Enhanced design basis for offshore wind farm load calculations based on met-ocean data from a floating lidar system

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Abstract. A design basis is an essential part of planning and realising an offshore wind farm project. Based on the data of local environmental conditions and the results of load calculations, wind turbine system and support structure designs are developed. This paper reports a measurement campaign with a Floating Lidar System in combination with an Acoustic Doppler Current Profiler that was carried out to provide all basic parameters of a standard design basis. On top of that, a procedure was established to develop an enhanced design basis for offshore wind farm load calculations based on site-specific and more detailed met-ocean data – including, for instance, the actual profiles for wind speed, wind direction, and current speed. A comparison of the results of various load case simulations based on the standard design basis, as well as the enhanced design basis, shows a great potential for realising a more cost-efficient design for a wind turbine system and support structure when utilizing such an enhanced design basis.

1. Introduction
Crucial for the planning and development of offshore wind farms is the design basis. In a design basis, the local environmental conditions and the soil conditions are described, serving as a basis for load calculations and the development of the final wind turbine system and support structure designs. Standards and guidelines, such as IEC 61400-1 [1] and IEC 61400-3-1 [2], are available, which can be used to determine all parameters for these load calculations. Met-ocean data of high accuracy are needed for the analysis to avoid unnecessarily high safety factors and, hence, costly structures. For this purpose, historical offshore weather data can be obtained from the following data sources, which are typically combined for the analyses: reanalysis data, data of weather forecast models, and observed weather data. These data are correlated with further measured met-ocean data on site – provided a local met mast is already existing.

In the past ten years, Floating Lidar Systems (FLS) have become established for measuring the wind conditions at sea relevant for offshore wind energy applications [4]. An FLS is defined as a wind lidar device, typically a vertically profiling wind lidar, placed on or integrated in a floating platform. It was shown in past studies – e.g. [5] – that the motions of the platform can be sufficiently compensated to minimize the impact on the 10-min mean wind speed and direction data derived from the lidar recordings. The reconstruction of comparable turbulence
statistics, such as the turbulence intensity (TI) parameter, which is typically derived on the basis of cup anemometer measurements, is more challenging.

The aim of the research project OptiDesign [6] has been to show that local measurements with an FLS and an Acoustic Doppler Current Profiler (ADCP) located on the sea bottom can provide met-ocean data from the specific position of a planned wind farm and can be used to develop a site-specific and advanced design basis with a high reliability. Furthermore, the relevance of using more detailed measurement data instead of purely following the standard recommendations has been investigated with respect to the final wind turbine system and support structure designs. The main findings of the project are presented in this contribution.

The paper is organised as follows: In section 2, following this introduction, the methodology of an enhanced design basis, which was developed during the project, is introduced. This includes the procedure for receiving all relevant parameters, as well as the extended simulation and load calculation approach. In the following section 3, at first, the measurement campaign is introduced, then, the post-processing of the measurement data is elaborated on, and, finally, the results of the load simulation scenarios are presented. The paper closes with section 4 in which the main conclusions are summarized.

2. Methodology

Within the OptiDesign project, a procedure was developed to show the effects of a site-specific and advanced design basis. Figure 1 illustrates the different steps of this procedure: First, site-specific met-ocean data is recorded during a measurement campaign using an FLS. The data set should meet all requirements of recommended practices, as, for example, collected in [7], as well as contain advanced data of the environmental conditions. Afterwards, this enhanced data set is used to simulate different load cases for a specific wind turbine – once, by using only standard parameters and, and a second time, by implementing the enhanced data. By comparing the results of the load simulations, the relevance is demonstrated with regard to an optimized design of the wind turbine system and support structure, which may result in a cost reduction for a wind farm.

![Figure 1: Procedure of developing a site-specific and advanced design basis, as developed within the OptiDesign project [6].](image)

2.1. Site-specific and advanced design basis

A measurement campaign with the Fraunhofer IWES Wind Lidar Buoy as FLS and an ADCP was carried out for recording site-specific met-ocean data according to the standard recommendations for wind turbine designs. It was shown within this project that all basic wind parameters of a design basis, such as wind speed and direction, as well as turbulence intensity, can be determined using an FLS. Besides the wind measurements, an ADCP mounted on the sea bottom measured the relevant wave parameters, such as significant wave height, peak period, and wave direction, as well as the current speed and direction in various depths.
Deviating from the standard recommendations, the assessment of advanced parameters for an enhanced design basis enables the inclusion of more detailed environmental condition data in the load simulations. The wind lidar system ZX 300 of the FLS can scan up to ten measurement heights between 15 m and 300 m that can be selected individually by the user. Thus, the behaviour of the wind shear over the entire rotor diameter can be analysed and taken into account in detail. This is becoming more and more important with increasing rotor diameters of the latest turbine generations. The assumption to calculate and simulate the wind profile according to the standard recommendations, considering only a shear exponent that is typically derived from two measuring heights up to hub height, is not reliable for these altitudes. Furthermore, an advanced analysis of the measured wind and current profiles, taking more detailed measurement data into account, provides more detailed information on the site-specific wind-wave-correlations.

2.2. Extended simulation and load calculation approach
To analyse the influences of an enhanced design basis on the design of a wind turbine and corresponding support structure, fully coupled aero-hydro-servo-elastic system simulations are required. Based on these, subsequent load calculations were performed for a selected set of relevant design load cases (DLCs) and the resulting ultimate and fatigue loads on the offshore wind turbine system evaluated.

For carrying out a large set of DLC simulations, a tool-chain for automated fully coupled system simulations has been developed. This utilises a computational model for wind turbine load calculations, based on the Modelica library for Wind Turbines (MoWiT) developed at Fraunhofer IWES [8, 9, 10]. The hierarchical structure of the modeling language Modelica allows for component-based modeling of complex offshore wind turbine systems, as presented on the right in figure 2. Aero-hydro-servo-elastic simulations in the time-domain, visualised on the left in figure 2, are then performed in the apt simulation tool Dymola.

![Figure 2: Computational model for wind turbine load calculations, adapted from [8].](image-url)
The framework for automated simulation, also developed at Fraunhofer IWES [11, 12] and shown in figure 3, uses the computational model of the wind turbine system as input for a programming framework coded in Python. In this, all different DLC settings are specified so that the setup and simulation of all DLCs can happen in an automated manner.

Figure 3: Schematic illustration of the framework for automated simulation, adapted from [13].

The considered DLCs, as presented in table 1, comprise both fatigue and ultimate load analyses and account – according to IEC 61400-3-1 [2] – for different operational conditions with and without faults in form of loss of the electrical network; normal (NTM) and extreme (ETM) turbulence, as well as extreme wind speed (EWM) models; normal (NSS) and extreme (ESS) sea states; normal (NCM) and extreme (ECM) current models; co-directional (COD) or misaligned (MIS) wind, as well as uni- (UNI) or multi- (MUL) directionality of the waves.

Table 1: Selected DLCs and their specification, according to IEC 61400-3-1 [2].

| DLC  | Operating state | Wind | Waves | Directionality | Current |
|------|-----------------|------|-------|---------------|---------|
| 1.2  | Operation       | NTM  | NSS   | MIS, MUL     | None    |
| 2.4  | Operation + fault | NTM  | NSS   | COD, UNI    | None    |
| 6.4  | Parked          | NTM  | NSS   | COD, MUL   | None    |
| 1.3  | Operation       | ETM  | NSS   | COD, UNI    | NCM     |
| 2.1  | Operation + fault | NTM  | NSS   | COD, UNI    | NCM     |
| 5.1  | Emergency stop  | NTM  | NSS   | COD, UNI    | NCM     |
| 6.1  | Parked          | EWM  | ESS   | MIS, MUL    | ECM     |
| 6.2  | Parked + fault  | EWM  | ESS   | MIS, MUL    | ECM     |

3. Results
The measurement campaign data analysis results and the subsequent load simulations are presented in the following.

3.1. Description of the measurement campaign
A three-month measurement campaign was carried out from January to April 2020 with the Fraunhofer IWES Wind Lidar Buoy in proximity to the wind farm “Meerwind Süd|Ost” of the OptiDesign project partner WindMW Service GmbH (figure 4). The wind farm area is located north of the German island Helgoland and has a homogeneous bathymetry with a water depth of approximately 24 m.

A longer measurement campaign of at least one year was not feasible within the project duration. Despite the short length, a broad spectrum of conditions including a very stormy...
Figure 4: Fraunhofer IWES Wind Lidar Buoy in proximity to the wind farm “Meerwind Süd|Ost”.

A weather period could be covered. With this data set, the site-specific behaviour of wind and wave parameters can be analysed with regard to the simulation of extreme loads.

Wind data from 15 m height up to 285 m measured by the FLS, as well as wave and current data in steps of 5 m depths measured by an ADCP system, were recorded. During the storm “Sabine” on 9th and 10th of February 2020, a maximum 10-min mean wind speed of 42.7 m/s (cf. figure 5) and a maximum significant wave height of 7.7 m (maximum individual wave height of 10.6 m) were obtained.

Figure 5: 10-min mean wind speed from 15 m to 285 m height in February 2020, measured by the Fraunhofer IWES Wind Lidar Buoy.
3.2. Post-processing of measurement data

Before post-processing the measurement data, a quality control was conducted in which the data was transformed to a uniform, equidistant data format. Recording errors, as well as unrealistic values and increments, were marked to be excluded in the post-processing.

The wind data post-processing involved the wind direction correction, utilizing the heading of the buoy, as well as the motion-correction of the lidar wind speed data, using the Fraunhofer IWES motion correction algorithm [5]. This algorithm processes the high-resolution lidar data of 1 Hz and 5 Hz motion data to correct the motion of the buoy due to waves and currents. The measured current and wave data was direction-corrected using the heading data of the ADCP.

With a specifically developed tool, all basic and advanced environmental parameters were automatically determined from the measurement data. Particularly, a method to correct the motion-affected turbulence intensity TI from FLS measurements, considering the obtained TI itself and the wind speed, was implemented (section 3.2.1). Furthermore, developed approaches for post-processing the measured wind speeds and directions at different elevations, as well as the current speeds in certain depths, enabled the incorporation of site-specific profiles into the numerical simulation environment (section 3.2.2). The data of the local measurements of the oceanographic parameters were additionally used to determine correlations between wind and wave parameters. Moreover, the post-processed FLS and ADCP data underwent a plausibility check by comparison with ERA5 reanalysis data, which was then also used to determine 50-year extreme event parameters, as mentioned in section 3.3.

3.2.1. Calculation of turbulence intensity from FLS measurements

An important component of a design basis is the turbulence intensity. It is well known that the TI values obtained by wind lidars differ from the TI obtained by cup anemometers, which are considered as the reference in current standards [14]. The motions from FLS platforms affect the time-resolved wind time series and increase the obtained TI significantly [5]. Within the OptiDesign project, a robust and simple method for correcting the motion-affected TI was developed using 10-min mean variables obtained by the FLS itself [6]. In a first step, the sensitivity of the TI deviations is studied for several variables. For the variables having a significant effect on the TI deviations, linear corrections terms were introduced and calibrated. Then, the resulting method was tested for two measurements at different locations. Due to the short period of the OptiDesign measurement campaign, the method was applied to the data set and compared to existing data.

A measurement campaign, executed in 2016 in the proximity of the FINO1 platform and covering a period of half a year, was used as a data basis for developing the TI correction method. As in the OptiDesign measurement campaign, the trialed FLS was the Fraunhofer IWES Wind Lidar Buoy equipped with a ZX wind lidar (WLBZ). In a first step, the sensitivity of the TI deviations, defined as the relative difference between obtained TI and reference, was studied, similar to remote sensing wind speed classification described in IEC 61400-12-1:2017 Annex L [3]. Various variables from the lidar data and buoy motions were considered, e.g. tilt or heave range, calculated for the corresponding 10-min periods. Linear correlations were applied to the TI deviations for these 10-min values. The variables showing the highest effect on the measured TI, identified by the coefficient of determination $R^2$, are the measured turbulence intensity $T_{I_{\text{measured}}}$ itself, as well as the wind speed $u_{\text{measured}}$, as presented in figure 6. Systematic sensitivities to motion parameters could not be identified. Corresponding to the identified sensitivities and assuming linear correlations, the resulting correction transfer function is defined as

$$T_{I_{\text{corrected}}} = p_1 \cdot T_{I_{\text{measured}}} + p_2 \cdot u_{\text{measured}} + \text{offset}.$$  (1)

The calibration of the transfer function using the FINO1 measurement data set results in $p_1 = 1.156$, $p_2 = -0.241$ and offset = $-8.415$.

1 https://www.ecmwf.int/en/forecasts/datasets/reanalysis-datasets/era5 (accessed on 15 February 2021)
In a next step, the method was applied to data sets from two measurement campaigns, executed in the Irish Sea and in the proximity of FINO3 in the North Sea, in order to validate the procedure. Figure 7 shows the wind speed bin averages for the measured TI, the corrected TI, as well as the met mast reference TI.

The method shows considerable improvements for both locations - displayed in figure 7 for the measurement altitudes around 100 m. Nevertheless, the method tends to underestimate the TI in the range from 4 m/s to 15 m/s by up to 1.5% for the Irish Sea, probably due to different sea state conditions. The comparison shows good results for a FINO3 trial for wind speeds exceeding 7 m/s.

For the OptiDesign project, the method was used to correct the motion-affected TI. The measurement campaign within this project has covered considerably less than a full year. Therefore, the adjusted TI was used for a comparison with the existing TI data, see figure 8. The
results show a good agreement between the corrected and existing data, so that the measurement data is interpreted as a verification of the existing data for wind speeds from 7 m/s to at least 19 m/s.

![Figure 8: Comparison of the measured TI, the corrected TI, as well as the existing TI-information (OptiDesign Ref.), for the location. Furthermore, the FINO1-TI is included.](image)

3.2.2. Enhanced parameters for advanced design basis

The results of the local lidar wind measurements up to 285 m show a wide distribution of the wind profile exponent $\alpha$ (cf. figure 9).

![Figure 9: Distribution of wind profile exponent $\alpha$, measured during the campaign.](image)
The corresponding wind speed profiles with reference to the mean wind speed at hub height are presented in the left chart in figure 10. There, it can be seen that, for wind speeds above 13 m/s, $\alpha$ is greater than 0.11. The wind profile exponent increases even further – above 0.14 – for wind speeds higher than 31 m/s.

Similarly to the wind speeds, the profile for the wind directions is extracted from the measurements and – again – referenced to the mean wind speed at hub height, as shown in the right chart in figure 10. It becomes clear, that the wind direction is not the same over the entire height, therefore also not over the entire rotor plane, but varying. Hence, there is a wind veer to be considered.

![Figure 10: Wind speed (left) and direction (right) profiles as for the wind speed at hub height.](image)

Evaluating the current speed data from the three-months measurement campaign yields the current speed profiles with reference to the mean wind speed at hub height, as presented in figure 11.

![Figure 11: Current speed profiles with reference to the mean wind speed at hub height.](image)
These actual profiles for both wind speed and wind direction (figure 10), as well as current speed (figure 11), should be considered for more realistic and less uncertain load calculations of wind turbines in contrast to the IEC 61400-1 and IEC 61400-3-1 standard recommendations.

3.3. Load simulation scenarios and final results

Three design bases of different levels of advancement are considered for performing the final DLC simulations:

- **Design basis 1 (DB 1)** is purely based on the IEC 61400-1 and IEC 61400-3-1 standard recommendations. DB 1 uses the already existing data from “Meerwind Süd|Ost”, supplemented by some data from HZG (Helmholtz-Zentrum Geesthacht) - coastDat hindcast data set\(^2\) - for some additional wind-wave-correlation data.

- **Design basis 2 (DB 2)** replaces some selected data in DB 1 through the post-processed data obtained from the three-months measurement campaign. Thus, the statistical properties of the wind speed, the correlation between wind and wave directions, as well as wave height, peak period, and current speed values depending on the prevailing mean wind speed at hub height, were updated in DB 2 based on the measurements. For extreme events, however, the extreme values of the three-months measurement period could only be taken for the one-year extreme values. As no extrapolation for any 50-year extreme event was possible directly based on the data from the measurement campaign, plausibility checks between the measurement data and the data from ERA5 were performed. Due to their good match, the ERA5 data set was used for supplementing the long-term data in DB 2.

- **Design basis 3 (DB 3)** uses and builds upon DB 2, however, further goes beyond the standard recommendations. Hence, DB 3 also includes the wind speed, wind direction, and current speed profiles obtained by means of the measurement campaign.

Based on the applied methodology, assumptions made, as well as incorporated measurement data, potentials and uncertainties were identified, as discussed in the following. For the load calculations based on each of the three design bases specified above, Fraunhofer’s IWT-7.5-164 reference wind turbine [15] supported by a monopile was used. The resulting moment curves along the tower and monopile for the three different design bases are presented in figure 12, based on the results from the design-driving DLC 6.2. A significant difference between the moment

![Figure 12: Resulting moment curves for the design-driving DLC and the considered design bases, zoom in on the marked rectangle (right).](https://www.coastdat.de/) (accessed on 15 February 2021)
curve from DB 1 compared to the curves from DB 2 and DB 3 is clearly visible. This deviation is mainly due to the fact that the reference wind speed in DB 1 was 50 m/s, while – based on the measurements – a more realistic reference wind speed of 37.2 m/s was used in DB 2 and DB 3. The detailed comparison of DB 2 and DB 3, shown on the right in figure 12, yields that above still water level DB 2 is more conservative, whereas below still water level higher loads are obtained in DB 3.

4. Conclusions
The final assessment of the data from a three-months measurement campaign with corresponding analyses and comparisons of the system responses and load results, based on three design bases of different levels of advancement, lead to the following main conclusions:

(i) FLS measurements provide — if appropriately post-processed — very accurate met-ocean data. Hence, FLS measurement data can be utilized as a more site-specific solution compared to model data.

(ii) To account for seasonal differences and effects, a measurement duration of at least one year is recommended. Environmental parameters for extreme events with longer return periods can still be extrapolated based on the measured data and standard recommendations.

(iii) Common standards recommend — understandably — rather conservative values for environmental parameters and design load cases; however, also do not capture more realistic and local effects, such as wind speed dependent and site-specific wind profiles. This is the reason why it is highly recommended to consider local measurement data in the design basis. Such an approach can allow for potentially more cost-efficient offshore wind turbine system designs but definitely locally appropriate design solutions.

The implementation and use of an enhanced design basis has a great potential for the development of new projects, particularly with regard to large rotor blades. A cost-efficient and site-specific design for the wind turbine system and support structure can be realised. Besides, the developed procedure has a great potential for improving the performance of old systems and extending their service life.

Acknowledgments
The authors acknowledge the financial support of the research project OptiDesign (2016-2020, FKZ 0324043A) that is funded by the German Federal Ministry for Economic Affairs and Energy (BMWi) on the basis of a decision by the German Bundestag and project management Projektträger Jülich (PtJ). Reference data for the turbulence intensity analysis was acquired by the FINO platforms, also funded and supported by the BMWi and PtJ. The FINO data is provided by the FINO-Datenbank, operated by the German Bundesamt für Seeschifffahrt und Hydrographie (BSH). The ERA5 data set was generated by the European Centre for Medium-Range Weather Forecasts ECMWF. Furthermore, we would like to thank our project partner WindMW Service GmbH and the company Jörss – Blunck – Ordemann GmbH for their collaboration in the joint research project OptiDesign.

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