distance from the coast, a high correlation coefficient of 0.936 was found for the year 2023 (figure 4.1(d)). In the next section, annual averaged wind speeds from ERA5 from 1970 until 2023 at 100 m height will be compared with results from lidar measurements in order to identify trends in long term wind resources.



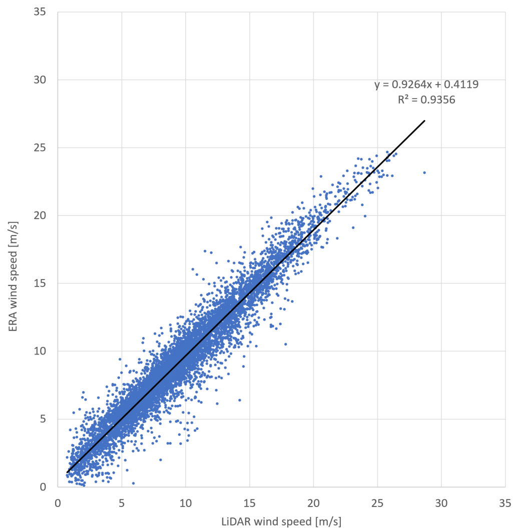
(a) LEG, period 2014-2023



(b) EPL, period 2016-2023



(c) K13-A, period 2016-2023



(d) L2-FA-1, year 2023

Figure 4.1: Correlation of lidar data with ERA5 data at 100 m height for all four platforms.

4.2 Establishment of long term wind resource

In order to identify trends in the long term wind resource at the North Sea, 10-year average wind speeds at 100 m height have been determined at the platform locations based on ERA5 wind data from 1970 until 2023. Figure 4.2 shows the annual average wind speed at 100 m height at the LEG platform including the 10-year moving average. For comparison, the annual averaged wind speeds from the lidar measurements for the years 2014 - 2023 are also included. The very good correlation between measurements and ERA5 data confirms the accuracy of the data, both from the lidar measurements and from ERA5. The 10-year average wind speed from ERA5 shows an increase of the wind speed in the years before 1995, with a maximum value of 9.5 m/s in that year. The minimum value is 9.2 m/s in 1979, the first year where the 10-year average wind speed is available in this data set. After 1995 the trend is the opposite: the 10-year average wind speed reduces to a minimum of 9.15 m/s in the year 2012. From that year, the 10-year average wind speed shows a more constant trend, and no more minimum or maximum values are reached.

The long term wind speed at 100 m height at the LEG platform is 9.31 m/s, based on 55 years of ERA5 data. This value will be multiplied with a single correction factor based on the correlation data from section 4.1. The standard deviation of the 10-year average wind speed over the last 20 years is 0.063 m/s resulting in a standard error of 0.014 m/s. The 95 % confidence interval of the long term wind speed can be calculated by adding and subtracting 1.96 times the standard error from the mean (i.e. $1.96 \cdot 0.014 = 0.03$ m/s). This all leads to a long term wind speed at the location of the LEG platform at 100 m height of 9.36 ± 0.03 m/s, see table 4.1.

For the location of the EPL platform the same trends are found, see figure 4.3. The long term wind speed at 100 m height, based on 55 years of ERA5 data, is 9.42 m/s with a standard deviation of the 10-year average wind speed over the last 20 years of 0.06 m/s. After correction based on the correlation data from section 4.1 the long term wind speed at the location of EPL at 100 m height is 9.51 ± 0.03 m/s, which is 1.5 % higher than at the LEG platform due to the larger distance from shore.

The same trends are also visible for the K13-A platform with the 10-year average wind speed reaching in 2001 (figure 4.4) and the L2-FA-1 platform (figure 4.5). For the location of K13-A at 100 m height the 95 % confidence interval of the long term wind speed is 9.76 ± 0.02 m/s, and for the location of L2-FA-1 at 100 m height the 95 % confidence interval of the long term wind speed is 10.02 ± 0.03 m/s.

Table 4.1: Long term wind speed at the platforms at 100 m height

Platform	Long term wind speed (100 m)
	m/s
LEG	9.36 ± 0.03
EPL	9.51 ± 0.03
K13-A	9.76 ± 0.02
L2-FA-1	10.02 ± 0.03

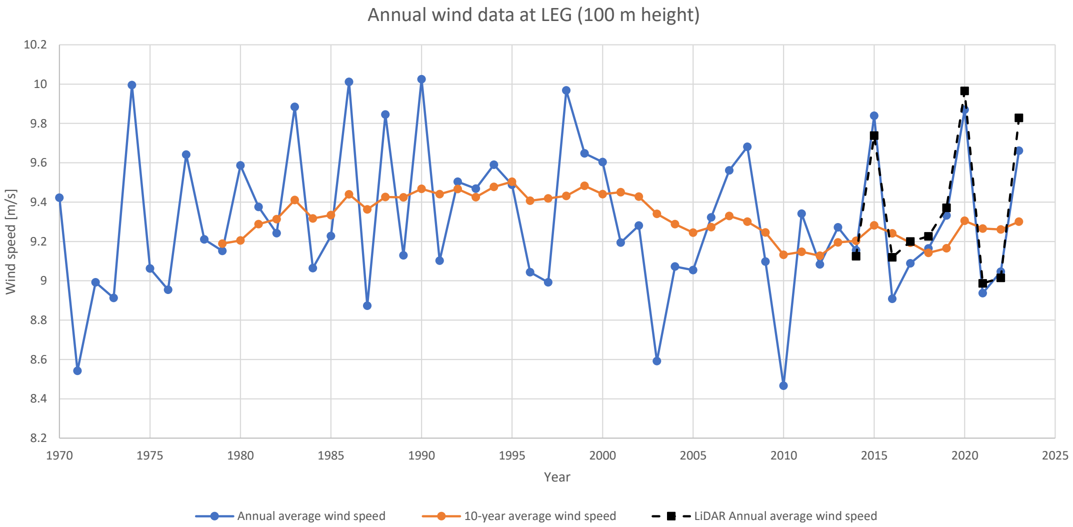


Figure 4.2: Long term wind data based on ERA5 at the LEG platform at 100 m height.

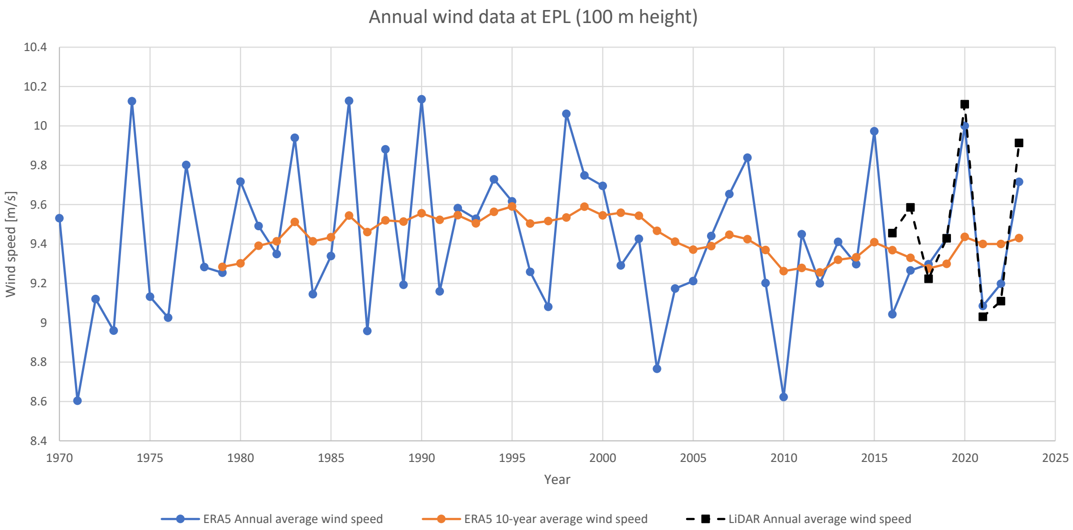


Figure 4.3: Long term wind data based on ERA5 at the EPL platform at 100 m height.

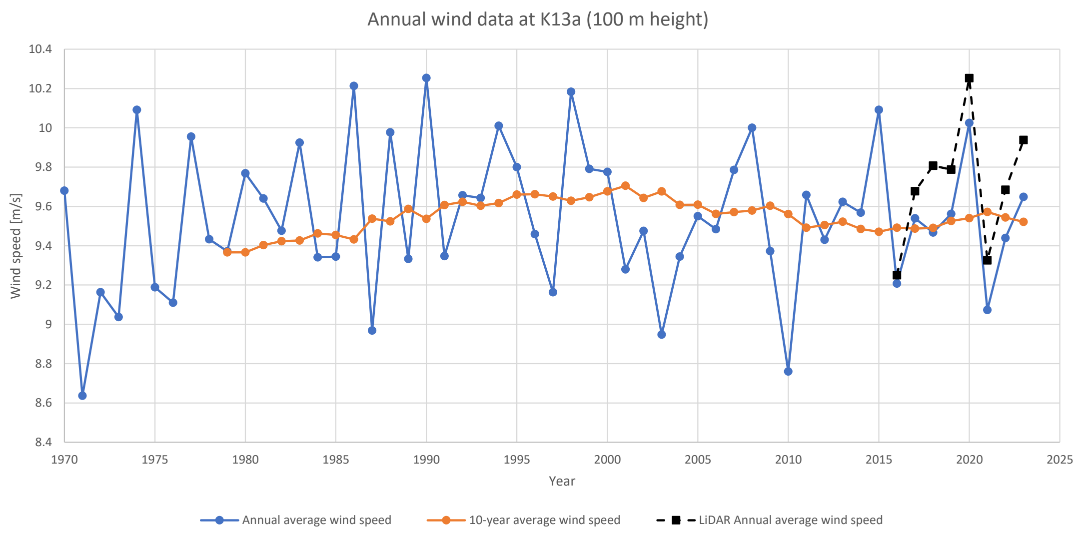


Figure 4.4: Long term wind data based on ERA5 at the K13-A platform at 100 m height.

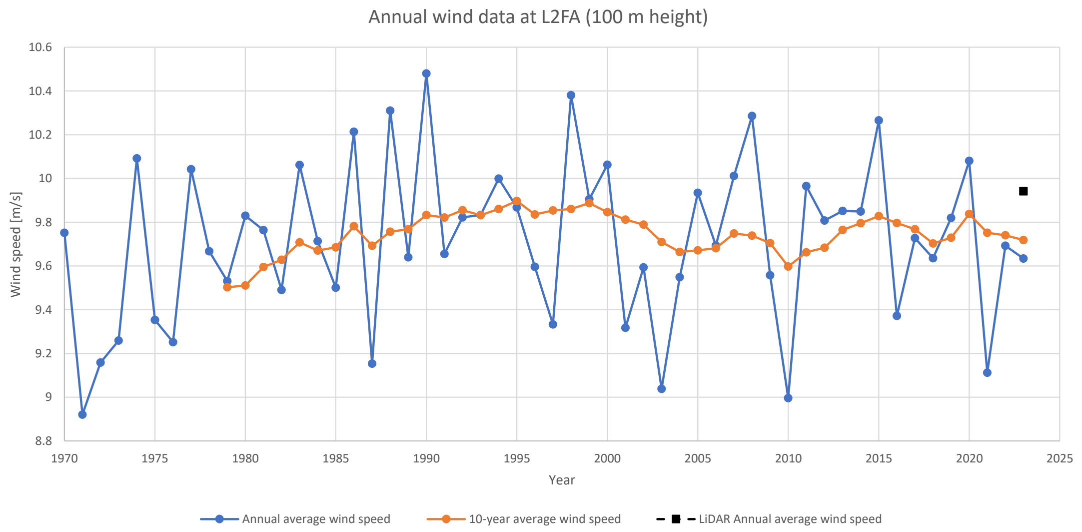


Figure 4.5: Long term wind data based on ERA5 at the L2-FA-1 platform at 100 m height.

5 Wake impact investigation of Borssele wind farm

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. Note that several Belgian wind farms are located south of the Borssele wind farm zone.

The distance between 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 and II of the Borssele wind farm became operational in April 2020 with a total installed capacity of 752 MW. 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 outside the Borssele 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. Some filtering has been applied to the dataset in order to increase the accuracy of the data regarding the wake effects:

- To ensure reliable wind direction data from the lidar data, the maximum difference in winddirection between EPL and LEG is ±10°.
- Only wind speed data is selected between 5.5 m/s 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, resulting in negligible wake effects.

Wind speed reductions from the Borssele wind farm at the platforms can be visualized by means of the ratio of the measured wind speeds of both platforms as a function of the wind direction. Figure 5.3 shows the change of this ratio (Δ_{WSR}) between EPL and LEG for the period when the Borssele wind farm was fully operational (2021-2023) and for the period before the Borssele wind farm became operational (2016-2020). For comparison, results from a wake simulation with FarmFlow [4] 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-ε turbulence model.

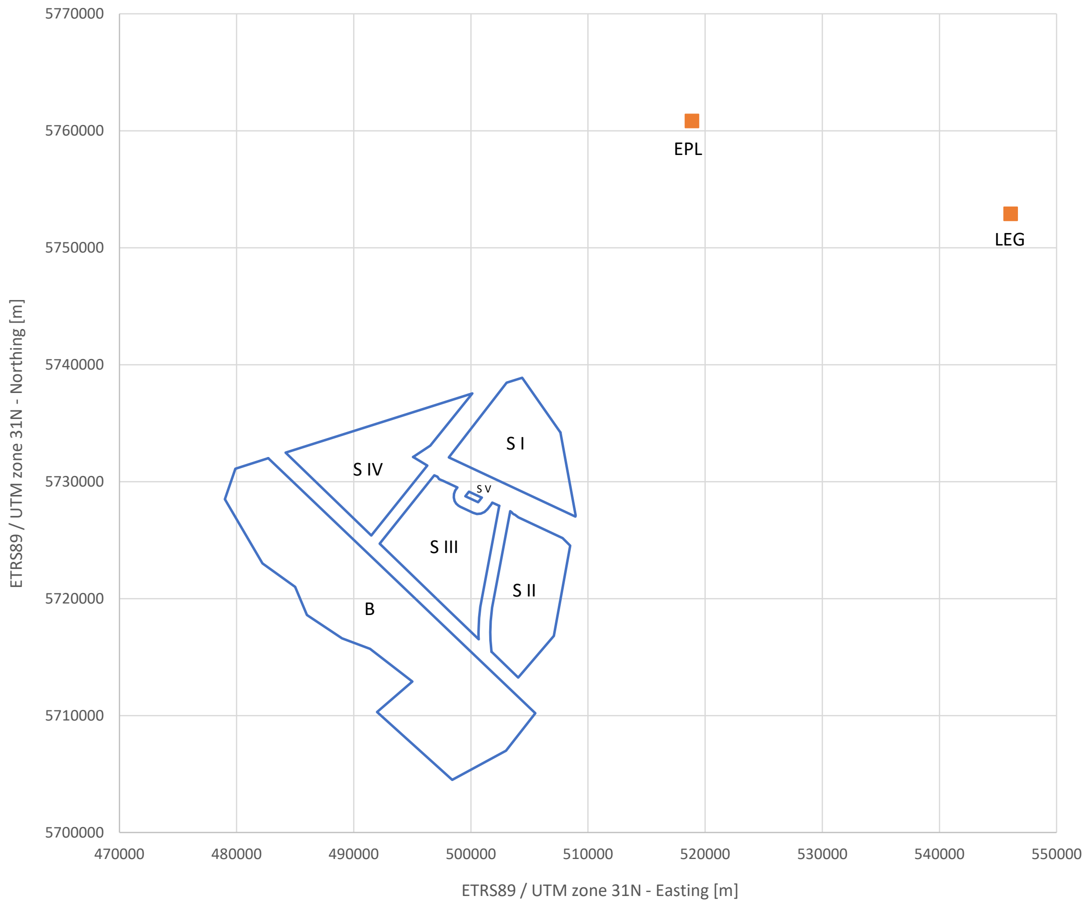


Figure 5.1: Map of the sites of Borssele offshore wind farm zone (S I, S II, S III, S IV and S V), the location of the Belgian wind farms (B) and the platforms EPL and LEG.

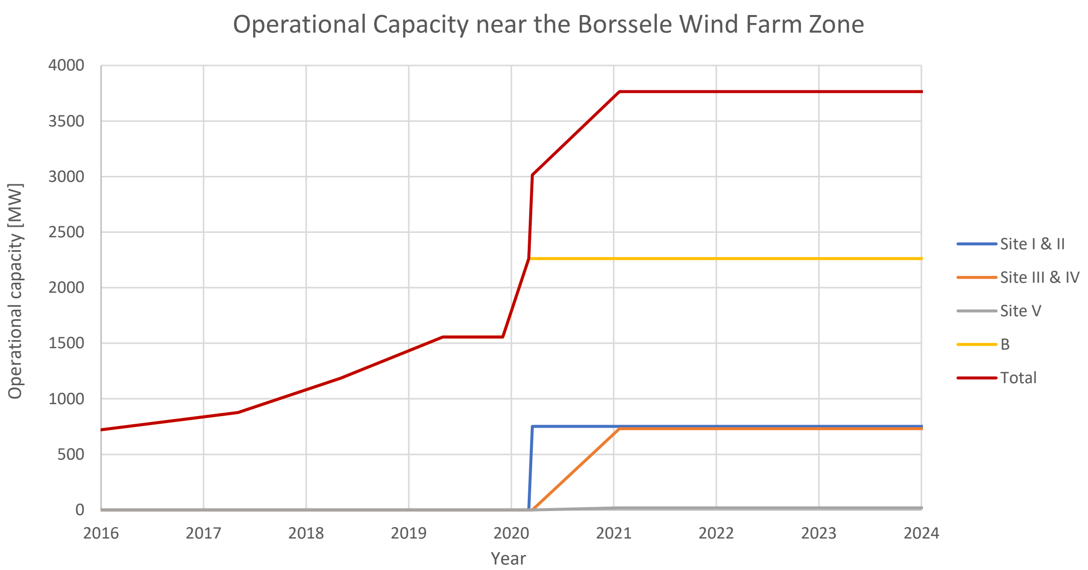


Figure 5.2: Time line of the installed and fully operational capacity at and near the Borssele offshore wind farm zone.

The results from the wake model show a reduction of the wind speed ratio between EPL and LEG ($U_{\mathrm{EPL}}/U_{\mathrm{LEG}} < 0$) around 210°, when the EPL platform is in the wake of the Borssele wind farm. For wind directions around 245°, when the other platform (LEG) is in the wake region of the Borssele wind farm, an increase of this ratio is found. For wind directions where both platforms are outside the wake region of the Borssele wind farm, the ratio does not change ($\Delta_{\mathrm{WSR}} = 0$).

The lidar data shows fluctuations also for wind directions outside the wake region of the Borssele wind farms, although these have much lower amplitude than for wind directions where one of the platforms is inside the wake region. It is important to note that both the minimum and the maximum value of the wind speed ratio occur where expected from the simulation results. The maximum change in the wind speed ratio is approximately 0.1, meaning that the wake effects from the Borssele wind farm can result in wind speed reductions of 10 %. Averaged over a 30° wide sector, the wind speed reduction at the EPL platform at 26.7 km distance is 5.8 %, and 3.6 % at the LEG platform at 43.2 km distance. The probability for wind speeds between 5 and 11 m/s at these 30° sectors is approximately 4.5 % according to the wind roses of figure 3.5 and figure 3.6. This leads to a total reduction of the average wind speed by wakes from the Borssele wind farms at the EPL platform of 0.29 % or with an average wind speed of 9.51 m/s a reduction of 0.028 m/s. For the LEG platform with an average wind speed of 9.36 m/s the total reduction is 0.18 % or 0.017 m/s.

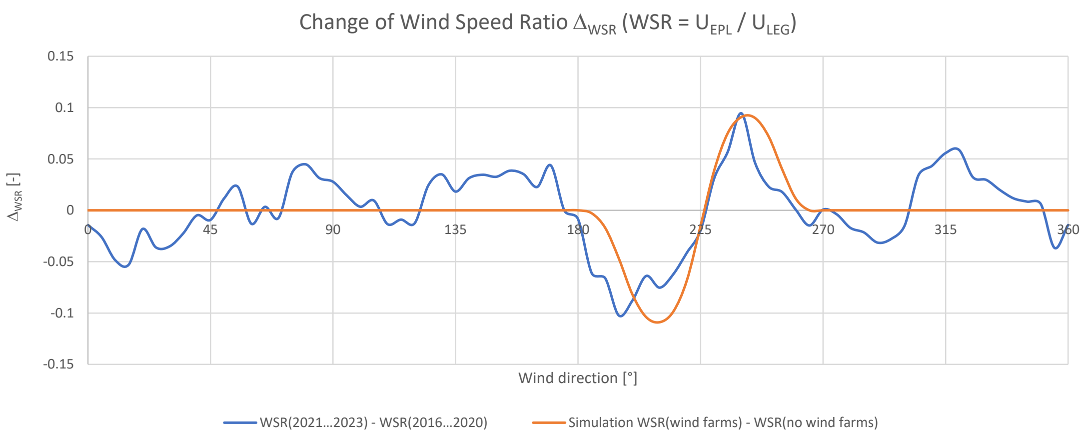


Figure 5.3: Change of the wind speed ratio between the platforms EPL and LEG for wind speeds between 5.5 m/s and 12.5 m/s in the periods 2016-2020 and 2021-2023. Results from a wake simulation are added for comparison.

6 Conclusions

Under the program *Wind op Zee* TNO performs for The Dutch Ministry of Climate Policy and Green Growth measurement campaigns in the North Sea since 2014 at different strategically chosen locations. Currently, the locations of the measurements are Lichteiland Goeree (LEG), Europlatform (EPL) and Wintershall platform K13-A. Since March 2023, a lidar has been deployed at a fourth platform, L2-FA-1, located north of the Frisian Islands. 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 these four platforms for the period 2014-2023, and ERA5 reanalysis data.

Correlations plots of the lidar measurements at the platforms show good correlation with ERA5 data at 100 m height, which makes ERA5 suitable as long term reference data in order to establish long term wind resources at these locations. All platforms show the same trends in the long term wind speed. Over a period of 55 years, the 10-year average wind speed shows a maximum in the year 1995 (2001 for the K13-A platform). Between 1995 and 2012 the 10-year average wind speed reduces with approximately 0.05 % after which the average remained more or less constant. The long term wind speed at platforms LEG, EPL, K13A and L2-FA-1 at 100 m height varies between 9.36 m/s and 10.02 m/s.

The wake effects of Borssele wind farm before and after construction are observed from measurements at LEG and EPL. A 4 year period before and a 3-year period after the wind farm Borssele became operational show a reduction of the wind speed at these platforms up to 10 %. The estimated reduction of the annual average wind speed by the Borssele wind farms is 0.028 m/s at the EPL platform and 0.017 m/s at the LEG platform.

7 Acknowledgements

The measurement campaign at the offshore platforms is carried out on the authority of the Ministry of Climate Policy and Green Growth of The Netherlands.

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