De-trending of turbulence measurements

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Abstract

Traditionally, turbulence is considered as a *stationary* stochastic process imposed on a given *constant* mean wind speed. However, measured (raw) turbulence intensities often display the characteristics of a *non-stationary* process, where the mean wind speed changes slowly with time. The change in mean wind speed appears as a *trend* in the wind speed time series, and often a *linear* trend is assumed.

Wind *resource measurements* typically include statistics of ten-minute mean and standard deviation, and for such data it is not possible to calculate the trend contribution directly, because this requires access to the basic time-series. However, including a suitable modelling of the mean wind speed time variation, it is possible to estimate an approximate (linear) trend correction based on statistical data only.

This paper presents such an algorithm for de-trending of turbulence standard deviation based on time series statistics only. The performance of the proposed de-trending algorithm is assessed using huge number of time series recorded at different types of terrain and orography. The strategy is the following: Based on the available time series information a *conventional* (linear) time series de-trending is performed and subsequently compared with the prediction from the proposed algorithm.

The de-trended turbulence intensities are reduced in the range of 3 – 15 % compared to the raw turbulence intensity. The performed analysis shows that the proposed model, based on statistical information only, accounts for approximately 80% of the “true” (linear) trend as evaluated on basis of the full time series information.

Introduction

Traditionally, wind statistics are recorded as “trended” turbulence, where the reported turbulence intensity consists of two parts – the de-trended stationary part and the trend related contribution. An example of trended and de-trended turbulence intensity distributions are shown in Figure 1, where the turbulence intensity has been assumed Log-Normal distributed. The reduction in the mean turbulence intensity caused by the de-trending is in this example 0.5 % in absolute terms (i.e. from 8.7 % to 8.2 %).

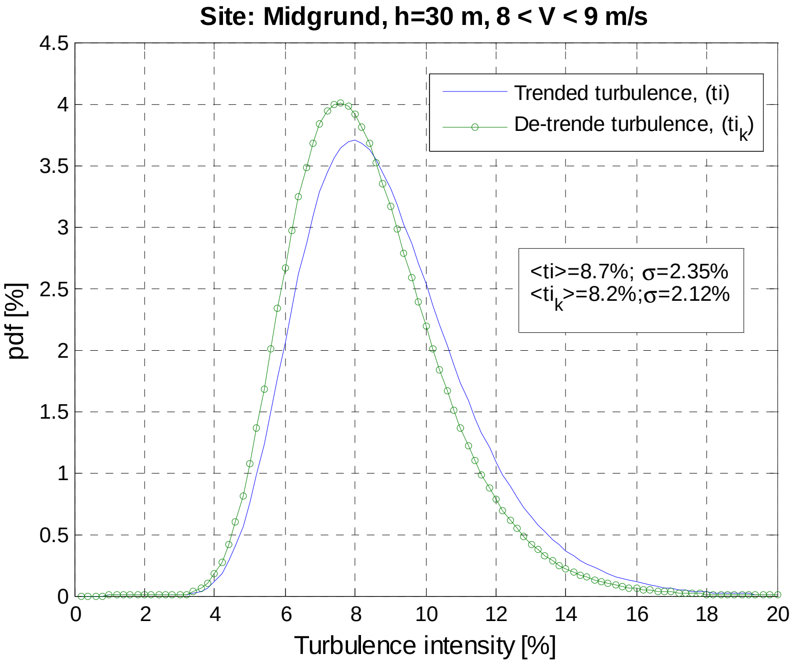

Figure 1: Example of LogNormal distributions of trended and de-trended turbulence intensities measured at Middelgrunden, DK

The trend contribution is basically caused by (mean) wind speed time variability as illustrated in Figure 2, and the derived statistics are presented in Table 1. Period “P3” illustrates that the trend contribution increases the turbulence intensity (*ti*) dramatically (i.e. from 12% to 53%) due to a frontal passage. Removal of the linear trend driven by the mean wind speed variation reduces the turbulence to 3 %.

The prediction of fatigue life consumption of wind turbine components depends strongly on the turbulence intensity, and isolating the “real” turbulence from the mean wind variability driven apparent turbulence contribution could improve the accuracy of the estimated wind turbine fatigue life consumption[1]. This is because the total “trended” turbulence, when used as input to turbulence generators that assumes stationary turbulence, will be distributed over the whole frequency range according to the assumed turbulence spectrum. However, in real life only the stationary part of the turbulence displays this prescribed frequency behaviour, whereas the contribution originating from in-stationary behaviour of the mean wind speed affects only the low frequency fluctuations.

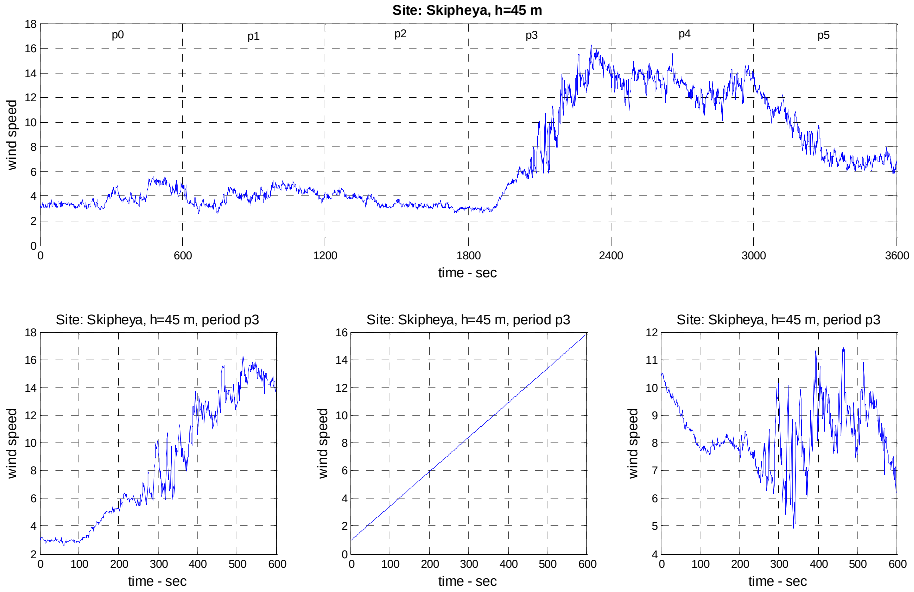

Figure 2: Example of signal de-trending; site=Skipheya; h=45m. a) full time-series of 3600 seconds; b) period=p3 (1800-2400 sec); c) trended signal and d) de-trended signal.

Table 1: De-trending of wind speed, site=Skipheya, h=45m.

Period	<v> [m/s]	Ti [%]	k [m/s]	ti_k [%]
P0	3.86	18.6	1.9	11.7
P1	4.07	14.7	1.2	11.9
P2	3.49	12.4	-1.3	6.6
P3	8.37	53.1	14.9	12.4
P4	13.04	6.9	-0.9	6.6
P5	8.49	24.2	-6.4	10.8

The purpose of the present paper is to quantify and qualify the trend contribution part of the turbulence intensity for arbitrary sites – only site statistics is required as input.

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[1] A complete fatigue estimation would include use of the de-trended part of the turbulence intensity for prediction of a predefined number of stationary load cases subsequently superimposed by fatigue contributions resulting from mean wind speed variations accounting for “jumps” between the defined stationary load cases [6], [7].

Linear detrending

The measured raw turbulence intensity, *ti*, is defined as:

$$ti = \frac{\sigma}{V} , \qquad (1)$$

where V is the mean wind speed, and σ is the corresponding standard deviation.

The turbulence intensity, *ti*, includes a *trend contribution* associated with the mean wind speed changes between consecutive periods which have to be identified. The size of this trend contribution can be significant and has to be removed before the analysis can take place. In the present treatment the trend is assumed to be *linear* during the measuring period T as specified in relation (2).

$$V_k = t \times \left[k / T \right] + V_o \qquad (2)$$

The slope, k/T, and the intercept, V_o, is fitted using a least square method for each time series. *k* is the denoted "stationarity factor" related to the period T, and V_k is the linear varying mean wind speed.

In the present analysis, the trend correction refers to time periods of length 600 seconds, and the de-trended signal thus emerges from the following decomposition of the raw signal x_t

$$x_t^{'} = x_t - \frac{t\,k}{600} + V_o + V \text{ ; } t \in [0;600] . \qquad (3)$$

Compared to the original signal, the derived de-trended signal, $x_t^{'}$, has identical mean value, but the standard deviation, the minimum and the maximum values are reduced as a result of the de-trending process. The procedure is demonstrated in Figure 2b, 2c, and 2d for a signal extracted from the time series shown in Figure 2a.

The *de-trended turbulence intensity,* ti_k , may be derived from the raw turbulence intensity, *ti*, and the stationarity factor, *k*, according to

$$ti_k = \frac{\sqrt{\sigma^2 - k^2/12}}{V} . \qquad (4)$$

Formula (4) is applicable for all turbulence measurements. Note, however, that the method requires determination of the stationarity factor for each individual period.

The contribution to the raw turbulence intensity, ti_t , origination from the linear trend can now be quantified as

$$ti_t = ti - ti_k . \qquad (5)$$

Time series of wind speed data

Analysis of the influences of de-trending requires a huge amount time series representing different terrain and orography types. [1], [2] contains a huge amount measured high quality wind field time series, which are indexed and organized in a searchable database. All the time series are indexed according to main statistical parameters like mean, standard deviation, minimum and maximum values. The indexed values are stored together with detailed information on the installed system, site specification, instrumentation, sensor height and a unique time stamp.

Currently, the wind database contains time series from both offshore and coastal[2] sites representing several European countries. An overview of the data suited for this investigation is given in Table 2.

Analysis of trend impact

The trend contribution to the turbulence intensity is determined for a number of offshore sites located in the northern part of Europe according to Table 2. The measurements are recorded at different heights, but only measurements

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[2] A site is defined as coastal when part of the wind passes water before "hitting" the instrumentation.

from the top located instruments have been included in this analysis[3]. The trend contribution has been determined for a mean wind speed of 15 m/s, corresponding to the IEC definition of turbulence intensity I_{15} [3].

As defined in the previous section the measured turbulence intensity, *ti*, consists of two parts denoted ti_t and ti_k, and the purpose of this analysis is to determine the size of ti_k and how it relates to *ti*.

Table 2: Offshore and coastal sites, extracted from the winddatabase.

	site	levels	hours
offshore	Bockstig,S	7	1382
	Gedsrev,DK	3	702
	Hornsrev,DK	1	13478
	Midgrund,DK	3	2075
	Roedsand;DK	3	619
	Vindeby;DK	7	2394
coastal	Alsvik;S	8	17500
	Ecn,NL	4	49
	Ecn_ems,NL	3	652
	Ecn_met,NL	1	142
	Emden,D	2	781
	Lyse,S	8	31355
	Nasudden,S	15	3069
	Norre,DK	7	746
	Ntk1500,DK	2	151
	Orkney,UK	2	6083
	Ski, N	6	20950
	Sle, N	5	3756
	Sprogoe, DK	1	527
	Vls, N	4	5956

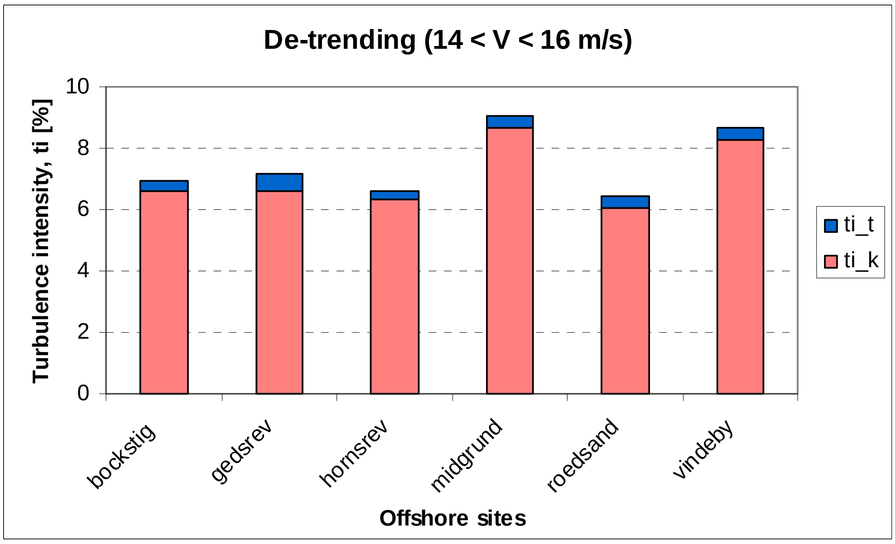

Figure 3: De-trending of offshore sites at 15 m/s.

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[3] The turbulence intensity decreases as function of height [5], but the top level has been selected as the most relevant for wind turbine utilization.

The average trend contribution for a number of Danish offshore locations, referring to a mean wind speed of 15 m/s, is approximately 0.5% with reference to an approximate average turbulence intensity of 6.5% - as shown on Figure 3. This indicates a reduction of 8% compared to raw turbulence intensity.

Due to the limited amount of available offshore measurements, a number of coastal sites have been included in the analysis, cf. Figure 4. The average trend contribution for the coastal sites is approximately 10%, but the variation is large compared to the offshore locations. This is most likely caused by the mixing onshore/offshore flow conditions and local weather systems with many frontal passages. The Norwegian sites (acronyms “ski”, “sle” and “vls”) have a large trend contribution, because these sites are located in the coastal area, which is dominated by frontal passages.

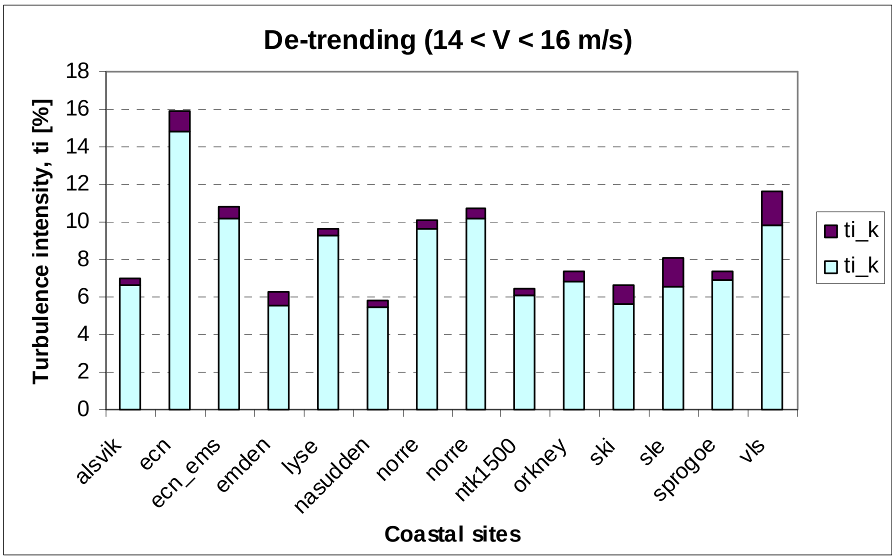

Figure 4:De-trending of coastal sites at 15 m/s.

Example of de-trending time series

De-trending of the offshore data has been applied to a horizontal wind speed signal measured with a 3-D sonic instrument (20 Hz) located 50 m above sea level at Horns Rev [4]. Only measurements from a free inflow sector has been analysed and Figure 5 shows a trend contribution for all wind speed bins of approximately 0.5%, corresponding to an average reduction in the turbulence intensity of the order 10% compared to raw turbulence intensity.

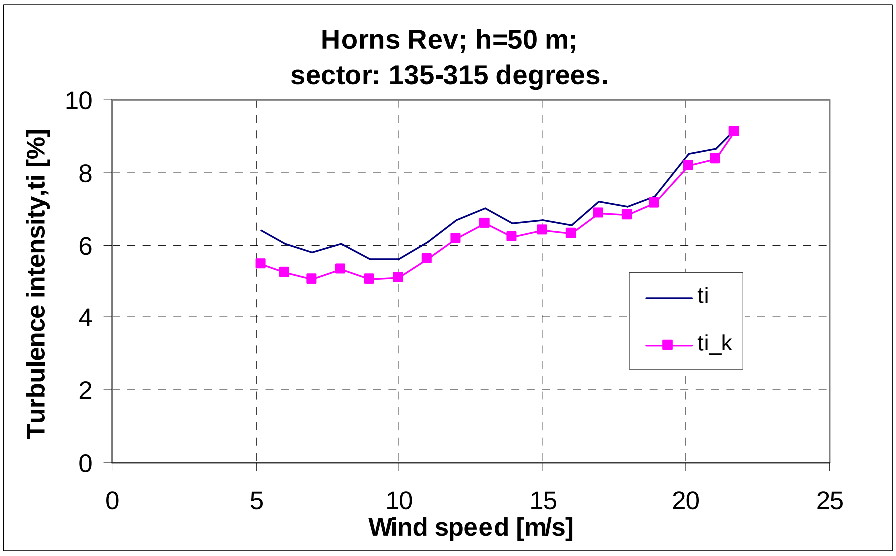

Figure 5: Trended and de-trended turbulence, measured at Horns Rev, DK; h=50m.

Analysis of the coastal data is based on measurements from Skipheya (N), h=101 m, which has been limited to an offshore sector and based on low frequency (~1 Hz) cup anemometer measurements. The measured trend contribution is close to 1% which, according to Figure 6, corresponds to approximately a 16% reduction compared to the raw turbulence intensity.

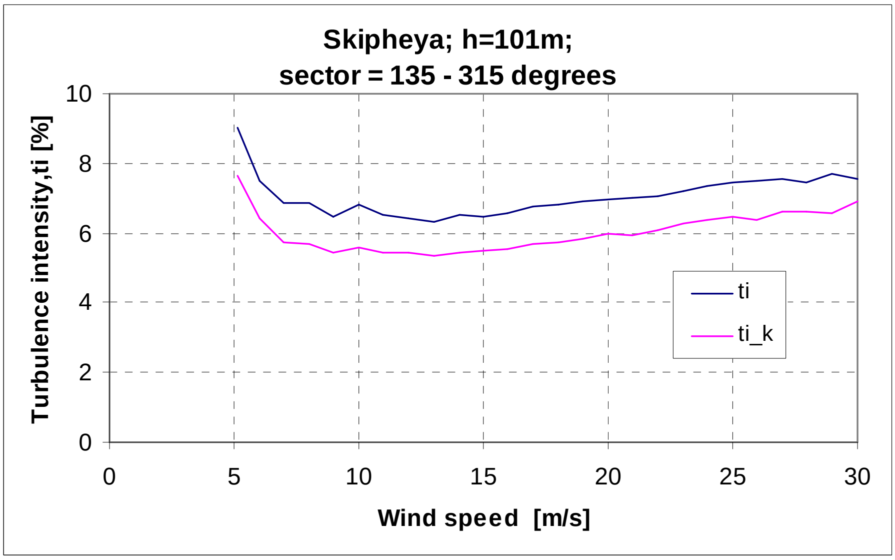

Figure 6: Trended and de-trended turbulence, measured at Skipheya, N; h=50 m.

Model for de-trending ressource data

De-trending of wind speed data requires knowledge of the stationarity factor as mentioned in the previous section. The stationarity factor is, however, *not* determined as part of a standard wind speed measuring campaign, which only include basic statistics e.g. mean and standard deviation. The time series are not stored, because the logger only stores “sum” variables, which prevents any further post processing.

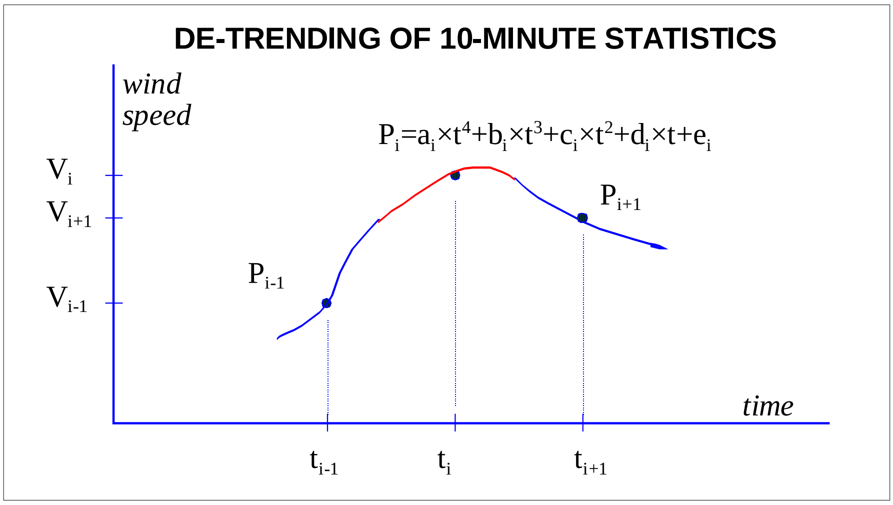

Figure 7: Model for de-trending 10-minute statistics.

To deal with this matter in an approximate manner, two different models have been formulated [8]. The first and simplest of these models includes only information of measured wind speeds to determine the stationarity factor. We will concentrate on validation of this model in the following. The second and advanced model is using both measured wind speeds and standard deviation values for the estimation of the trend correction factor. This model will be evaluated in [8].

Based on three consecutive mean wind speed values, it is possible to estimate the stationarity factor.

The simple model consists on three individual spline functions (polynomials) Figure 7, which are dedicated to each of the three wind speed intervals, and the problem is to determine the polynomial coefficients. This is done by solving a linear system of equations derived by imposing internal *constraints* on the involved polynomials to assure sufficient smoothness in the transition between these as well as to assure the correct measured mean wind speed values. Having determined the polynomial coefficients the stationarity factor (k_i) at time t_i is determined using formula (6).

$$k_i = 4\times t_i^3 \times a_i + 3\times t_i^2 \times b_i + 2\times t_i \times c_i + d_i \qquad (6)$$

The stationarity factor k_i, representing each triple of consecutive of measurements, is inserted to (4) before the trend contribution can be determined.

Validation of de-trending resource data

The simple model has been applied on measurements from 4 offshore/coastal sites with low to moderate turbulence (ti<7%) and from 2 pastoral sites with moderate to high turbulence (ti>16%). The normalized turbulence intensities from the a conventional de-trending process are shown on Figure 8 as function of mean wind speed, together with the analog values as obtained from the suggested model. In addition, the raw turbulence intensity has also been indicated for each site on Figure 8. The figure shows that 1) 70 - 80% of the trend contribution has been determined with the simple model for offshore and costal sites; and 2) 50-70 % of the trend contribution has been determined for pastoral, flat terrain.

Discussion

The results presented in Figure 8 indicate the validity of the simple model for determining the trend contribution of resource data. The model performance weakens when determining the trend contribution for sites with high turbulence (>7%), and this needs to be verified more together with a verification of the advanced model described in [8].

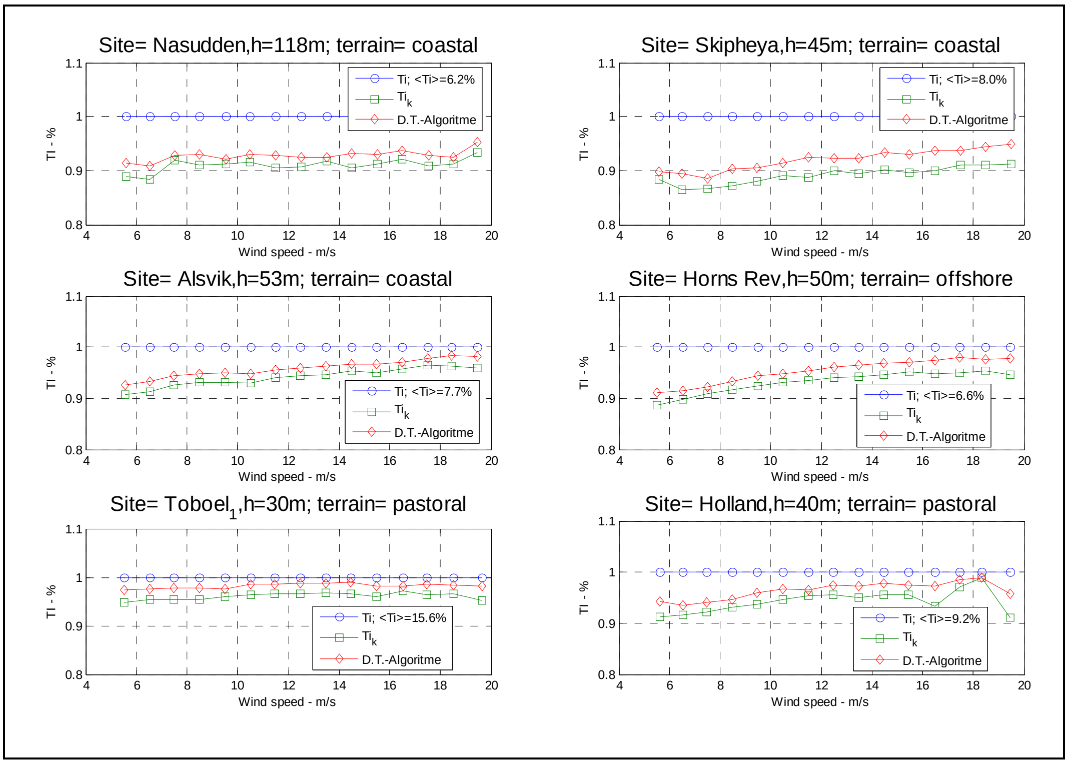

Figure 8: De-trending of 10-minute values as function of mean wind speed.

Conclusion

De-trending the turbulence intensity at offshore sites reduces the mean turbulence intensity of the order of 6-8%, and this reduction is valid for the whole operational range for a wind turbine.
A simple model for de-trending resource data has been implemented and the validation demonstrates that the model is able to determine 70-80% of the trend contribution at low to medium turbulence levels ($\leq$ 7%). De-trending of turbulence intensity indicates a substantial reduction in the simulated stochastic tower loads.

Acknowledgement

This analysis has benefited from measurements downloaded from the internet database: "Database of Wind Characteristics" located at DTU, Denmark. Internet: "http://www.winddata.com/". Wind field time series from the following sites have been applied: Horns Rev (ELSAM, DK); Näsudden and Alsvik (Dept. of Meteorology, Uppsala University); Gedser rev, Vindeby, Rødsand and Middelgrunden (Risø National Laboratories, Denmark); and Skipheia (Norwegian University of Science and Technology, Norway).
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