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Site Assessment of the floating wind turbine Hywind Demo

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Abstract

This Site Assessment predicts which environmental conditions an object at the Hywind Demo site will be exposed to. The work is based on 2 years of data from a Seawatch buoy located at the site. By use of Gumbel distributions the 50 year extreme values of wind gust at 3.5 m height (30.5 m/s), ocean current speed at 20 m depth (1.4 m/s) and significant wave height (13.3 m) have been found.

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Keywords: Site Analysis; Offshore wind; Hywind; Buoy; Measnet

1. Introduction

In 2009 Statoil installed the world's first full-scale floating wind turbine off the coast of Karmøy in the North Sea. The Hywind Demo is a 2.3 MW floating turbine with a 65 m hub height and a rotor diameter of 82.4 m [1]. In order to estimate the expected wind energy output and costs of such a project it is crucial to predict the average wind speed at turbine hub heights [2].

This work aims to estimate the conditions of wind, ocean currents and waves at the Hywind Demo site, based on 2 years of data from a Seawatch buoy located 200 m west of the turbine, as displayed in Figure 1. Further, it is of special interest to estimate the extreme environmental conditions at the site in order to estimate the extreme loads on the turbine. For onshore wind the Measnet guidelines [4] are widely used for site assessments, and as there do not exist similar guidelines for offshore sites, these guidelines are used for the Hywind Demo site [5].

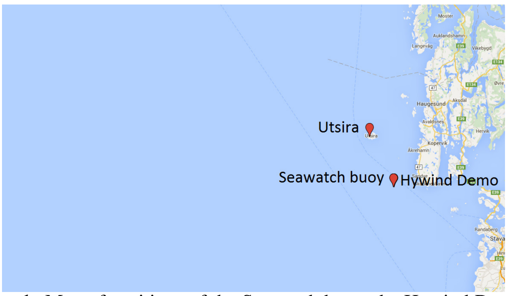

Fig. 1: Map of positions of the Seawatch buoy, the Hywind Demo turbine and the meteorological station at Utsira from Google Maps [3].

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2. The Seawatch buoy

The Seawatch buoy was deployed (59°08.42'N, 5°01.78'E) from August 13th 2009 until September 19th 2011. 76 % of the data from this time period are available. Data are stored as time series for parameters characterizing wind, ocean currents and waves. The overall height of the Seawatch buoy is 8.6 meters, the diameter is 1.76 meter and the weight is 710 kg [6].

Figure 2 is a schematic of the Seawatch buoy carrying instruments measuring the following metocean parameters [6]:

- Wind speed, direction and gust at 3.5 m above the sea level
- Wave height, period and direction relative to mean sea level
- Current speed and direction, from 3 to 180 m depth.
- Air pressure near the sea level
- Air temperature 3.5 m above sea level
- Air humidity 3.5 m above sea level
- Water temperature at 2 and 3 m depth
- Conductivity of the water at 2.0 m below the sea surface

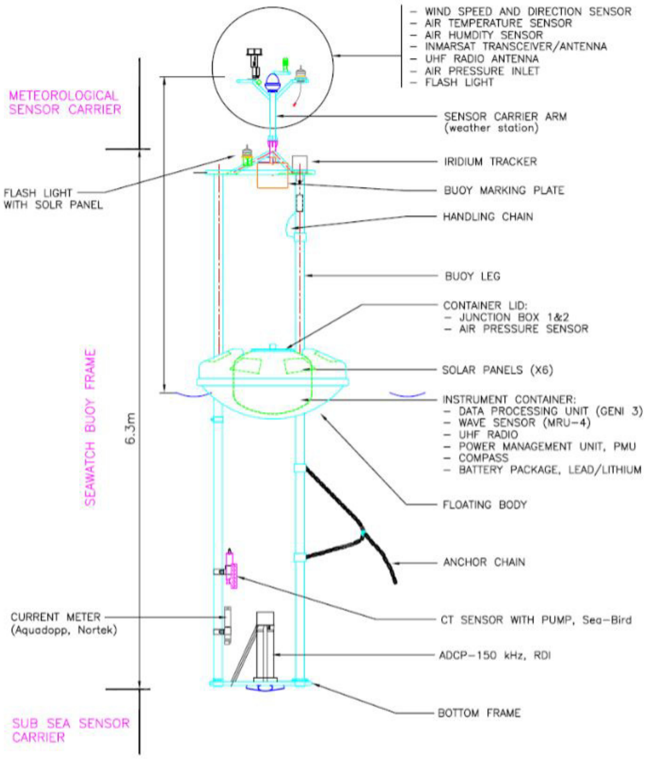


Fig. 2: The Seawatch buoy

3. Method

3.1. Wind speed profile

Wind data are measured every second at 3.5 m height and saved as 10-minute mean and 3 second gust values. The mean wind speed profile variation with height above the surface is described by the power law [7, 8, 9], with the power law exponent $\alpha = 0.11$, based on the recommendations and findings of DNV [8], Hsu et al. [10], Johnson [11] and Turk et al. [12]. Atmospheric stability is not considered in this work.

3.2. Long term extrapolation of the mean wind speed data

Measure-Correlate-Predict (MCP) algorithms analyze wind speed and direction data measured at a target site and a nearby reference site and find a relationship between the two data sets used to predict long term data at the target site [13]. In the following, the Matrix Time Series algorithm [13] is used to long term extrapolate the mean wind speed data from the buoy. 10 years of data from the nearby meteorological station Utsira have been used as reference data. Utsira is an island located approximately 20 km North of the Hywind demo site, as indicated in Figure 1. In order to evaluate the correlation between the buoy data and the reference data, the coefficient of determination, R^2, is calculated for both the wind speed and the wind direction correlation [14].

3.3. Ocean current

The depth at the Hywind site is 210 m. The current speed and direction have been measured every second with 10 m intervals down to 180 m and saved as 10 minute averages. The mean speed at all depths in addition to the no-slip condition at the bottom are used to obtain the velocity profile.

3.4. Waves

Every second the Seawatch buoy measured several parameters characterizing the waves at the Hywind site, all parameters were saved as 10 minute averages. The significant wave height, H_{m0}, equals $4\sqrt{m0}$ where $m0$ is the area (zeroth-order moment) of the wave spectrum. The distribution of H_{m0} has been normalized with respect to the number of data and a height of 0.5 m.

3.5. 50 year extreme values for wind, wave and ocean current

The 50 year extreme values for wind, ocean current and wave are found by fitting selected annualised maximum values to a Type 1 Generalized Extreme Value (GEV) distribution, also known as the Gumbel distribution [15]. The maximum values are expanded to be the probabilities of occurrence in a year. These values are called annualized peaks, U*. Only the highest annualised peaks are used for the curve fit by the improved Harris algorithm [16].

As only 2 years of data are available, several maximum values are extracted from each year of data in order to perform the curve fit [15]. For all metocean parameters, the time series are separated into independent storms, which are events in which a threshold value is exceeded before dropping back below that threshold. If storm events are closer than 48 hours, they are merged into one storm and only one maximum value is extracted from each storm. The threshold value is 20 m/s for wind, 1 m/s for ocean current and 5 m for waves.

The Type 1 GEV requires that the buoy data can be modelled by, for example, the Weibull distribution. This is widely accepted for wind speed distributions [15] and according to ISO 19901-1:2005 [17] it is also applicable to other metocean parameters. It will be shown that the Weibull distribution describes the current and wave data well, and therefore the Gumbel distribution will be used to estimate the 50 year extreme of all metocean parameters, in accordance with DNV [18].

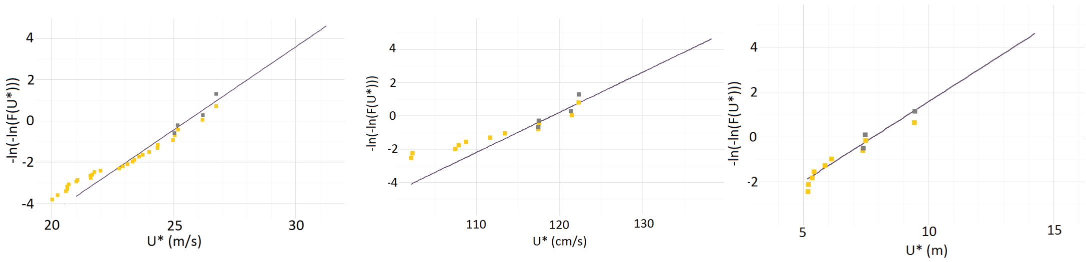
4. Results

4.1. Measured values in the period and estimated 50 year extreme values

Table 1 displays the mean and maximum measured values and the 50 year extreme estimated values for wind gust, ocean current and wave. The maximum wave height (15.8 m) was measured in February 2011, and the strongest surface current (1.5 m/s) was measured in February 2010.

Table 1: Mean and maximum measured values and estimated 50 year extreme values.

Data	Mean value	Maximum value	50 year extreme
Wind gust data at 3.5 m	9.0 m/s	26.7 m/s	30.5 m/s
Significant wave height	1.5 m	9.4 m	13.3 m
Ocean current speed at 20 m depth	0.3 m/s	1.2 m/s	1.4 m/s



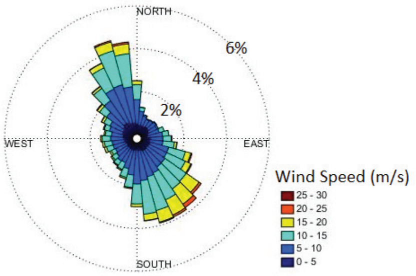
(a) Wind gust **(b)** Current **(c)** Wave

Fig. 3: The blue line is the best fit Gumbel for wind gust, current and wave, yellow squares are the annualized peaks and grey squares are the adjusted plotting positions utilized for the curve fit.

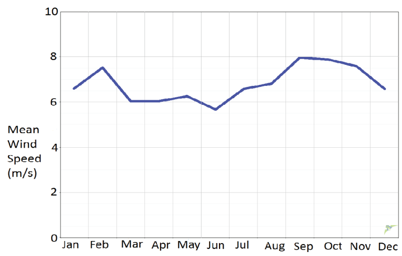
Figures 3a-3c show how well the annualised maximum values for wind, ocean current and wave fit a linearised Gumbel distribution.

4.2. Wind

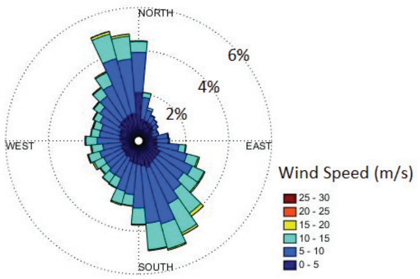
Figure 4 displays the wind direction distributions and the monthly mean wind speeds for the buoy data and the long term extrapolated data. Calculating the coefficient of determination, R^2, [14] between the buoy data and the reference data from Utsira in the period Aug 2009-Sept 2011 results in $R^2_{speed} = 0.77$ and $R^2_{dir} = 0.94$.



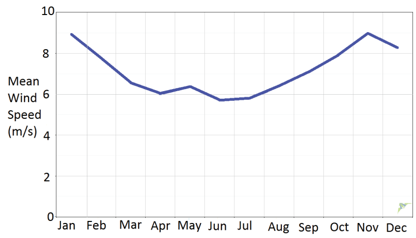
(a) Wind direction distribution for the buoy data



(b) Monthly mean wind speeds for the buoy data



(c) Wind direction distribution for the long term extrapolated buoy data



(d) Monthly mean mind speeds for the long term extrapolated buoy data

Fig. 4: Wind direction distribution and monthly mean wind speeds for the buoy data and the long term extrapolated buoy data.

Table 2 shows the measured mean and maximum values of the wind speed for the buoy data (3.5 m), the long term extrapolated data (3.5 m) and the Utsira reference data (10 m). The Utsira reference data is shown for two time periods in order to highlight that the period Aug 2009-Sept 2011 was a calm period at Utsira and thus a calm period at the nearby Hywind Demo site.

Table 2: Mean and maximum values for the averaged wind speed data. The buoy data and the long term extrapolated buoy data at 3.5 m height, the Utsira data at 10 m height.

Data	Period	Height	Mean value	Maximum value
Buoy data (10-min)	Aug 2009-Sept 2011	3.5 m	6.7 m/s	18.8 m/s
Utsira data (60-min)	Aug 2009-Sept 2011	10 m	7.1 m/s	24.6 m/s
Utsira data (60-min)	Nov 2005-Dec 2015	10 m	7.9 m/s	33.8 m/s
Long term extrapolated buoy data (60-min)	Nov 2005-Dec 2015	3.5 m	7.2 m/s	27.6 m/s

Vertical extrapolation to hub height using the power law with $\alpha = 0.11$ gives a mean wind speed of 9.5 m/s for the buoy data (2 years) and 10.0 m/s for the long term extrapolated buoy data (10 years). For the long term extrapolated buoy data the 50 year extreme value is 31.3 m/s at 3.5 m height and 44.7 m/s at hub height (65

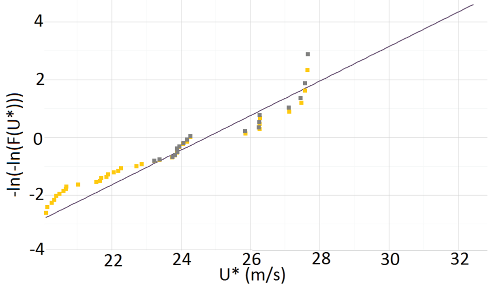


Fig. 5: The blue line is the best fit Gumbel for the long term extrapolated buoy wind data, yellow squares are the annualized peaks and grey squares are the adjusted plotting positions utilized for the curve fit.

m) based on 60-min mean values. The best Gumbel fit for the long term extrapolated buoy data at 3.5 m is shown in Figure 5.

4.3. *Ocean current*

The ocean current data at 20 m and 140 m depth have been fitted to Weibull distributions, as shown in Figure 7, both with $R^2 = 0.99$. Figure 6 shows the ocean current velocity profile based on mean velocities. The direction the ocean current flows towards is shown in Figure 8.

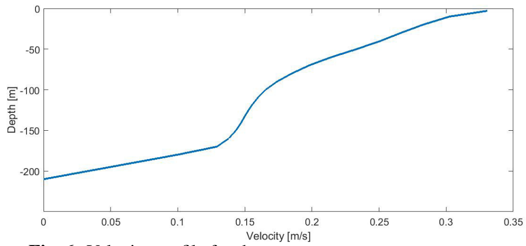
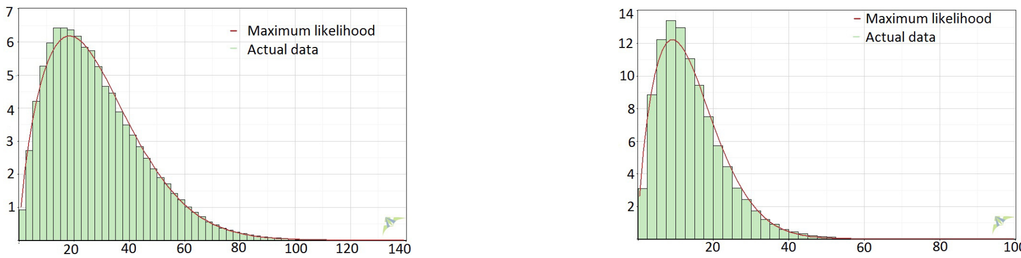


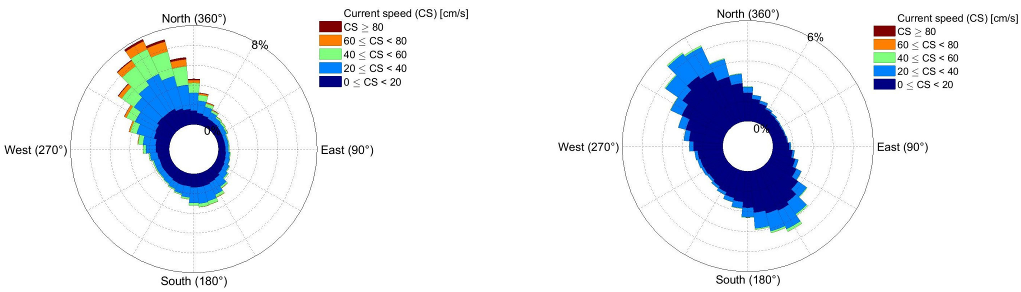
Fig. 6: Velocity profile for the mean ocean current



(a) 20-meter depth. k=1.68 c=31.44cm/s

(b) 140-meter depth. k=1.67 c=15.84cm/s

Fig. 7: Best fit Weibull distribution for the current speed at different depths. x-axis represents current speed in cm/s while y-axis is frequency in %.



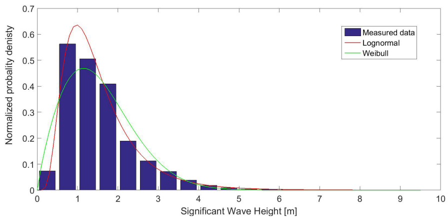
(a) 20-meter depth

(b) 140-meter depth

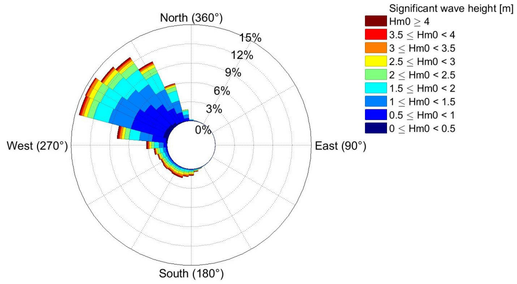
Fig. 8: Distribution of the current speed vs direction at different depths.

4.4. *Waves*

The normalized probability distribution of the significant wave height, the Weibull distribution and the lognormal distribution [19] are plotted in Figure 9a. R^2=0.92 for the Weibull distribution [19] (k = 1.85, c = 1.74). Figure 9b illustrates the direction of the mean spectral wave, where the direction is in degrees measured clockwise from True North and describes the direction the waves are coming from.



(a) Normalized distribution of significant wave height



(b) Distribution of significant wave height vs mean spectral wave direction

Fig. 9: Results of the significant wave height, H_{m0}.

4.5. *Other meteorological data*

The mean values of the environmental parameters for the entire period are Air Temperature 8.4°C, Pressure 1011.5 hPa, Air Density 1.25 kg/m^3, Relaitve Humidity 80.7 %, Water temperature at 2m depth 9.6°C and Salinity 31.60 PSU.

5. Data Quality Assessment

The data recovery rate for the wind and wave data is 99.5% when only the periods the buoy was measuring are considered. For the entire period, September and December have particularly low data recovery rates, about 35%. The data recovery is about 90% for each month for the ocean current data, with lower recovery rates for September (65%) and April and December (55%). The reference data from Utsira has a recovery rate of 95.5%.

6. Discussion

6.1. *Wind*

The monthly mean wind speeds portrayed in Figure 4 for the buoy data and long term extrapolated data both show seasonal variations with higher wind speeds occurring during winter. The buoy data has a low recovery rate especially for December (35%) which explains the more uneven curve for this data as displayed in Figure 4b. The buoy data has a very similar wind direction distribution as the long term extrapolated buoy data, the main difference being that the long term extrapolated buoy data has a somewhat higher frequency of winds coming from the west, as Figure 4 shows.

A prerequisite for conducting a long term extrapolation is that a high correlation between the target and reference data exist [4]. Although the Hywind Demo site and Utsira are located close to each other they experience different conditions as the wind speed profile at Utsira will experience a stepwise change in the surface boundary conditions and a speed-up effect as it reaches the island [20]. This effect is not present at the Hywind Demo site and is believed to cause the poor wind speed correlation, $R^2_{speed} = 0.77$, which leads to uncertainties regarding the long term extrapolated values in Table 2. The wind direction correlation on the other hand is quite high, $R^2_{dir} = 0.94$, indicating that the wind direction distribution at the site should have a higher frequency of winds coming from the west than displayed in Figure 4a.

Figure 3a shows that the wind gust data fit the Gumbel distribution quite well, although the highest U^* value lies above the distribution. As these data were measured in a calm period, the poor curve fit in the tail of the distribution indicates that objects at the site likely will have to experience a higher 50 year extreme value than 30.5 m/s. The long term extrapolated values in Figure 5 do not fit the Gumbel distribution well, especially not in the tail. In addition, the wind speed correlation is low. The 50 year extreme value of 31.3 m/s at 3.5 m height is thus a very rough estimate as is the value of 44.7 m/s at hub height.

6.2. Ocean Current

The Weibull distributions in Figure 7 fit the measured data well with $R^2 = 0.99$, although the peaks of both Weibull distributions are a bit lower than the measured values. The width of the distribution is most narrow for the deepest measurements which induces that the current velocity is more stable there. The velocity profile in Figure 6 indicates that a certain range (∼100-160 m depth) is less affected by both the boundary layer at the bottom and the air-sea interface induced layer at the top. The points in Figure 3b do not perfectly correlate with the linearised Gumbel distribution, implying that the 50 year extreme value of 1.4 m/s is a rough estimate. Myrhaug's observation of surface currents up to 2.5 m/s and the presence of significant eddies along the west coast of Norway [17] further emphasize this finding.

6.3. Waves

Figure 9b clearly shows that most of the waves are coming from north-west. Significant wave heights above 3 meters are rare and 98% of the significant wave heights are less than 4 meters, as Figure 9a shows. The Weibull distribution in this figure fits the data well, although the values are low for significant wave heights below 2 m. With $R^2 = 0.92$ it is still acceptable to apply the Gumbel distribution to estimate the 50 year extreme value. Figure 3c shows that the Gumbel fit for estimating the 50 year extreme value is fair, causing 13.3 m to be a reasonable estimate for the 50 year extreme value. However, comparison with the studies of Tucker [19], Massel [21] and ISO 19901-1:2005 [17], indicates that the buoy will have to withstand higher significant wave heights than 13.3 m. This is in agreement with the fact that the buoy was performing measurements during a calm period.

7. Conclusion

For the Hywind Demo site, seasonal variations are observed, with maximum values of all metocean parameters; wind, current and wave, occurring in late winter. The prevailing flow direction for all metocean parameters is found to be parallel to the coastline. The Weibull distribution describes the metocean parameters well. Therefore it is appropriate to fit the maximum values to the Gumbel distribution when estimating the 50 year extreme values.

The 2 years the Seawatch buoy did measurements was a relatively calm period. Therefore it is reason to believe that the 50 year extreme values for wind gust and wave should be higher than 30.5 m/s and 13.3 m, respectively. As eddies are present at the west coast of Norway, the 50 year extreme value of current at 20 m depth, is expected to be higher than 1.4 m/s.

In order to correct for the calm measuring period, a long term extrapolation of the buoy wind data was conducted. Due to a low wind speed correlation of $R^2_{speed} = 0.77$ between the target and reference data and a poor Gumbel fit, the calculated 50 year extreme value of 44.7 m/s at hub height is found to be inaccurate. The presented long term wind direction distribution is more plausible with a wind direction correlation of $R^2_{dir} = 0.94$.

Acknowledgments

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