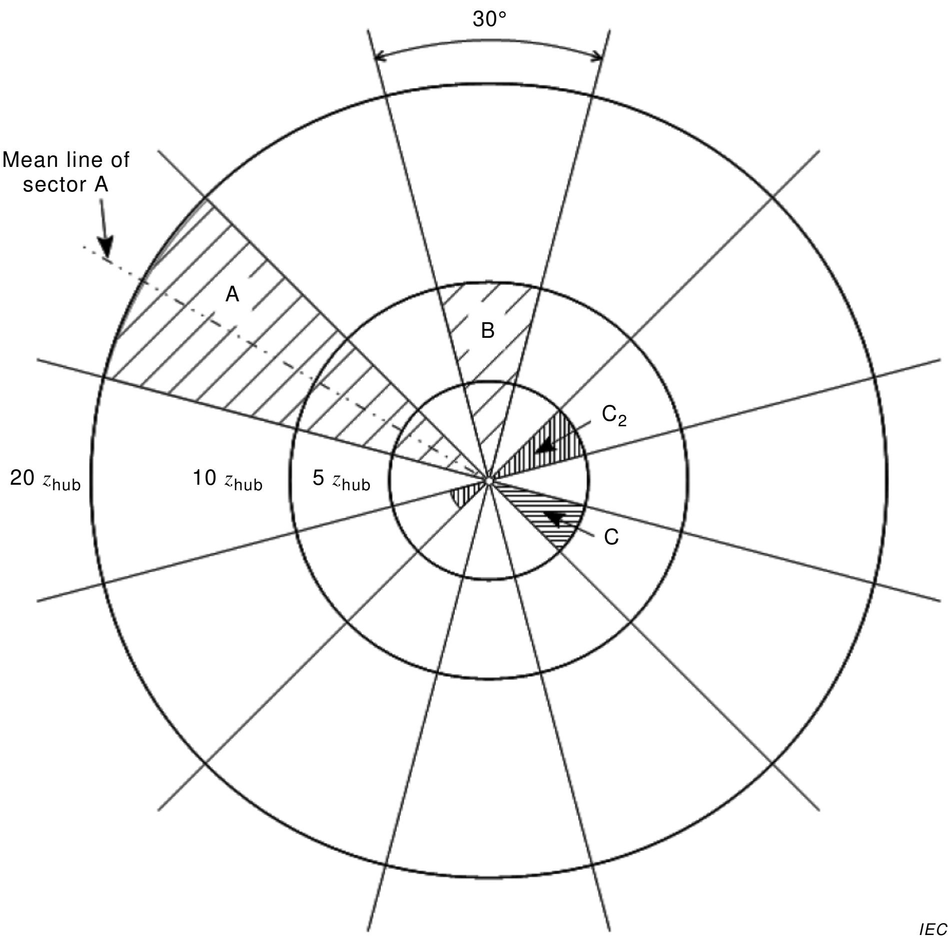
vertically on the fitted planes. Accordingly, the terrain variation from the fitted plane denotes the distance, along a vertical line, between the fitted plane and the terrain at the surface points.

The resolution of surface grid and its original source map used for terrain complexity assessment should not exceed 50 m.

The circle sectors shall be 30°. For the circle sectors with radius 5 z_{hub} the area used to fit the plane may be extended 2 z_{hub} downwind of the wind turbine position, see Figure 10.



Key

A radius 20 z_{hub}

B radius 10 z_{hub}

C radius 5 z_{hub}

C_2 radius 5 z_{hub} extended 2 z_{hub} behind the wind turbine position

Figure 10 – Examples of 30° sectors for fitting the terrain data

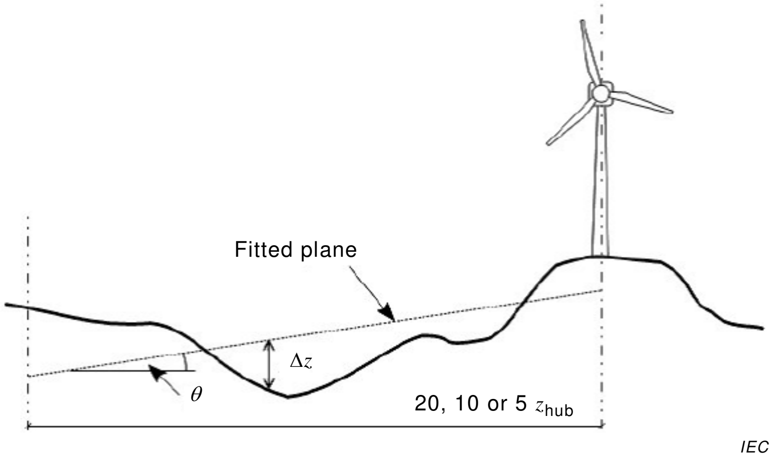


Figure 11 – Terrain variation (Δz) and terrain slope (θ)

Using thus defined slope and terrain variation, terrain slope indices (TSI) and terrain variation indices (TVI) for each circle area are given by the following equations:

$$
\begin{aligned}
TSI_{30} &= \sum_{i=1}^{12} f_{\text{Energy}}(i) \cdot |\theta(i)| \\
TVI_{30} &= \sum_{i=1}^{12} f_{\text{Energy}}(i) \cdot \frac{D_{\text{TV}}(i)}{R} \\
TSI_{360} &= k_1 \cdot \theta_{360} \\
TVI_{360} &= \frac{D_{\text{TV360}}}{k_2 \cdot R}
\end{aligned}
\tag{34}
$$

where

TSI_{30}, TSI_{360}	are the terrain slope indices calculated from 30° sectors and 360° circle area, respectively;
TVI_{30}, TVI_{360}	are the terrain variation indices calculated from 30° sectors and 360° circle area, respectively;
i	is the wind sector index (1, 2, ..., 12);
$f_{\text{Energy}}(i)$	is the percentage of the wind energy coming through ith 30° sector, $\sum f_{\text{Energy}}(i) = 1$;
$\theta(i)$	is the slope of fitted plane for ith 30° sector;
θ_{360}	is the slope of the fitted 360° circle plane;
$D_{\text{TV}}(i)$	is the standard deviation of terrain variation in ith 30° sector;
D_{TV360}	is the standard deviation of terrain variation of the 360° circle area;
R	is the radius of the circle area;
k_1	is the empirical adjustment factor for TSI_{360}, k_1 = 5/3;
k_2	is the empirical adjustment factor for TVI_{360}, k_2 = 3.

TSI_{30} is the mean absolute value of the slopes of the twelve sector-wise fitted planes weighted by energy inflow. Similarly, TVI_{30} is the mean value of the twelve sector-wise standard deviations of terrain variation normalized by the circle radius, weighted by the energy inflow.

TSI_{360} is the slope of the fitted 360° circle plane adjusted by an empirical factor k_1.

TVI_{360} is the standard deviation of terrain variation in 360° circle area, normalized by the circle radius and adjusted by an empirical factor k_2.

Terrain is assessed for terrain complexity by means of two indices TSI and TVI for each of the three circle areas ($5\,z_{hub}$, $10\,z_{hub}$, and $20\,z_{hub}$). For both indices, three complexity categories low (L), medium (M) and high (H) are defined, see Table 5. If the TSI_{30} and TVI_{30} values as well as the TSI_{360} and TVI_{360} values for all three circle areas are below the threshold value for category L, the site is assessed as not complex. If not, the site is assessed as complex and assigned one of the three complexity categories, L, M or H, depending on the highest category TSI or TVI for any of the circle areas.

Table 5 – Threshold values of the terrain complexity categories L, M and H

Radius of circle area	Sector amplitude of fitted plane	Threshold values (lower limit)					
		Terrain slope index (TSI)			Terrain variation index (TVI)		
		L	M	H	L	M	H
$5\,z_{hub}$	360°	10°	15°	20°	2 %	4 %	6 %
$5\,z_{hub}$	30°						
$10\,z_{hub}$							
$20\,z_{hub}$							

11.2.2 Assessment of turbulence structure at the site

The turbulence structure, i.e. the ratios of the three components of turbulence, of a site shall be determined primarily from measurements at the site. When there are no site data, it may be estimated by an appropriate flow model.

Alternatively, it may be estimated from the complexity of the site. Values shown in Table 6 may be assigned depending on the complexity category defined according to the procedure described in 11.2.1.

Table 6 – Values of lateral and vertical turbulence standard deviations relative to the longitudinal component depending on terrain complexity category L, M and H

	Category		
	L	M	H
σ_2/σ_1	0,85	0,93	1,00
σ_3/σ_1	0,60	0,65	0,70

The turbulence structure correction parameter C_{CT}, which may be used in the assessment of the structural integrity by reference to wind data in 11.9, may be defined by the following equation[30]:

$$C_{CT} = \sqrt{1+\left(\hat{\sigma}_2/\hat{\sigma}_1\right)^2+\left(\hat{\sigma}_3/\hat{\sigma}_1\right)^2} \Big/ \sqrt{1+\left(\sigma_2/\sigma_1\right)^2+\left(\sigma_3/\sigma_1\right)^2}$$

30 If C_{CT} is less than 1, C_{CT} = 1,0 shall be used.

in which σ_1, σ_2 and σ_3 are values of the three components of turbulence, at hub height and at wind turbine location, averaged over a wind speed range between 0,6 V_r and 1,6 V_r. The design values for the Kaimal and Mann models can be obtained from Annex C.

When there are no measured site data, the values in Table 7 may be used for C_{CT} depending on the complexity category of the site.

Table 7 – Values of turbulence structure correction parameter depending on terrain complexity category L, M and H

	Category		
	L	**M**	**H**
C_{CT}	1,05	1,10	1,15

Interpolation between the values in Table 6 and Table 7 is allowed.

11.3 Wind conditions required for assessment

11.3.1 General

The site wind parameters shall be either measured and extrapolated, or calculated using appropriate methods (e.g. monitoring measurements made at the site, long-term records from local meteorological stations, simulation models or local codes and standards). Simulation models shall be validated against representative data.

11.3.2 Wind condition parameters

The following parameters shall be derived for the position of the wind turbine at hub height:

- extreme 10 min average wind speed[31], V_{50}, at hub height with a return period of 50 years;
- wind speed probability density function, $p(V_{hub})$;
- wind speed standard deviation $\hat{\sigma}$ from the ambient turbulence (estimated as the mean value of the standard deviation of the longitudinal component) and the standard deviation $\hat{\sigma}_\sigma$ of $\hat{\sigma}$ at all wind speeds required in 11.9 or 11.10;
- extreme ambient wind speed standard deviation[32], $\hat{\sigma}_{1,ETM}$, with a return period of 50 years;

[31] The load partial safety factors for DLC 6.1 and DLC 6.2 are derived by assuming that the coefficient of variation of the annual maximum wind speed, COV, is smaller than 15 %. If COV is larger than 15 %, they can be increased linearly by a factor η from 1,0 at COV = 15 % to 1,15 at COV = 30 %. If $\eta > 1,0$ an adjusted value of the extreme 10 min average wind speed of $\tilde{V}_{50} = \sqrt{\eta}\ V_{50}$ can be used in the assessment of the structural integrity, see 11.9 and 11.10. COV of the annual maximum wind speed can approximately be obtained assuming a Gumbel distribution and assuming that for example 50 year and 100 year return values of the wind speed, V_{50} and V_{100}, are available. The parameters α and β are obtained from:

$$\alpha = \frac{V_{100} - V_{50}}{p_{100} - p_{50}},\quad \beta = V_{50} - \alpha\, p_{50}\quad \text{with}\quad p_{100} = -\ln\left(-\ln\left(1 - \frac{1}{100}\right)\right)\quad \text{and}\quad p_{50} = -\ln\left(-\ln\left(1 - \frac{1}{50}\right)\right)$$

COV is determined from

$$\text{COV} = \frac{\sigma}{\mu} = \frac{\pi}{\sqrt{6}} \frac{1}{\frac{\beta}{\alpha} + 0,5772}$$

[32] The extreme ambient wind speed standard deviation $\hat{\sigma}_{1,ETM}$ may be derived using an appropriate extrapolation method, for example, the IFORM method, or estimated by:

- flow inclination;
- wind shear[33];
- air density.

Where there is no site data for the air density, it shall be assumed that the air density is consistent with ISO 2533, suitably corrected for annual average temperature.

The bin width of any wind speed used in the above shall be 2 m/s or less, and the wind direction sectors shall be 30° or less. All measurements, except air density, shall be available as function of wind direction, given as a 10 min average.

Attention should be given to wakes from significant structures and orographic obstacles within a distance from the wind turbine of 20 times the characteristic length of the structure or the orographic obstacle. The influence can be neglected if the bottom edge of the rotor is at least four times higher than the height of the structure or the orographic obstacle.

In regions prone to hurricanes, cyclones and typhoons, the extreme wind speed shall be evaluated by appropriate methods, for example as given in Annex J.

For cold climate, additional parameters should be derived for the position of the wind turbine. Icing condition may be assessed according to Annex L.

11.3.3 Measurement setup

The requirement for and use of measurements for wind turbine site suitability assessment and wind resource assessments differ in many respects, and therefore a balance needs to be found between the amount and the quality of measurements.[34] Furthermore, for the purposes of a wind turbine site suitability measurement campaign, additional criteria should be taken into consideration.

- The measurement system should be installed in locations broadly representative of the majority of site areas (e.g. forest, ridge lines, plains, valleys, slopes and obstacles).
- The exact number and location of measuring systems recommended is very site-specific and depends upon the terrain, extent and ground cover of the proposed wind farm as well as the expected complexity of the flow regime and the on-site validation of the flow model to be used in the analysis.
- The wind condition measurement heights as well as the number of sensors should be chosen to be representative. Measurements should be performed at a range of heights within the proposed turbine rotor’s swept area. Consideration should be given to surrounding terrain and vegetation.
- The vertical separation distance between the sensors should enable a robust analysis of the vertical wind shear, for example a separation of at least one third of the rotor diameter.
- A temperature as well as pressure sensor should be installed.
- 10 minutes averaging time, based on at least 1 Hz (mean, standard deviation and maximum wind speed, mean of wind direction and mean temperature) should be used.
- If measurements are performed in a cold climate zone, then additional heated sensors should be used and their performance relative to unheated sensors considered.

$$\hat{\sigma}_{1,\mathrm{ETM}} = \hat{\sigma} + k_\mathrm{p}\hat{\sigma}_\sigma;\;\; k_\mathrm{p} = 0{,}01\left(\frac{V_\mathrm{ave}}{(\mathrm{m/s})} - 21\right)\left(\frac{V_\mathrm{hub}}{(\mathrm{m/s})} - 5\right) + 5$$

33 Shear values with high variability have been reported for certain areas in connection with highly stratified flow, complex terrain or severe roughness changes. In this case using the average wind shear may not be sufficient.

34 IEC 61400-12-1 and IEA Recommendation 11 illustrate best-practice guidelines for measurement equipment installation and setup.

- In complex terrain, all wind components should be measured, for example with a 3D-ultrasonic anemometer.

11.3.4 Data evaluation

The recommendations with respect to data coverage and period are the following.

- The measurement period can deviate depending on the quality of data and the reliability of the correlation to a reference long term source. Where seasonal variations contribute significantly to the wind conditions, the monitoring period should be long enough to include these effects (the minimum to capture seasonal effects would be 12 months).
- The data coverage in each month should be sufficiently high to adequately represent the monthly variation in wind conditions.

During data evaluation, a quality check and filtering should be performed and documented. A measure-correlate-predict (MCP) procedure may be performed to extend the data.

The average value of the wind speed standard deviation $\hat{\sigma}$, i.e. the standard deviation of the longitudinal turbulence component, and its standard deviation $\hat{\sigma}_\sigma$ shall be determined using appropriate statistical techniques applied to measured and preferably linearly de-trended data.

A long-term assessment is normally required for the estimation of the extreme wind speed, long-term mean wind speed as well as air density, but only if the available long term source is appropriate and sufficiently reliable.

Alternative methods can be used. These methods should aim to improve the representativeness of the measurements for the site.

The above mentioned methods and procedures shall be documented.

11.4 Assessment of wake effects from neighbouring wind turbines

Wake effects from neighbouring wind turbines during power production shall be considered. The assessment of the suitability of the wind turbine at a site in a wind farm shall take into account the deterministic and turbulent flow characteristics associated with single or multiple wakes from upwind machines, including the effects of the spacing between the machines, for all ambient wind speeds and wind directions relevant to power production.

The increase in loading generally assumed to result from wake effects may be accounted for by the use of an added turbulence approach, or by using more detailed wake models. In either case, the wake model shall include adequate representation of the effect on loading of ambient turbulence and discrete and turbulent wake effects.

For fatigue calculations, the effective turbulence intensity I_{eff} may be derived according to Annex E.

The added turbulence for fatigue and ultimate loads may be assumed to be the same.

The DWM model described in Annex E is generally applicable to both fatigue and extreme load cases.

11.5 Assessment of other environmental conditions

The following environmental conditions shall be assessed for comparison with the assumptions made in the design of a wind turbine:

- normal and extreme temperature ranges;

- icing, hail and snow;
- humidity;
- lightning;
- solar radiation;
- chemically active substances;
- salinity.

11.6 Assessment of earthquake conditions

There are no earthquake resistance requirements for standard class turbines because such events are only design driving in a few regions of the world. No earthquake assessment analysis is required for sites already excluded by the applicable local seismic code due to their weak seismic action. For locations where the seismic load cases described below are critical, the engineering integrity shall be demonstrated for the wind turbine site conditions. The assessment may be based on Annex D. The evaluation of load shall take into account the combination of seismic loading with other significant, frequently occurring operational loads.

The seismic loading shall depend on ground acceleration and response spectrum requirements as defined in local codes. If a local code is not available or does not give the ground acceleration and response spectrum, an appropriate evaluation of these parameters shall be carried out.

The ground acceleration shall be evaluated for a 475-year return period.

The earthquake loading shall be superposed with operational load that shall be the largest of

a) mean loads during normal power production determined at V_r,

b) loads during emergency stop at V_r, and

c) loads during idling or parked condition at no wind and V_{out}.

The partial safety factor for load for all load components shall be 1,0. The material safety factor for steel can be set to 1,0.

The seismic load evaluation may be carried out through response spectrum methods, in which case the operational load is added using the SRSS (square-root-sum-of-squares) or equivalent load combination arising from the seismic loading.

The seismic load evaluation may be carried out through time-domain methods, in which case sufficient simulations shall be undertaken to ensure that the operational load is representative of the time averaged values referred to above.

The number of tower natural vibration modes used in either of the above evaluations shall be selected in accordance with a recognized seismic code. In the absence of such a code, consecutive modes with a total modal mass of 85 % of the total mass shall be used.

The evaluation of the resistance of the structure may assume elastic response only, or ductile energy dissipation. However, it is important that the latter is assessed correctly for the specific type of structure in use, in particular for lattice structures and bolted joints.

The acceleration response spectrum at the engineering bedrock and seismic response evaluation method are described in Annex D. The response spectrum method shall not be used if it is possible that seismic action will cause significant loading of structures other than the tower.

11.7 Assessment of electrical network conditions

The external electrical conditions at the wind turbine terminals at a proposed site shall be assessed to ensure compatibility with the electrical design conditions. The external electrical conditions shall include the following[35]:

- normal voltage and range including requirements for remaining connected or disconnecting through specified voltage range and duration;
- normal frequency, range and rate of change, including requirements for remaining connected or disconnecting through specified frequency range and duration;
- voltage imbalance specified as a percentage negative phase-sequence voltage for symmetric and unsymmetrical faults;
- method of neutral grounding;
- method of ground fault detection/protection;
- annual number of network outages;
- auto-reclosing cycles;
- required reactive compensation schedule;
- fault currents and duration;
- phase-phase and phase-ground short-circuit impedance at the wind turbine terminals;
- background harmonic voltage distortion of the network;
- presence of power line carrier signalling if any and frequency of same;
- fault profiles for ride-through requirements;
- power factor control requirements;
- ramp rate requirements; and
- other grid compatibility requirements.

11.8 Assessment of soil conditions

The soil properties at a proposed site shall be assessed by a professionally qualified geotechnical engineer, with reference to available local building codes.

11.9 Assessment of structural integrity by reference to wind data

11.9.1 General

It is possible to complete the assessment of structural integrity by comparison of the wind parameter values for the site to those used in design. The assessment can be performed separately for the fatigue load suitability and the ultimate load suitability.

11.9.2 Assessment of the fatigue load suitability by reference to wind data

A wind turbine is suitable for a site with respect to fatigue loading when the following conditions are all satisfied.

a) The site value of the wind speed probability density function at hub height $p(V_{hub})$ shall be less than or equal to the design probability density function at all values of V_{hub} between the wind speeds V_{ave} and $2V_{ave}$. If the turbine has been designed with the wind speed distribution in 6.3.2.1 and the shape parameter k of the site-specific Weibull wind speed distribution is greater than or equal to 1,4, then, k shall fulfil the following equation, which

[35] The turbine designer may need to take account of grid compatibility conditions. The list represents a set of minimum requirements. Local and national grid compatibility requirements need to be anticipated at the design stage.

depends on the site-specific mean wind speed at hub height normalized by the design mean wind speed, see Figure 12:

$$6{,}5 \times \frac{V_{\text{ave,site}}}{V_{\text{ave,design}}} - 4{,}5 \le k \le -6{,}0 \times \frac{V_{\text{ave,site}}}{V_{\text{ave,design}}} + 8{,}0 \quad (35)$$

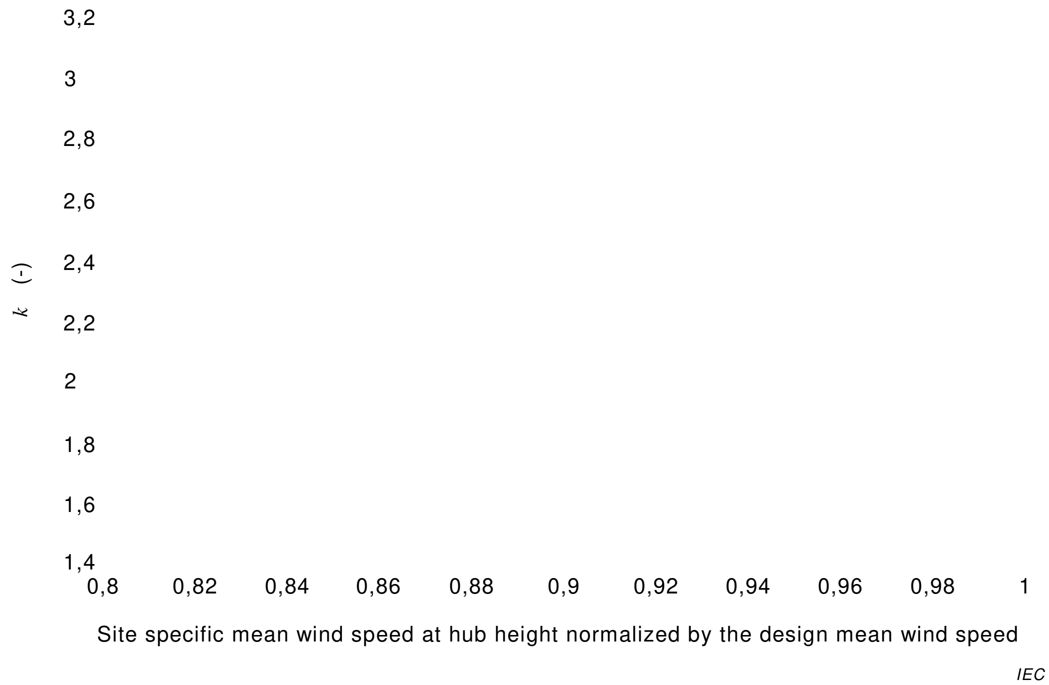


Figure 12 – Possible combinations of normalized mean wind speed and Weibull shape parameter k (shaded area)

b) An adequate assessment of the ambient turbulence intensity and wake effects can be performed by verifying that the wind speed standard deviation σ_1 from the normal turbulence model (NTM) used in design is greater than or equal to the effective wind speed standard deviation $\hat{\sigma}_{\text{eff}}$ (see Annex E) between the wind speeds V_{ave} and $2V_{\text{ave}}$, i.e.

$$\sigma_1 > \hat{\sigma}_{\text{eff}} \left(= I_{\text{eff}} V_{\text{hub}}\right) \quad (36)$$

Guidance for calculating I_{eff} can be found in Annex E. In case of complex terrain, the estimated 90 % quantile of the wind speed standard deviation, i.e. $\hat{\sigma}_{\text{c}}$, shall be increased in order to account for the distortion of the turbulent flow. This can be done by additional multiplication with a turbulence structure correction parameter C_{CT} as defined in 11.2.

c) The site flow inclination, taken as the wind energy weighted mean from all directions, shall be between –8° and +8°. Where there are no site data or calculations for the flow inclination, it shall be assumed that the flow inclination is equal to the slope, θ, for the 30° sector within a distance of $5z_{\text{hub}}$ or the $5z_{\text{hub}}$ area extended by $2z_{\text{hub}}$ downwind of the wind turbine position from the wind turbine, see 11.2.

d) The energy weighted average over all wind directions and wind speeds during power production of the vertical site wind shear exponent α shall be in the range of 0,05 to 0,25. Where there are no site data for the wind shear, it shall be calculated taking topography and roughness of the surrounding terrain into account.

e) The average site air density shall be less than the one specified in 6.4.2 for wind speeds greater than or equal to V_{r}. As an alternative, for an air density greater than the one specified in 6.4, it shall be demonstrated that the following condition applies:

$$\rho_{\text{design}} \times V_{\text{ave,design}}^2 \geq \rho_{\text{site}} \times V_{\text{ave,site}}^2 \qquad (37)$$

11.9.3 Assessment of the ultimate load suitability by reference to wind data

A wind turbine is suitable for a site with respect to ultimate loading when the following conditions are all satisfied.

a) The design value of the wind speed standard deviation, σ_1, (see Equation (10)) shall be greater than or equal to the site value of the estimated 90 % quantile[36] of the wind speed standard deviation at all values of V_{hub} between the wind speeds 0,6 V_r and 1,6 V_r, i.e.

$$\sigma_1 \geq \hat{\sigma} + 1{,}28\, \hat{\sigma}_\sigma \qquad (38)$$

In case of complex terrain, the estimated 90 % quantile of the wind speed standard deviation shall be increased in order to account for the distortion of the turbulent flow. This may be done by additional multiplication with a turbulence structure correction parameter C_{CT} as defined in 11.2.

b) The site estimate of the extreme 10-min average wind speed V_{50} at hub height with a return period of 50 years shall be less than or equal to V_{ref}. Alternatively, the wind turbine site central estimate of extreme 3 s average wind speed at hub height with a return period of 50 years shall be less than V_{e50}. For Class S turbines, both the extreme 3 s average wind speed and the extreme 10 min average wind speed shall be assessed. V_{50} shall be modified according to Footnote 24 when the coefficient of variation of the annual maximum wind speed is larger than 15 %. If the average site air density is different from the one specified in 6.4.2, it shall be demonstrated that the following condition applies:

$$\rho_{\text{design}} \times V_{\text{ref}}^2 \geq \rho_{\text{site}} \times V_{\text{50,hub}}^2 \qquad (39)$$

c) It shall be demonstrated that the site-specific extreme ambient wind speed standard deviation does not exceed the ETM model in 6.3.3.4.

d) In case of wake situations, it shall be demonstrated that the maximum centre-wake wind speed standard deviation in the most severe direction does not exceed the ETM model in 6.3.3.4. Alternatively, it can be demonstrated that the ambient site-specific extreme turbulence does not exceed the ETM model used for DLC 1.6 in Annex B and that the minimum site-specific inter-turbine distance does not fall below s_{min} from DLC 1.6. For determination of the site-specific turbulence, the site-specific conditions, the frequency of the wake situations and the wind farm layout shall be accounted for.

11.10 Assessment of structural integrity by load calculations with reference to site-specific conditions

The demonstration shall comprise a comparison of loads and deflections calculated for the specific wind turbine site conditions with those calculated during design, taking account of the reserve margins and the influence of the environment on structural resistance. The calculations shall account for variations of wind conditions with mean wind direction and speed as well as for wake effects, vertical wind shear, mean wind flow angle, etc.

For the fatigue loading, a comparison of damage equivalent moments and damage equivalent load of the load duration distribution of the driving torque is sufficient for verification of components. For ultimate loading a comparison of contemporaneous loads is not required.

Turbulence structure shall be based on site-specific values. Where there are no site data for the components of turbulence and the terrain is complex, values for the ratios of the

[36] The right hand side of Equation (38) represents an approximation of the 90 % quantile.