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Ejsing Jørgensen, Hans; Nielsen, M.; Barthelmie, R.J.; Mortensen, N.G.

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Modelling offshore wind resources and wind conditions

Hans E. Jørgensen, Morten Nielsen, Rebecca J. Barthelmie and Niels G. Mortensen

Wind Energy Department, Risø National Laboratory
P.O. Box 49, VEA-118, 4000 Roskilde, Denmark
T (+45) 46 77 50 34, F (+45) 46 77 59 70
www.risoe.dk/vea, vea@risoe.dk

Abstract

The paper reviews the status of modelling offshore wind resources and wind conditions using the WAsP and WAsP Engineering models – experiences gained over the last decade, current engineering practices and challenges for the future. The paper aims at answering the basic question: how well can we estimate site wind conditions, described in the IEC 61400-1 and other standards, for offshore wind farm sites?

Whether modelling the wind in the coastal zone or further offshore, the physical modelling should reliably describe the wind speed profiles over water, including the influence of the surface roughness length and atmospheric stability. The modelling outputs required and analysed here are: mean wind speed (V_{ave}) and Weibull parameters (A, k), reference wind speed (V_{ref}) and characteristic turbulence intensity (I_{15}). WAsP and WAsP Engineering modelling results are compared to measurements at offshore met. masts, as well as onshore data sets and other modelling results.

The available meteorological input data may be observations from ships or lighthouses, measurements from offshore masts, wind atlas data sets, NCEP/NCAR reanalysis data, and data from meso-scale models (e.g. KAMM).

The topographical input data discussed are: simple land/sea maps, WAsP roughness rose descriptions, Coastline Extractor coastline maps and hand-digitised coastline / roughness maps. The importance of roughness classification and map diameter is also discussed.

Current engineering practices with respect to vertical datum, water roughness length, wake decay constant, WAsP parameters, wind indices etc. are summarised and discussed.

The challenges offshore are mostly related to the wind field and wind conditions at heights between 50 and 200 m a.s.l. – partly outside the operational envelope of the WAsP programs. In addition, reliable and representative data sets are scarce at these heights. Another challenge is related to the modelling of wake effects in large offshore farms. Possible extensions of today's engineering procedures and practices are outlined.

Keywords

Offshore, wind resources, wind conditions, IEC 61400-1, WAsP, WAsP Engineering.

Introduction

Siting wind turbines offshore is expensive. The higher costs of infrastructure like foundations and cable connections to land are at least partly offset by typically higher and more persistent wind speeds (Pryor and Barthelmie, 1999). Developments offshore tend to be larger in order to reduce the cost per unit but there are many unresolved issues relating to large wind farms, in particular the behaviour of wind turbine wakes. Here we describe use of the WAsP and WAsP Engineering models to predict wind resources and new applications including modelling of turbulence and extreme winds to meet wind turbine standards.

Offshore wind resources

The WAsP program (Troen and Petersen, 1989; Mortensen *et al*., 2005) has been used successfully to estimate offshore wind resources at a number of existing and planned offshore wind farms (Barthelmie *et al*., 1999). There are a number of issues involved and these are described in brief below.

The roughness length over water varies with e.g. wind speed, distance to the coast (Charnock, 1955). For wind resource assessment these variations over a one-year period or longer are insignificant (Barthelmie, 2001) and a value of 0.0002 m can be used (as is used in WAsP). This is illustrated in Figure 1, which shows the wind speed extrapolation factor for different heights and different roughness lengths assuming a logarithmic profile is appropriate. The correct way to set roughness length for water in WAsP is to use 0 for the roughness length. This identifies water surfaces and WAsP sets the heat flux statistics differently over water surfaces. If extrapolation of the wind speed profile is made using heights lower than 10 m (e.g. buoy data) then the variation in surface roughness with wind speed is important and must be taken into account. This will not be done automatically in WAsP. Using the anemometer height closest to hub height is clearly the most optimal method.

In contrast to measurements made over land, which are typically given above ground level, there is no standard for reporting the height of offshore measurements. WAsP will assume that the height is above mean sea level so it is important to understand the reference for measurement heights for individual projects. Examples of this might be:

- mean sea level (MSL),
- highest astronomical tide (HAT),
- mean low water (MLW)
- height above mast base (mast base is usually ~2 m above MSL but can be more)

Limited work has been done so far on the effect of tidal range on wind speed profiles which indicate that tidal range does not affect mean offshore wind resource estimates (Barthelmie, 2001; Khan *et al*., 2003). This assumes that the lowest extrapolation height is 10 m. It is also worth noting that in coastal areas where a moderate to large tidal range exposes tidal flats assuming that these are always water will result in a non-conservative estimate in WAsP because of the modified surface roughness.

The WAsP standard for wake decay coefficients (k) is 0.075 onshore and 0.05 offshore. For small offshore wind farms (~2 rows) 0.05 seems to be correct (e.g. Tunø Knob, Vindeby) but for large offshore wind farms internally generated turbulence may mean that 0.075 is more correct. Using data collected by sodar (Barthelmie *et al*., 2003) the wake decay coefficient for the Vindeby wind farm was estimated as 0.052. Modelled wake decay coefficients for large offshore wind farms are currently being investigated with data from Horns Rev and Nysted. Using WAsP and a test case for a Danish standard wind climate at Horns Rev where 72 turbines are installed gives the following result:

$k = 0.050 \Rightarrow$ total wake losses 8.7%

$k = 0.075 \Rightarrow$ total wake losses 6.7%

It is unclear which is more accurate so probably the best approach at present is to use a more conservative (larger losses) estimate, which is obtained using the lower value.

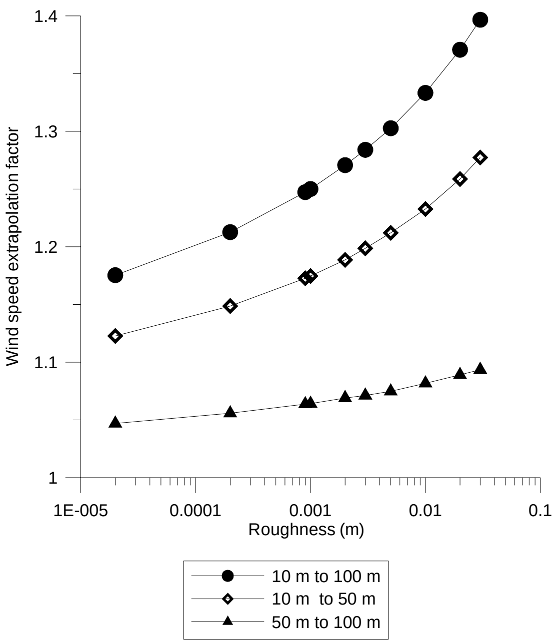

Figure 1. Wind speed profile extrapolation factors for different heights and different roughness lengths assuming a logarithmic profile applies.

Offshore wind conditions

In the new IEC 61400 standard (ed. 3, draft version) there are several wind conditions, which have to be considered when designing a wind farm. The wind conditions, which are important for offshore turbines, are:

1. Extreme winds
2. Wind shear
3. Wind speed probability
4. Turbulence (ambient)
5. Park turbulence

By using a combination of WAsP (Mortensen *et al.*, 2005) and WAsP Engineering (Jørgensen *et al.*, 2005) it is possible to estimate some of these conditions. Extreme winds, ambient turbulence and wind shear can be estimated using WAsP Engineering, and the wind climate, i.e. the wind speed probabilities, can be estimated by using WAsP. To estimate the park or wake turbulence, the model of Sten Frandsen (described in IEC 61400, ed. 3) has further been implemented; this model requires input from both WAsP and WAsP Engineering (ambient turbulence, wind speed probabilities and park set-up, including turbine types). In the following, we describe how WAsP and WAsP Engineering can be utilised to estimate the different wind conditions.

Extreme winds

One of the important siting parameters offshore is the extreme wind, i.e. the 50-year wind, which is important for calculating the loads on the turbine blades and the dimensions of the structure in general. There are at least three ways to obtain the extreme winds:

1. Measurements at the local site
2. Prediction by measurements at a nearby site
3. Predictions by reanalysis data, i.e. results of a global numerical weather prediction model using historic weather observations.

The first method requires that measurements have been made for a long period of time – of the order of 10 years – to reduce the uncertainty in the 50-year wind estimate. This is the ideal information, but unfortunately a local time-series of sufficient duration is usually unavailable.

If nearby measurements are available, we use a method for extreme winds similar to the wind atlas methodology (Troen and Petersen, 1989) used by WAsP for the mean wind climate. Consider the following problem: "What will the corresponding winds over a flat terrain with the roughness $z_{0,2}$ at a height z_2 be, assuming that "Site 2" is in the same climatic regime as "Site 1"? At Site 1 (which is most likely located onshore) we have N annual wind speed maxima sorted in ascending order, i.e.

$U_1, U_2, \ldots, U_N$

If the measurements had been taken over a flat terrain with roughness $z_{0,1}$ at height z_1 at "Site 1", we can apply the following very simple procedure: For each of the yearly maxima (here divided into wind direction sectors) we do the following:

1. Find the friction velocity u_* from the log-law at "Site 1"
2. Use the "geostrophic drag law" to find the geostrophic wind G:

   $$G = \frac{u_*}{\kappa}\sqrt{\left[Log\left(\frac{u_*}{f\,z_{01}}\right) - A\right]^2 + B^2}$$

   where constants A and B are 1.8 and 4.5, respectively (Troen and Petersen, 1989).
3. Use the "geostrophic drag law" in reverse to find u_* at "Site 2".
4. Find the wind speed from the log-law at "Site 2".

If the site is situated in a more complex terrain with respect to roughness and orography then the calculation becomes more complicated. Here, we apply WAsP Engineering, which take speed-up and changing roughness into account. The corresponding maxima at site 2 can now be fitted to a Gumbel distribution:

$$P(u < U) = Exp\left(-Exp\left(-\frac{u-\beta}{\alpha}\right)\right)$$

and the 50-year wind can subsequently be estimated.

If no measurements are available, we employ the third method using model data from a reanalysis data set, e.g. the NCEP/NCAR data set. Wind speed predictions at several heights are found in this data set, but currently we prefer to estimate the geostrophic wind by gradients in the sea-level pressures estimated by modelled surface pressures. The NCEP/NCAR reanalysis model provides ten-minute averaged data, i.e. with an averaging time in accordance with the IEC standard, but the reanalysis data are only calculated every six hours. These time gaps in the data record introduce a negative bias in the extreme wind statistics, since in general the peak of a storm will occur in the interval between two subsequent data records. Larsén and Mann (2005) investigated this sampling problem using a stochastic model with realistic time correlation and found that the extreme values in the NCEP/NCAR data set have a negative bias of 13% relative to the extremes of contiguous 10-min values. Consequently, we add 13% to the extreme wind statistics to compensate for discontinuous sampling. The advantage of using the NCEP/NCAR reanalysis data is that long time-series – with no missing values – are readily available. The disadvantages are that the model data are obtained with a very coarse grid resolution and further calculated with unrealistic values of the surface roughness length z_0. At Risø, we are currently working on procedures to reduce these uncertainties (Larsén *et al*., 2004; Larsén and Mann, 2005).

When using the NCAR/NCEP reanalysis data in WAsP Engineering, the data have been converted to a so-called reduced geostrophic atlas, which corresponds to winds measured at 10 m a.g.l. over a flat terrain with a roughness length of 5 cm. The data have further been corrected due to the time and grid resolution by which the data have been made. This atlas wind can then be applied to a site and the 50-year wind speed U_{50} can be obtained.

The input to the WAsP Engineering program is a file describing the regional extreme wind climate. This file lists near-surface extreme winds over an idealized flat terrain with uniform roughness. For this purpose the extreme wind and the corresponding wind direction from the reanalysis dataset are transformed to winds at 10 m height over an idealized flat terrain with a uniform surface roughness of 0.05 m by the geostrophic drag law theory. Figure 2 shows statistics of the NCEP/NCAR extreme winds over idealized flat terrain for all directions. Also shown is a fitted Gumbel distribution estimating the extreme winds for various return periods. The error bound of the 50-year extreme wind is ±1.2 ms^{-1}.

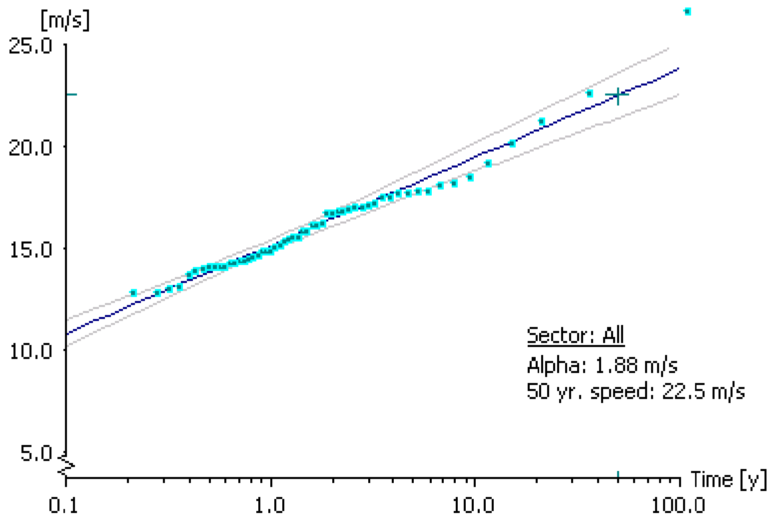

Figure 2. Regional extreme wind distribution for idealized terrain estimated from NCEP/NCAR reanalysis data. The actual data points and fitted theoretical distribution are shown.

Probability density function

The IEC 61400 standard defines a design probability density function by the reference velocity, i.e. the site-specific 50-year extreme wind velocity V_{ref}. This design probability density function is a Rayleigh distribution (equal to a Weibull distribution with k = 2) and it has the average velocity $V_{ave} = 0.2\ V_{ref}$. The standard specifies that the probability density must be less than the design probability density in the range 0.2-0.4 V_{ref}. Wind distributions at individual turbine positions calculated by WAsP are compared to design probability density functions calibrated by the reference velocity found by WAsP Engineering.

Vertical wind shear

The IEC 61400 standard specifies that the vertical wind shear averaged for all wind directions must be in the range $0 \le \overline{\alpha} \le 0.2$. WAsP Engineering models the local flow taking topography and surface roughness into account, and estimates the wind shear at hub height for all wind directions. The average values are calculated as

$$\overline{\alpha} = \sum_{i=0}^{N-1} f_i \alpha_i$$

where index i refers to the wind direction sector and f to the frequency of occurrence calculated by the WAsP program. Problems related to wind shear are more likely in complex terrain than offshore.

Free-stream turbulence intensity

The turbulence model of WAsP Engineering includes the effects of vortex stretching by the mean flow plus gradual changes induced by the changing surface roughness (Mann, 2000). As in WASP, the effects of thermal stratification or re-circulation zones in very complex terrain are not included, but thermal stratification is most pronounced at low wind speeds and not expected to significantly enhance the fatigue loads. The calculated free-stream turbulence intensities, both averaged and specified for each wind-direction sector, are given for each turbine site. Figure 3 shows an example of measured and estimated free-stream turbulence intensities from the Horns Rev wind farm area.

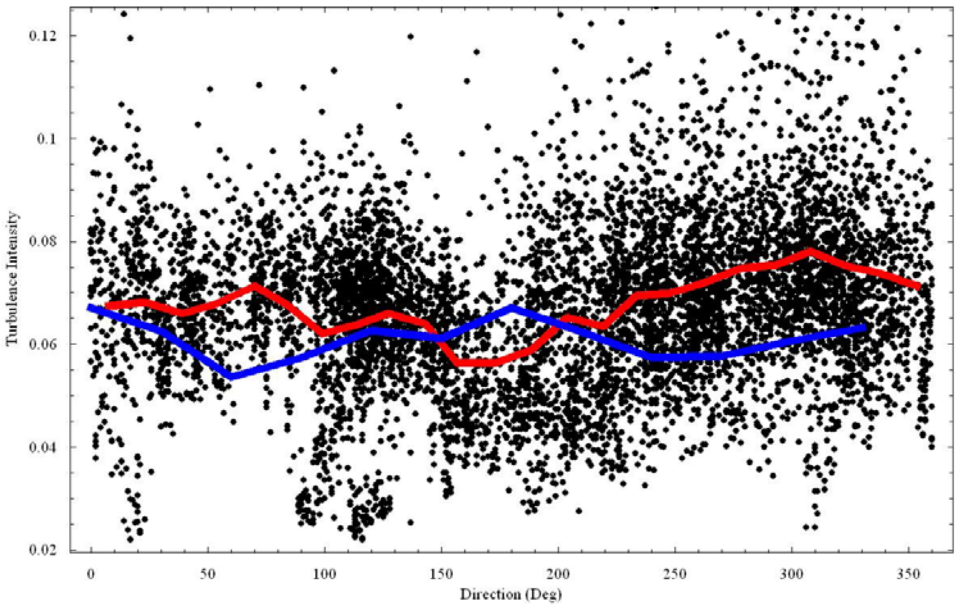

Figure 3. Shows the measured turbulence intensity at 69 meters at Horns Rev versus direction (before the wind farm installation). The measurements are show for wind speeds from 10 to 15 ms^{-1}; the red curve is the average and the blue is the corresponding WAsP Engineering model.

Wake turbulence

Fatigue damage of wind turbines inside a wind farm is enhanced by wakes from neighbouring turbines. The accumulated effect may be quantified by the effective turbulence, which is defined as the turbulence intensity resulting in the same fatigue damage as the probability-weighted turbulence intensity of winds from all directions. Fatigue damage is proportional to turbulence intensity raised to the Wöhler-curve exponent *m* of the material of the structural component in question. Thus the effective turbulent intensity for a particular wind speed and material is

$$I_{\text{eff}}(u) = \left\{ \int_0^{2\pi} I^m(u,\theta)\, p(\theta|u)\, d\theta \right\}^{1/m}$$

where $I(u,\theta)$ is turbulence intensity as a function of wind speed and direction and $p(\theta|u)$ is the probability of the wind direction given the specified wind speed.

Here we apply a slightly modified version of the model described in Appendix D of the IEC61400 standard and further explained by Frandsen (2005). The modifications are introduced in order to utilize the information from the WAsP and WAsP Engineering models and to further account for wind farm layouts with irregular turbine arrays.

The WAsP and WAsP Engineering results include turbulence intensity I_j, frequency of occurrence f_j and Weibull parameters A_j, k_j for *N* sectors at each turbine site, usually twelve sectors as in the present study. The probability of winds with a given direction for a specific wind speed is calculated as

$$p(\theta|u) = \frac{p(u|\theta)\, p(\theta)}{p(u)} = \frac{p(u|A_j,k_j)\, f_j}{\sum_{i=0}^{N-1} p(u|A_i,k_i)\, f_i}$$

where the index *j* refers to the wind direction sector and the wind speed probability is defined by the Weibull parameters *A* and *k*. Depending on the wind direction, the local conditions will include situations with free flow and situations with wake exposure. The corresponding turbulence intensities are written as I_0 and I_T, where the former is provided by WAsP Engineering and the latter is calculated by the following IEC 61400 formula

$$I_{T,j} = \sqrt{\frac{0.9}{\left(1.5 + 0.3 d_{\min}\sqrt{u/c}\right)^2} + I_0^2}$$

applying a velocity scale of $c = 1\,\text{m/s}$ and the distance of the closest turbine $d_{\min}$, which is normalized by the turbine hub height. Wake exposure depends on wake geometry and thereby on the downwind distance, but Frandsen (2005) has shown that a simplified model with a top-hat wake profile and a fixed angle of exposure independent on the distance and set to 0.06 times the full horizon, or 21.6 degrees, produces sufficiently accurate results. We have adopted this simplification as the IEC 61400 standard recommends it. Figure 4 shows an example of the estimated directional distribution of the turbulence intensity at a selected site. At this specific site the most turbulent conditions occur when the wind comes from the directions of the closest turbines.

Frandsen (2005) further suggested including the effect of variability between random 10-min sample periods. At present we do not include this effect, as it is not yet adopted by the IEC 61400 standard.

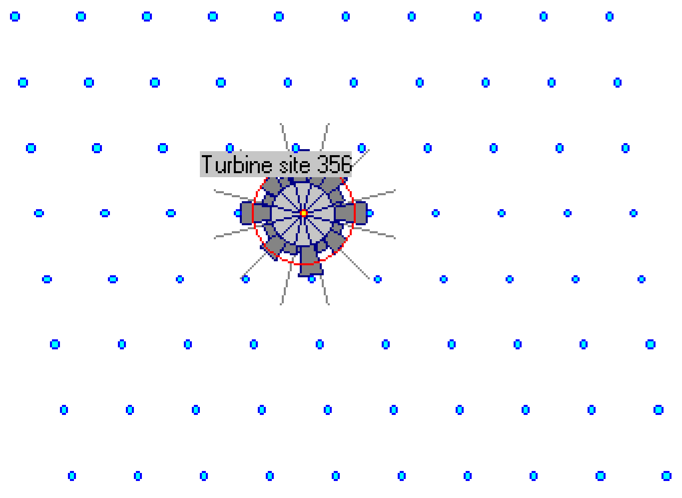

Figure 4. Turbulence intensity at Horns Rev site 356 as a function of wind direction for a wind speed of 5 ms^{-1}. Dark grey indicates wake-induced turbulence and light grey indicates free-stream ambient turbulence calculated by WAsP Engineering. The red circle indicates the effective turbulence intensity for a Wöhler-curve exponent of m=4.

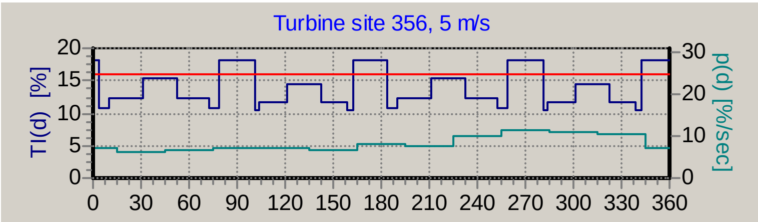

Figure 5. Turbulence intensity at 5 ms^{-1} as a function of wind direction (similar as Figure 3).

Another effect is the enhancement of background turbulence due to blending of wakes from multiple upstream turbines. The IEC 61400 standard specifies how this effect should be quantified, again following Frandsen (2005).

The effects of excluding 10-min randomness, neglecting directional dependence free-stream turbulence intensity, and using a fixed angle of wake exposure rather than the initial model of Frandsen (2005), are of the same order of magnitude. Calculations of wind farms in complex terrain indicates that the contributions by these de-selected model features are all relatively small, but together they might enhance the effective turbulence intensity by about 2%, corresponding to the difference between the IEC 61400 design classes.

The free-stream turbulence intensities predicted by WAsP Engineering does not depend on wind speed, since thermal effects are not included in the flow and turbulence models. The additional wake-induced turbulence intensity will, however, decrease with increasing wind speed and so will the effective turbulence intensity, i.e. the combined effect of winds from all directions. The red curve in Figure 6 show an example of such a variation, which, of course, will depend on wind farm layout, local wind distribution, and Wöhler number. The curves labelled A, B, C in the figure refer to the IEC Normal Turbulence Model (NTM). The effective turbulence is calculated for all wind speeds, all sites, and with a range of Wöhler coefficients representative for different turbine components.

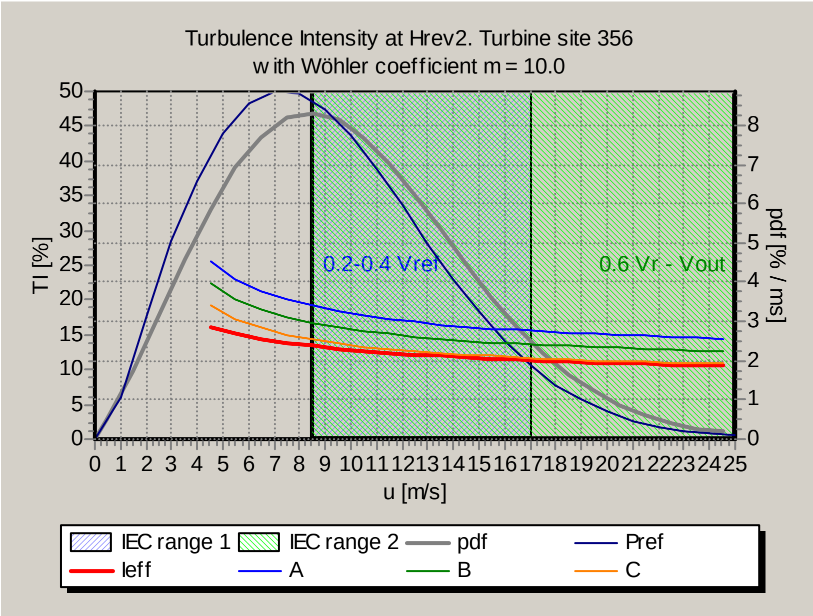

Figure 6. Effective turbulence intensity at Horns Rev turbine site 356, with Wöhler coefficient m=4. The curves labelled A to C are effective turbulence intensities of the IEC normal turbulence model for the standard wind turbine classes.

Summary and conclusions

The WAsP program predicts the wind resource using observed data, also for offshore locations. In offshore applications, the stability-induced correction of the wind profile is different and the surface roughness depends on the wind-speed. Furthermore, the smooth surface reduces the ambient turbulence intensity, so wind-turbine wakes develop more slowly and the associated correction on the energy production is generally more significant.

The IEC 61400 standard specifies turbine safety criteria, and the WAsP Engineering program includes analyses of the wind-related external conditions. The fifty-year extreme wind is an important parameter but, unfortunately, local measurements of sufficient duration and quality are generally not navailable offshore. Instead the extreme wind is estimated by data from a nearby coastal meteorological station or by long records from global circulation models, e.g. the NCEP/NCAR reanalysis data set. In either case the wind speed data are corrected by a flow model predicting the site-specific wind, which then is analysed statistically.

The IEC standard quantifies fatigue loads by a characteristic turbulence intensity, defined as the constant turbulence with the same the expected structural effect as time-varying turbulent conditions, and therefore depending on the material of the structural component under consideration. WAsP Engineering calculates the free-stream turbulence intensity of winds from any direction, using a flow model in balance with the surface roughness and elevation of nearby land. The turbulence from upstream turbine wakes is predicted by a model described in the standard and this is added to the modelled free-stream turbulence. The calculated effective turbulence is a function of wind speed and must not exceed the design turbulence specified in the turbine certificate.

WAsP Engineering also models the shear of the wind profile and inclination of the flow lines at each wind profiles. These parameter are more relevant in complex terrain than offshore.

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