5 LOADS SITE COMPLIANCE & LOAD RESPONSE

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5.1 Introduction, definitions, and step-by-step guide

Establishing a proper layout and selecting a suitable turbine model are important steps in developing a wind energy project. Wind turbines are typically designed for 20 years lifetime and according to a number of standard climatic design classes, e.g., the IEC classes IA or IIIC. The Roman numeral defines the wind speed class I, II or III, and the letter defines the turbulence class A, B or C. Class IA is the strongest standard class, and the least strong class is IIIC.

Installing a turbine of the incorrect class on a site could result in premature structural failure and ruin a project. On the other hand, installing a turbine from a class above that required could add unnecessary extra costs, making a project financially unviable.

The windPRO modules SITE COMPLIANCE and LOAD REPONSE help the user determine which particular turbine class is suitable for a site. The modules also help the user identify critical risks of a project.

The requirements of the wind turbine design classes are defined in the international standard:

> IEC 61400-1 ed. 3 (2010) “Wind turbines Part 1 - Design requirements” [1, 2]

Most sections concern design requirements of the standard wind turbine classes. However, Section 11 describes “assessment of a wind turbine for site-specific conditions”, i.e., the assessment of whether a wind turbine class complies with the conditions in a particular site and layout or, in other words, “site compliance”.

5.1.1 Requirements of IEC 61400-1 standards: ed. 4 (2019), ed. 3 (2010) and ed. 2 (1999)

Table 1 in the IEC 61400-1 ed. 3 defines the fundamental design parameters of the standard wind turbine climate classes described above.

Wind turbine class	**I**	**II**	**III**	**S**
Vref [m/s]	50.0	42.5	37.5	Values Specified by the designer
A Iref [-]	0.16			
B Iref [-]	0.14			
C Iref [-]	0.12			

Table 1. IEC 61400-1 ed. 3 “Table 1”.

Section 11 of the IEC 61400-1 ed. 3 (2010) standard (henceforth referred to as the “IEC standard”) describes seven main parameters used to classify the site. Firstly, there is a parameter describing the terrain complexity then six parameters relating to the site’s wind climate. Together, these seven “Main IEC checks” are:

- Terrain complexity
- Extreme wind
- Effective turbulence
- Wind speed distribution
- Wind shear
- Flow inclination
- Air density

The standard also lists a number of “other environmental conditions” to be assessed for a site. Of these additional parameters, we have selected three parameters which are more likely to be critical and which can be estimated with an acceptable accuracy. These parameters referred to as “Other checks” are:

- Earthquake hazard
- Lightning rate
- Extreme and normal temperature range

The omitted parameters are “Icing, hail and snow”, “Humidity”, Salinity”, “Solar radiation” and “Chemically active substances”.

Section 11.1 of the IEC standard ([1], p 52) describes how to compare a site specific wind climate to the design climate for the relevant IEC class, e.g., IIB, to prove that the site conditions do not violate the turbine class.

> *“…It shall be shown that the site-specific conditions do not compromise the structural integrity. The demonstration requires an assessment of the site complexity, see 11.2, and an assessment of the wind conditions at the site, see 11.3. For assessment of structural integrity two approaches may be used:*
>
> *a) a demonstration that all these conditions are no more severe than those assumed for the design of the wind turbine, see 11.9;*
>
> *b) a demonstration of the structural integrity for conditions, each equal to or more severe than those at the site, see 11.10.*
>
> *If any conditions are more severe than those assumed in the design, the structural and electrical compatibility shall be demonstrated using the second approach.”*

In short, ‘approach a’ means that, if all the wind climate checks in SITE COMPLIANCE are OK, it can be concluded that a turbine class is suitable. But, if one or more climate checks are exceeded, ‘approach b’ should be used – which corresponds doing the load calculation in LOAD RESPONSE based on the results from SITE COMPLIANCE.

IEC 61400-1 ed. 2 (1999)

As of windPRO version 3.1 SITE COMPLIANCE and LOAD RESPONSE also support the now obsolete second edition of IEC 61400-1 released in 1999 [23]. The reason to support this older version is that some conservative manufacturers are still selling turbines certified according to this second edition (ed. 2). In addition, new wind farm extensions can influence existing turbines certified to ed. 2, and their suitability must be evaluated according to their original design standard.

The design parameters partly have different definitions in ed. 2 and ed. 3. The reference wind speed Vref is defined in the same way, as the extreme wind speed with 50 years return period. However, the “reference” turbulence intensity is defined differently. In ed. 3, “Iref” is the mean turbulence at 15m/s. In ed. 2, the turbulence parameter is called “I15” and is the 84th percentile of turbulence at 15m/s.

Wind turbine class		**I**	**II**	**III**	**IV**	**S**
	Vref [m/s]	50.0	42.5	37.5	30.0	Values Specified by the designer
	Vave [m/s]	10.0	8.5	7.5	6.0	
A	**I15 [-]**	0.18				
	a [-]	2				
B	**I15 [-]**	0.16				
	a [-]	3				

Table 2. IEC 61400-1 ed. 2 “Table 1”.

The implementation of ed. 2 in SITE COMPLIANCE is based as closely as possible on the ed. 3 implementation, without violating the intention of ed. 2. The reason for this approach is that ed. 3 was created to handle several problematic or too open issues in ed. 2. Appendix VI summarizes the requirements in the IEC 61400-1 ed. 2 (1999).

IEC 61400-1 ed. 4 (2019)

Appendix VII summarizes the requirements in the IEC 61400-1 ed. 4 (2019).

5.1.2 Typical modes of use

SITE COMPLIANCE can be used with various qualities of input data and external software licenses. The following five main modes are available:

1. Mast data & flow model(s)
2. Mast data only
3. No mast data
4. 3rd party WTG results (*.xml)
5. Ambient site result

From windPRO 4.0 SITE COMPLIANCE offers the option to modify each main modes as an Offshore site. The implication of this modification is described in appendix XI.

Full functionality is obtained for projects with site mast(s) with multiple measuring heights and valid external licenses for both WAsP[1] and WAsP Engineering (WEng 3)[2] and pre-run WAsP-CFD[3] flow results available (alternatively pre-run Flowres results, from any CFD model). When using WAsP, the module is considered to be operating in its main mode. In this mode, a WAsP Engineering license is not a requirement, but it adds additional calculation options which improve the quality of the results.

Minimum data level is the second mode *Mast data only.* This mode requires only an on-site mast with multiple measuring heights and no external software licenses to calculate all main checks.

Mode three, *No mast data,* is for projects with no on-site mast, as is typically the case in mature markets with many installed WTGs like Denmark or Germany. This mode requires valid external licenses for WAsP and WEng 3 as well as regional wind statistics (wind atlas / lib file) to complete all seven main IEC checks.

In Mode one, there are two sub-modes for the WAsP setup: *Long term corrected wind statistics* and *Mast directly*. The first sub-mode covers the situation where a long term corrected wind statistics has been generated via MCP for each on-site mast. This mode ensures a WAsP calculation which is consistent with any PARK calculations based on these wind statistics. The second sub-mode (*Mast directly*) integrates the STATGEN calculation for each mast and so includes both steps of the two-step WAsP procedure, taking the on-site mast data directly as input. This sub-mode opens the possibility to perform a simple long-term correction within SITE COMPLIANCE, as this is required in the IEC standard if on-site data is not representative of the long-term.

Mode four provides the possibility to load results of the main IEC checks provided by a 3rd party. These results can be used in LOAD RESPONSE but cannot be combined with any calculation of the IEC checks in SITE COMPLIANCE. The required file format is an xml-file, either with all WTGs in one file or one file for each WTG. This xml-format is also available as a result-to-file option for standard SITE COMPLIANCE calculations.

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[1] http://www.wasp.dk/Products/WAsP.aspx
[2] http://www.wasp.dk/Products/WEng.aspx
[3] http://www.wasp.dk/Software/WAsP-CFD
Note: that WAsP ≥11 is required to use WAsP-CFD results in WAsP

5.1.3 Step-by-step guide

For a quick step-by-step getting-started introduction to SITE COMPLIANCE and LOAD RESPONSE, the user is recommended to use windPRO Quick Guides:

SITE COMPLIANCE Quick Guide

LOAD RESPONSE Quick Guide

Lifetime Analysis Quick Guide

5.2 SITE COMPLIANCE

5.2.1 Setting up a SITE COMPLIANCE calculation

Subsections:

Before starting the SITE COMPLIANCE calculation make sure you have a licensed version of SITE COMPLIANCE and that your windPRO project contains the following data/licenses:

1. A layout of WTG objects

2A. A digital elevation model: line object or elevation grid object (TIN)

3A. A site mast with multiple heights (all carefully checked and cut to a number of full years)

And/Or

3B. A site data object (with a wind statistic)

A valid WAsP license

A valid WEng license

And/Or

3C. A valid WAsP 11 license

And WAsP-CFD result files

And/Or

3D. A Flowres result file(s)[4] (export from any external CFD model)

Or

3E. A predefined xml-file[5] with “3rd party results” for the main IEC checks

The following section 5.2.1 describes the important setup steps of a SITE COMPLIANCE calculation tab by tab. Note that not all tabs described in the following will be available in each of the main modes.

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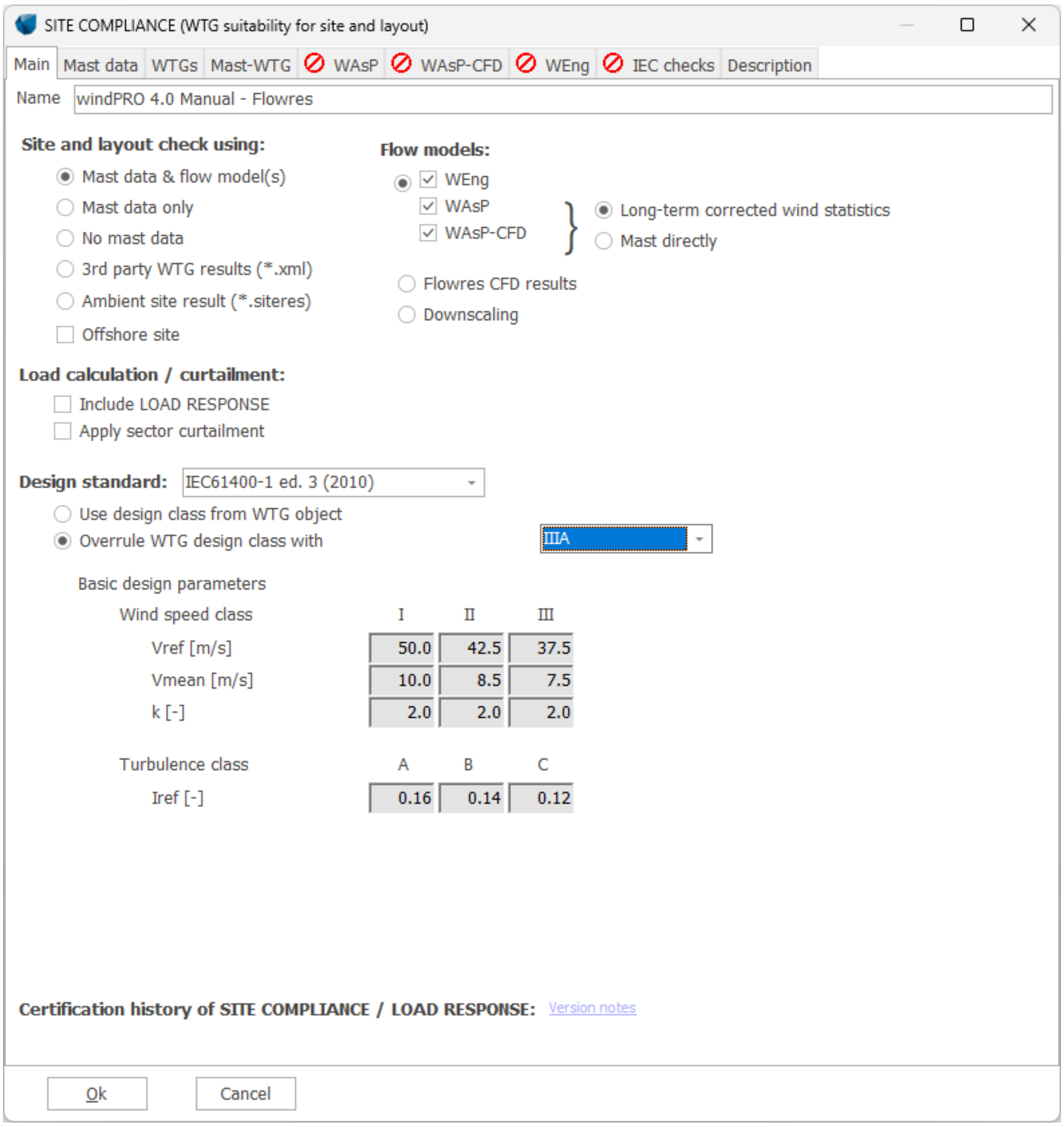
[4] See Flowres format in: http://www.emd.dk/files/flow/EMD_technote_Generalized_Flow_Request_Result.pdf

[5] See xml format specification in: http://www.emd.dk/files/windpro/windPRO_third_party_Load_Response.pdf

5.2.1.1 Main

On the Main tab of SITE COMPLIANCE, the general mode of use (described previously) is selected under *Site and layout check using:*. The appropriate choice depends on the availability of on-site measurements and licenses for the flow models WAsP, WAsP Engineering (WEng) or WAsP CFD. Alternatively, external (CFD) flow results in Flowres files or external 3rd party IEC check results in xml files can be used.



Name: windPRO 4.0 Manual - Flowres

Site and layout check using:

- ● Mast data & flow model(s)
- ○ Mast data only
- ○ No mast data
- ○ 3rd party WTG results (*.xml)
- ○ Ambient site result (*.siteres)
- ☐ Offshore site

Flow models:

- ● ☑ WEng
- ☑ WAsP
- ☑ WAsP-CFD
  - ● Long-term corrected wind statistics
  - ○ Mast directly
- ○ Flowres CFD results
- ○ Downscaling

Load calculation / curtailment:

- ☐ Include LOAD RESPONSE
- ☐ Apply sector curtailment

Design standard: IEC61400-1 ed. 3 (2010)

- ○ Use design class from WTG object
- ● Overrule WTG design class with: IIIA

Basic design parameters

Wind speed class	I	II	III
Vref [m/s]	50.0	42.5	37.5
Vmean [m/s]	10.0	8.5	7.5
k [-]	2.0	2.0	2.0

Turbulence class	A	B	C
Iref [-]	0.16	0.14	0.12

Certification history of SITE COMPLIANCE / LOAD RESPONSE: Version notes

Figure 1. Main tab in SITE COMPLIANCE setup, showing all sub tabs.

The *Flow models* with a valid license should be ticked. WEng 3 and WAsP / WAsP-CFD are only selectable if valid licenses are available. Note that selection of WEng requires that WEng version 3 or newer is installed and licensed and that the PC has internet access. The license system of WEng and non-dongle based WAsP versions (from version 11) will check license status regularly via the internet.

If a valid license is available for LOAD RESPONSE, the *Include LOAD RESPONSE* option can be checked to include load calculations based on the IEC main check results for each wind turbine.

If curtailment criteria have been defined on the individual WTG objects to shut down in certain wind speed and direction intervals, these curtailment criteria may be included by checking the option *Apply sector curtailment*. The curtailment will influence the result of the Effective turbulence check due to reduced wake effects from shut down turbines. Curtailment also affects results in LOAD RESPONSE because a shutdown turbine will experience less fatigue loads.

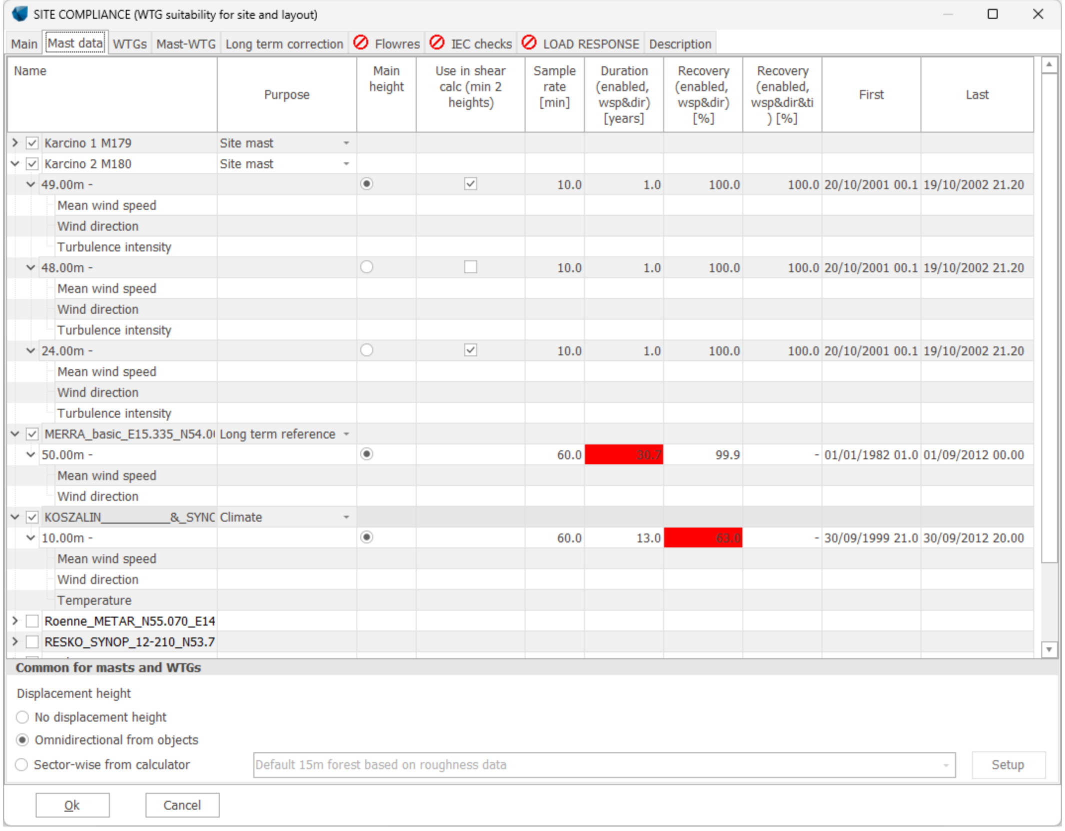
The *Design standard* must be selected between the options: IEC61400-1 ed. 4 (2019), IEC61400-1 ed. 3 (2010) or IEC61400-1 ed. 2 (1999).

If a *Design class* is not set individually in each of the relevant WTG objects, *Overrule* option may be selected to select the *Design class*. The basic design parameters are summarized for each design class in the table below the overrule selection. If *Class S* is selected, the empty fields for class S in the summary table becomes editable to fill in the class design values. The checkbox “Wind speed dependent TI90” enables a table to explicitly define custom TI design values for each wind speed bin, instead of just filing the Iref class S field.

5.2.1.2 Mast data

On the *Mast data* tab, the relevant *Site masts* must be selected by checking them. Once a mast is selected, it expands, and the *Main height* must be selected. This is the height used as basis in all IEC calculations and in WAsP calculations if “run in *Mast directly* mode” is used. If multiple heights are available, the heights to be used in calculation of vertical shear (i.e., wind speed variation with height) must be checked (including the main height).

Note that if any fields such as *Sample rate*, *Duration* or *Recovery* are shaded red, this indicates potential problems. The IEC standard requires 10-minute data to be used for on-site measurements, and that data should not be seasonally biased, i.e., duration should be an integer number of years.
If available, one or more *Long term reference* series may be selected as well. This is done by checking it and setting the *Purpose* to *Long term reference*. A third *Purpose* available is *Climate*, which may be used in case no temperature series has been measured on the site mast.



Name	Purpose	Main height	Use in shear calc (min 2 heights)	Sample rate [min]	Duration (enabled, wsp&dir) [years]	Recovery (enabled, wsp&dir) [%]	Recovery (enabled, wsp&dir&ti) [%]	First	Last
☑ Karcino 1 M179	Site mast								
☑ Karcino 2 M180	Site mast								
49.00m -		●	☑	10.0	1.0	100.0	100.0	20/10/2001 00.1	19/10/2002 21.20
Mean wind speed									
Wind direction									
Turbulence intensity									
48.00m -		○	☐	10.0	1.0	100.0	100.0	20/10/2001 00.1	19/10/2002 21.20
Mean wind speed									
Wind direction									
Turbulence intensity									
24.00m -		○	☑	10.0	1.0	100.0	100.0	20/10/2001 00.1	19/10/2002 21.20
Mean wind speed									
Wind direction									
Turbulence intensity									
☑ MERRA_basic_E15.335_N54.0	Long term reference								
50.00m -		●		60.0	🟥 30.7	99.9	-	01/01/1982 01.0	01/09/2012 00.00
Mean wind speed									
Wind direction									
☑ KOSZALIN__________&_SYNC	Climate								
10.00m -		●		60.0	13.0	🟥 63.0	-	30/09/1999 21.0	30/09/2012 20.00
Mean wind speed									
Wind direction									
Temperature									
☐ Roenne_METAR_N55.070_E14									
☐ RESKO_SYNOP_12-210_N53.7									

Common for masts and WTGs

Displacement height
○ No displacement height
● Omnidirectional from objects
○ Sector-wise from calculator Default 15m forest based on roughness data

Figure 2. Mast data tab showing a typical setup with a Site mast, a Long term reference series and a Climate mast (typically the nearest 10m Synop station for long-term temperature data).

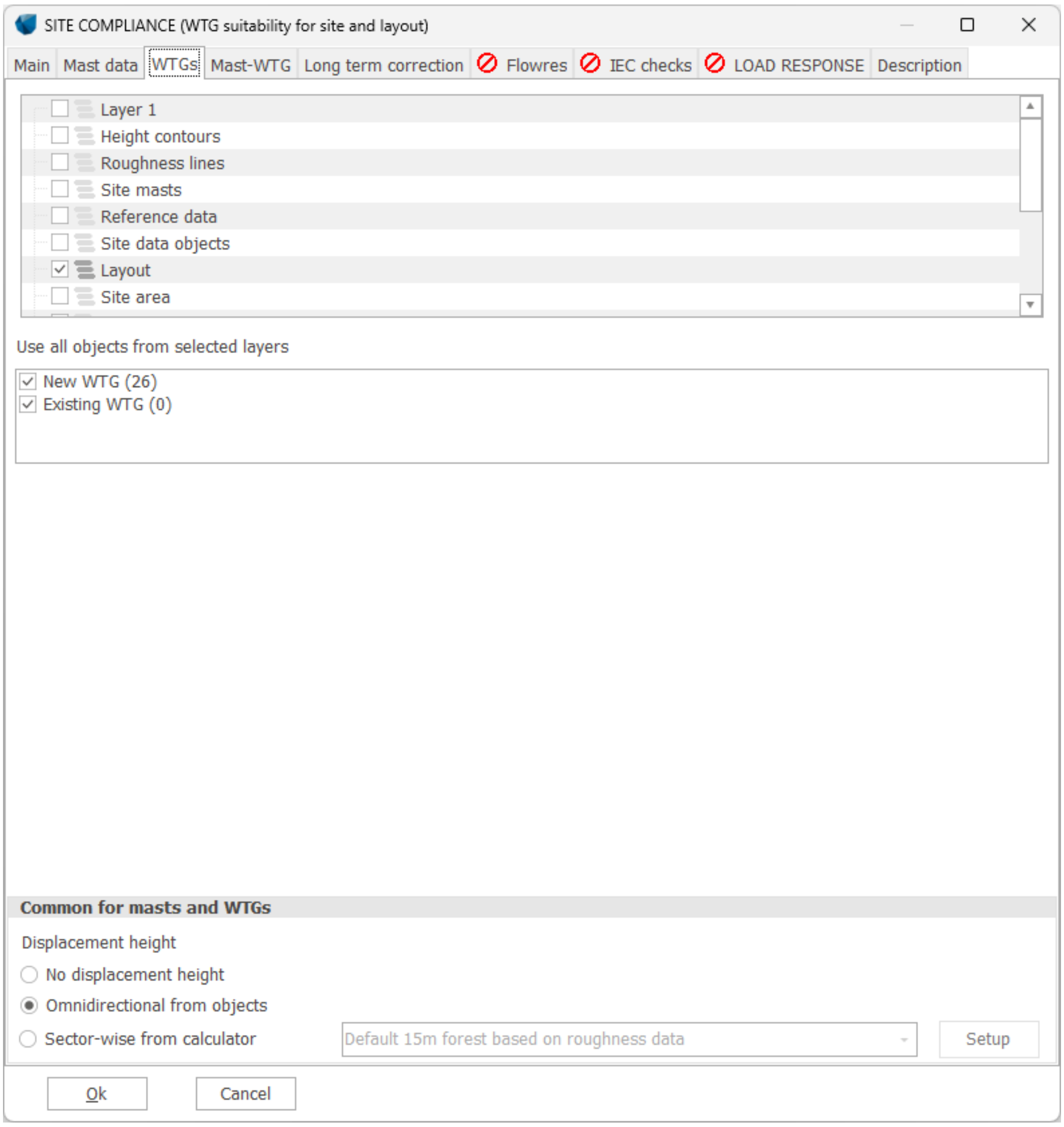
5.2.1.3 WTGs

On the *Layout* tab, the WTGs of the project are selected. In SITE COMPLIANCE, the IEC checks are performed only for WTGs classified in the project as *New* WTGs. *Existing* WTGs which are selected are included in relevant calculations (e.g., wake effects), but no individual results appear for such WTGs. Check the layer(s) with the

New WTGs and adjust individual selection at the bottom of the tab if only some WTGs in the layer are to be included.

Note that at the bottom of the page you may select whether you want to have the object description or the user label in the site tables, graphs and reports.

WTGs in noise reduced modes should generally be avoided as the wind speed at rated power is extracted from the power curve as part of a main IEC check. This may not work well for power curves in reduced mode.



☐ Layer 1
☐ Height contours
☐ Roughness lines
☐ Site masts
☐ Reference data
☐ Site data objects
☑ Layout
☐ Site area

Use all objects from selected layers

☑ New WTG (26)
☑ Existing WTG (0)

Common for masts and WTGs

Displacement height
○ No displacement height
● Omnidirectional from objects
○ Sector-wise from calculator — Default 15m forest based on roughness data

Figure 3. Layout tab, where the relevant project WTGs (New WTGs) are selected.

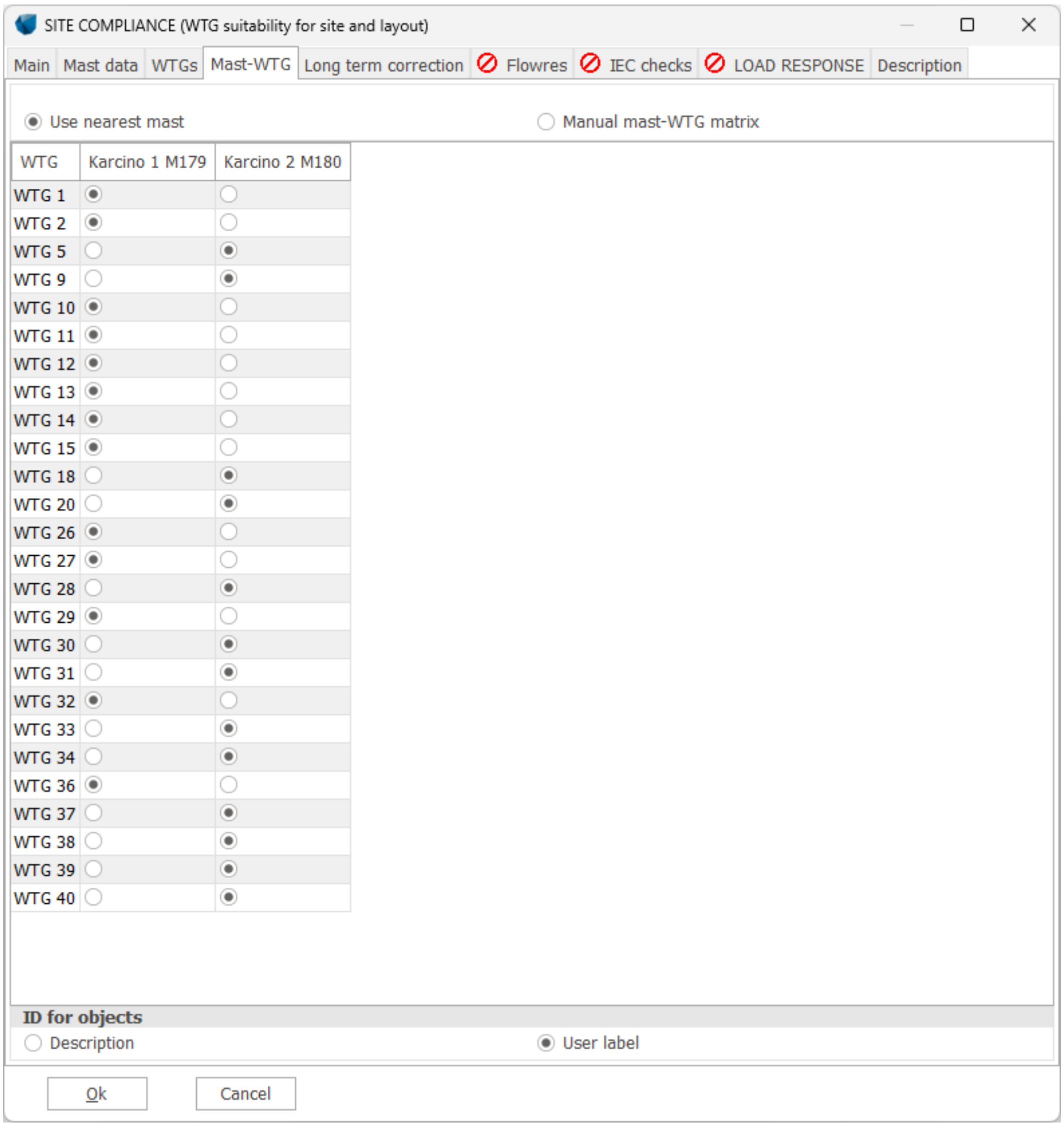
Displacement height (Common for mast and WTGs)

There are three options for displacement height (see Figure 3, left side): “No displacement height”, “Displacement height from objects” and “Displacement height calculator”. The last two options are relevant if omnidirectional displacement heights have been set on mast or WTG objects. The “calculator” (last option) is the most complete option as it works with sector wise displacement heights and a buffer zone around forests with fractional ramp down of displacement heights for nearby forests.

5.2.1.4 Mast-WTG

This tab is only available in modes one and two where an on-site mast is available. Here, the user decides which mast to use for which WTG. The default setup for Mast-WTG link choses the nearest mast for each WTG.

However, this may be adjusted manually where there are multiple choices for mast by selecting the *Manual mast-WTG matrix*.



● Use nearest mast ○ Manual mast-WTG matrix

WTG	Karcino 1 M179	Karcino 2 M180
WTG 1	●	○
WTG 2	●	○
WTG 5	○	●
WTG 9	○	●
WTG 10	●	○
WTG 11	●	○
WTG 12	●	○
WTG 13	●	○
WTG 14	●	○
WTG 15	●	○
WTG 18	○	●
WTG 20	○	●
WTG 26	●	○
WTG 27	●	○
WTG 28	○	●
WTG 29	●	○
WTG 30	○	●
WTG 31	○	●
WTG 32	●	○
WTG 33	○	●
WTG 34	○	●
WTG 36	●	○
WTG 37	○	●
WTG 38	○	●
WTG 39	○	●
WTG 40	○	●

ID for objects
○ Description ● User label

Figure 4. Mast-WTG tab – the appropriate site mast should be chosen for each WTG.

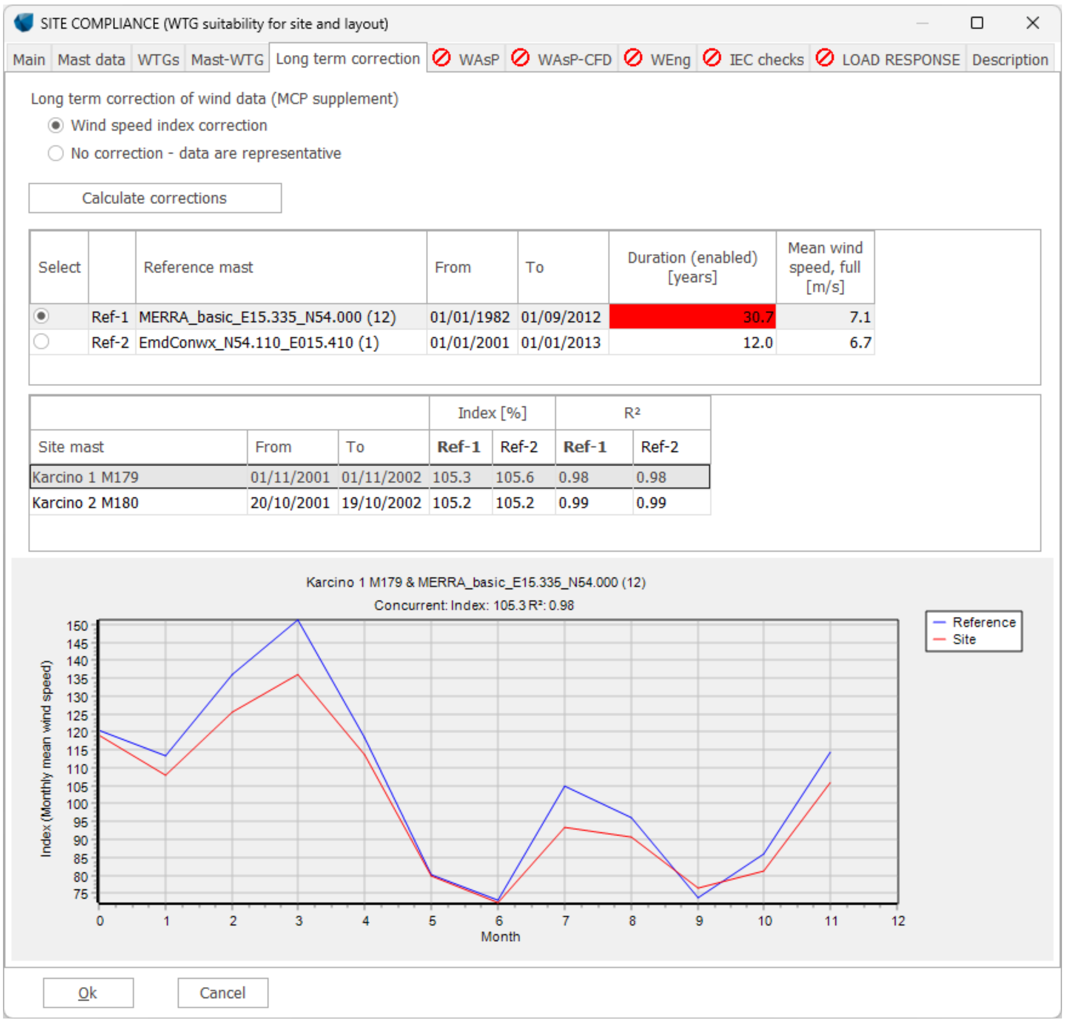
5.2.1.5 Long term correction

This tab is only available in mode one and two and when WAsP mode is set to *Mast directly*. In these cases, it is important to evaluate whether the measurement period of the mast(s) is long-term representative. If not, a long-term correction may be appropriate and can be applied from within SITE COMPLIANCE.

Note that this tab offers a simple alternative to the typical procedure of making a long term corrected wind statistics for each site mast via MCP and using the WAsP option *Long-term corrected wind statistics* on the *Main tab*.

The long-term correction available within SITE COMPLIANCE supplements the MCP methods in the MCP module as it is a wind speed index correction, where the index correction in MCP is based on an energy index. Another reason for this difference is that, in SITE COMPLIANCE, the focus is loads and not energy.

Where the selection is *No correction - data are representative*, no further action is required. If a long term series was setup on the *Mast data* tab and it fully overlaps with the Site mast data, then the option *Wind speed index correction* may be selected. By selection of this option, the *Calculate corrections* button turns yellow and must be clicked. Evaluate the results for each site mast (if more than one) in terms of *Index* and *R²* (correlation coefficient). The plot is only shown for the one selected.



Long term correction of wind data (MCP supplement)

● Wind speed index correction

○ No correction - data are representative

Select		Reference mast	From	To	Duration (enabled) [years]	Mean wind speed, full [m/s]
●	Ref-1	MERRA_basic_E15.335_N54.000 (12)	01/01/1982	01/09/2012	30.7	7.1
○	Ref-2	EmdConwx_N54.110_E015.410 (1)	01/01/2001	01/01/2013	12.0	6.7

			Index [%]		R²	
Site mast	From	To	Ref-1	Ref-2	Ref-1	Ref-2
Karcino 1 M179	01/11/2001	01/11/2002	105.3	105.6	0.98	0.98
Karcino 2 M180	20/10/2001	19/10/2002	105.2	105.2	0.99	0.99

Karcino 1 M179 & MERRA_basic_E15.335_N54.000 (12)

Concurrent: Index: 105.3 R²: 0.98

Figure 5. Long-term correction tab.

An index of 100% means that the mast period is representative of the long-term. A value either above or below 100% means that the mean wind speed measured by the site mast must be corrected by the appropriate amount (inverse index) to represent the long term climate.

The index is calculated from the reference series as the ratio of the mean wind speed of the concurrent period divided by the mean of the full length of the series. Correlations coefficients are based on concurrent monthly mean wind speeds, which are also plotted on the graph where they are normalized to an average of 100.

5.2.1.6 WAsP

The *WAsP* tab is available if *WAsP* was checked on the main tab. Options on this tab depend on the selected WAsP mode. In WAsP mode, *Mast directly* a single *Site data object* must be selected to define the terrain and roughness maps to send to WAsP (see below).

Current WAsP version: WAsP 12

Setup

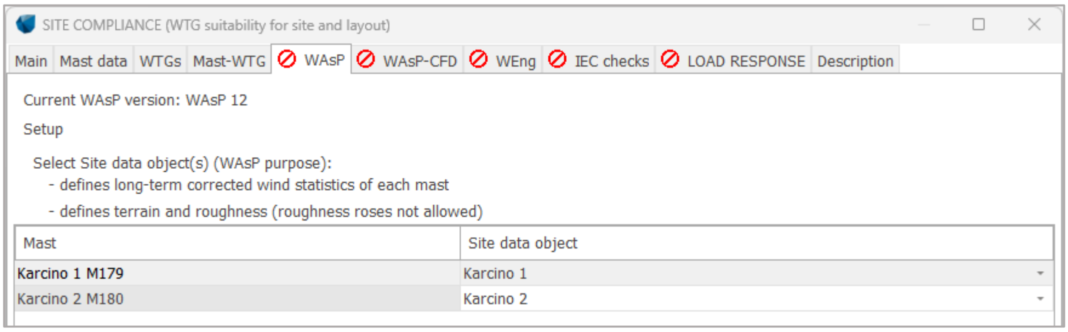
Select site data object (Statgen purpose):

- defines terrain and roughness (roughness roses not allowed)

Site data: STATGEN (4)

Figure 6. WAsP tab in WAsP mode Mast directly.

Running SITE COMPLICANCE in WAsP mode *Long-term corrected wind statistics*, a *Site data object* with a wind statistics must be selected for each mast (only one in the case illustrated). Please ensure that the selected wind statistics in each site data object, in fact, holds a long-term corrected wind statics for the mast.



Current WAsP version: WAsP 12

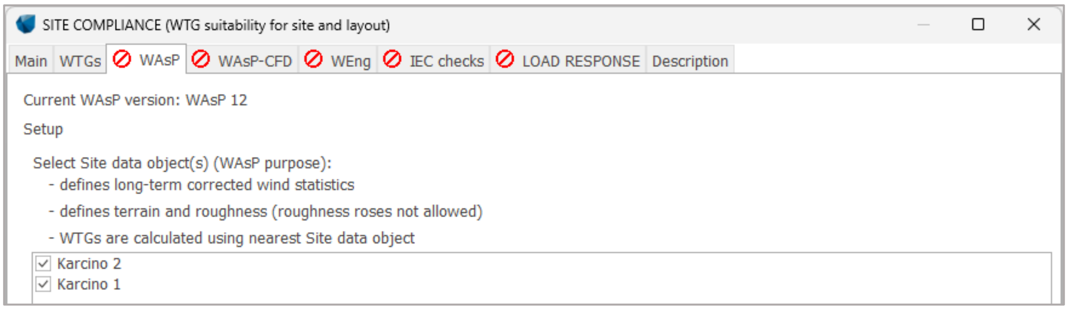
Setup

Select Site data object(s) (WAsP purpose):
- defines long-term corrected wind statistics of each mast
- defines terrain and roughness (roughness roses not allowed)

Mast	Site data object
Karcino 1 M179	Karcino 1
Karcino 2 M180	Karcino 2

Figure 7. WAsP tab in WAsP mode Long-term corrected wind statistics.

In *No mast* mode, the WAsP tab requires the user to check the *Site data objects* to be used in the calculation. The nearest site data objects will then be used for each WTG.



Current WAsP version: WAsP 12

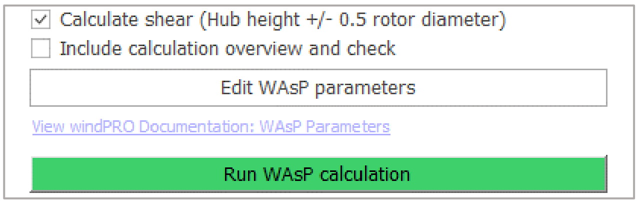
Setup

Select Site data object(s) (WAsP purpose):
- defines long-term corrected wind statistics
- defines terrain and roughness (roughness roses not allowed)
- WTGs are calculated using nearest Site data object

☑ Karcino 2
☑ Karcino 1

Figure 8. WAsP tab in No mast mode.

When the Site data object(s) has been selected, the WAsP calculation is run by clicking the green *Run WAsP Calculation* button. WAsP parameters may be adjusted by clicking the *Edit WAsP parameters* button.



☑ Calculate shear (Hub height +/- 0.5 rotor diameter)
☐ Include calculation overview and check

Figure 9. WAsP tab – ready to run the calculation or change WAsP parameters.

Figure 10. WAsP tab, before and after successful calculation.

When the WAsP calculation is complete the calculation button turns white and the red stop sign on the WAsP tab becomes a green tick mark (see Figure 10).

Displacement height

See section Displacement height.

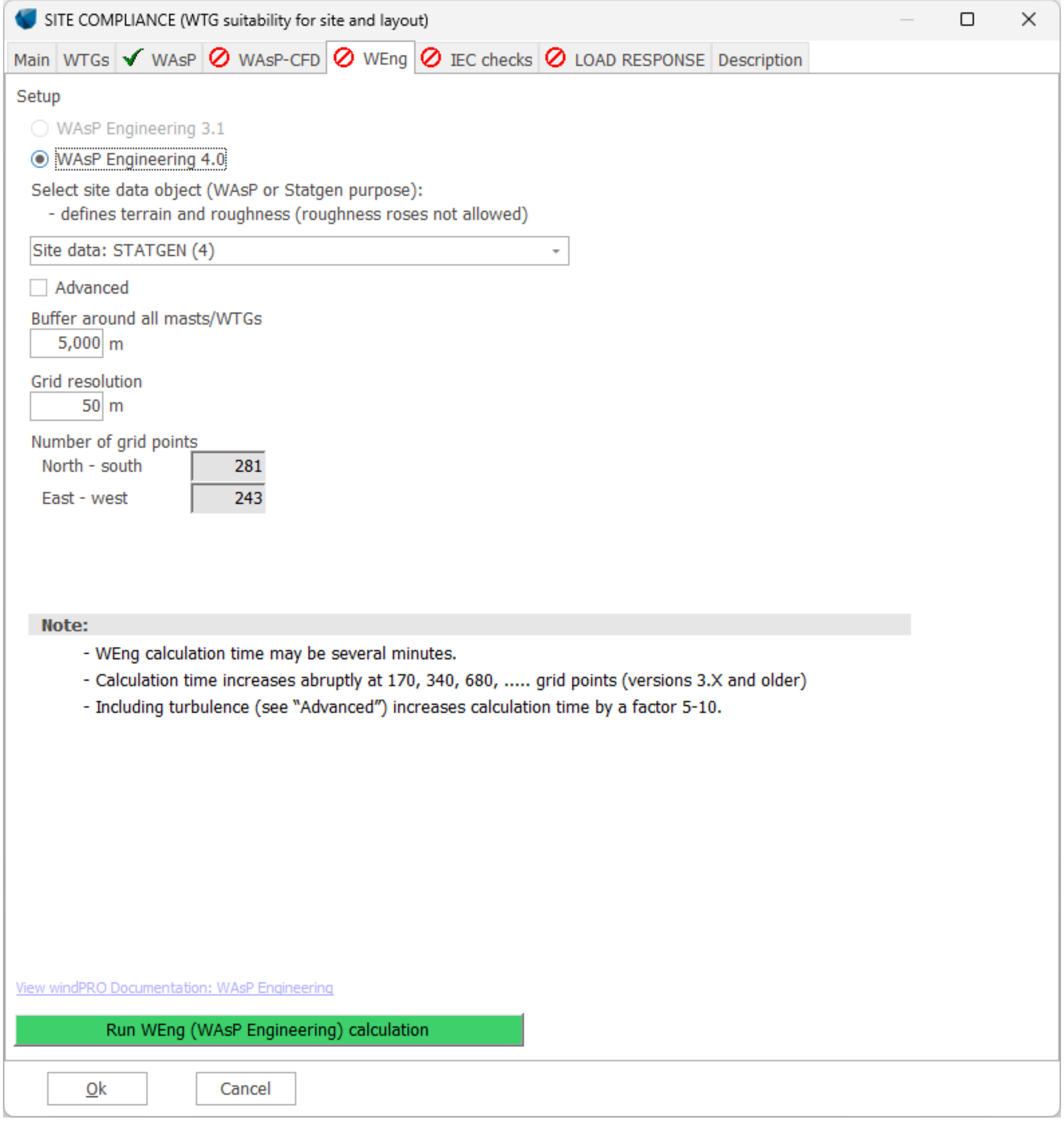
5.2.1.7 WEng

SITE COMPLIANCE offers an easy-to-use integration of WAsP Engineering 3 (WEng 3) and later versions. We recommend using WEng 4 for stability (available in windPRO 3.1 SP1). The integration requires full external installation and licensing of WEng, and turns windPRO into the GUI of the WEng flow model. This has enabled a significant simplification of setting up and running WEng. Contrary to WAsP, WEng is a grid-based model that calculates the flow parameters (except turbulence) for each grid point of an entire rectangular calculation domain defined by the user.

First, a *Site data object* must be selected to define the terrain and roughness maps passed to WEng.
Then a *Buffer around all masts/WTGs* must be chosen. This buffer distance defines the extension of the calculation domain. Default is 5km, which is a compromise between accuracy and calculation time. In cases with prominent roughness changes just beyond 5km or large scale terrain features, the buffer should be extended as required.

The grid resolution defaults to 50m which, typically, is acceptable. In sites with rapid variations in terrain, such as a narrow ridge, a finer resolution should be chosen.

Notice that if the *Buffer* or *Grid resolution* is changed the *Number of grid points* will update accordingly. The calculation time of WEng is optimized if the *Number of grid points* stays just below 170, 340 or 680 …etc., in both directions. This is due to internal zero-padding inside WEng.



Setup

○ WAsP Engineering 3.1
● WAsP Engineering 4.0

Select site data object (WAsP or Statgen purpose):
- defines terrain and roughness (roughness roses not allowed)

Site data: STATGEN (4)

☐ Advanced

Buffer around all masts/WTGs
5,000 m

Grid resolution
50 m

Number of grid points
North - south 281
East - west 243

Note:
- WEng calculation time may be several minutes.
- Calculation time increases abruptly at 170, 340, 680, ... grid points (versions 3.X and older)
- Including turbulence (see "Advanced") increases calculation time by a factor 5-10.

Figure 11. WEng tab.

Once appropriate settings are made, the calculation can be performed by clicking the green *Run WEng (WAsP Engineering) calculation* button. A WEng calculation may take several minutes. A main reason is that turbulence is predicted for each WTG and mast position.

Figure 12. WEng tab before and after successful calculation.

Note that for larger domains and fine resolutions, in particular WEng 3.x may crash. WEng does not inform windPRO that it has crashed but windPRO's connection to WEng simply times-out. In such cases it is possible to have windPRO automatically dump a WEng project with the WEng calculation setup (wind direction and domain) which caused the crash. This file will be named "WEngCrashProject.wep" and is situated in the windPRO project root folder. This WEng project file may be opened and tested directly in WEng and if the crash is reproduced, the project should be passed directly to the WAsP/WEng support team at DTU for diagnostics and further help. To enable this option see WEng *Advanced setup.*

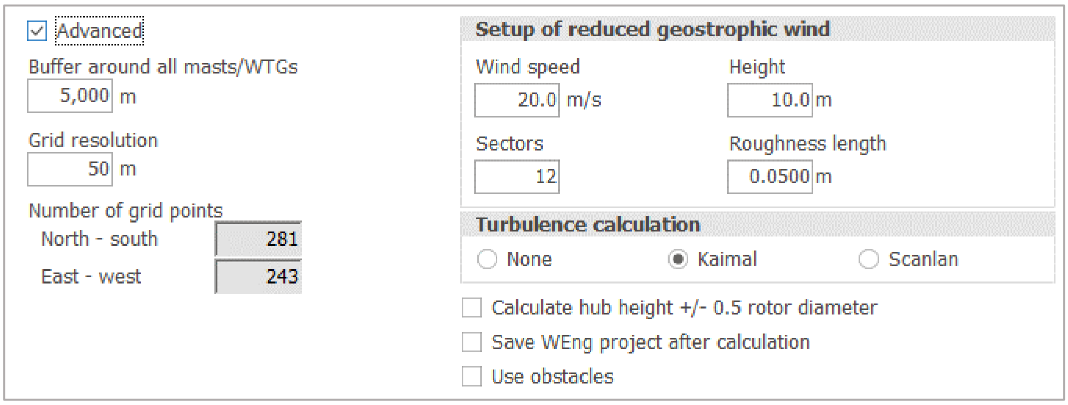
Displacement height

See section Displacement height.

If displacement heights have been set, either for the Meteo or WTG objects, in the WEng calculation, the typical effect is to decrease predicted wind speeds at the object in question, whereas predicted turbulence and wind shear will normally increase.

Advanced setup

Prior to running the WEng calculation, the *Advanced* setup options may be reviewed and adjusted.



☑ Advanced

Buffer around all masts/WTGs: 5,000 m

Grid resolution: 50 m

Number of grid points
North - south: 281
East - west: 243

Setup of reduced geostrophic wind

Wind speed: 20.0 m/s
Height: 10.0 m
Sectors: 12
Roughness length: 0.0500 m

Turbulence calculation

○ None ● Kaimal ○ Scanlan

☐ Calculate hub height +/- 0.5 rotor diameter
☐ Save WEng project after calculation
☐ Use obstacles

Figure 13. WEng tab, Advanced setup.

This setup illustrates how the flow modelling actually works inside WEng via the *Setup of reduced geostrophic wind* that allows adjustment of *Wind speed*, *Height*, *Roughness length* and the number of *Sectors*.

As WEng is a linearized model, the results of the WEng flow modelling in terms of relative speed-up factors and turbulence intensity will not depend on this setup. Only in the special case of offshore or semi offshore conditions is extra caution needed as, here, the linearity does not hold due to increasing sea roughness with wind speed. In such special cases, it is advised to run WEng and close SITE COMPLIANCE and export the WEng flow results via right-clicking on the calculation and choosing *Result-to-file*. The wind speeds predicted for each WTG in the result should match approximately the expected extreme wind speed for the WTGs. If the result is too low or high, the reduced geostrophic *wind speed* can be adjusted accordingly in the WEng advanced setup to properly model the flow conditions during the on-site extreme wind conditions.

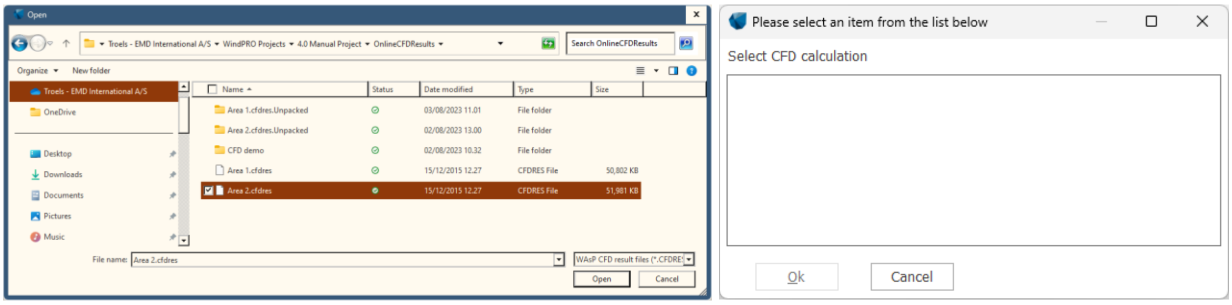
Turbulence calculation lets the user deselect the calculation of turbulence via the option *None* or choose the alternative model *Scanlan*. However, it is recommended to use the default choice of including turbulence with the model *Kaimal*.

Note that dump of a WEng project file and use of obstacles is activated in these advanced settings. The obstacle option is only active for WEng version 4.X and newer.

5.2.1.8 WAsP-CFD

From windPRO 3.0, SITE COMPLIANCE integrates flow results from WAsP-CFD. The integration requires a full external installation and licensing of at least WAsP 11 and that a WAsP-CFD calculation (the cluster calculation which establishes the raw CFD flow results) has been performed using appropriate CFD tiles which cover the relevant masts and turbine positions.

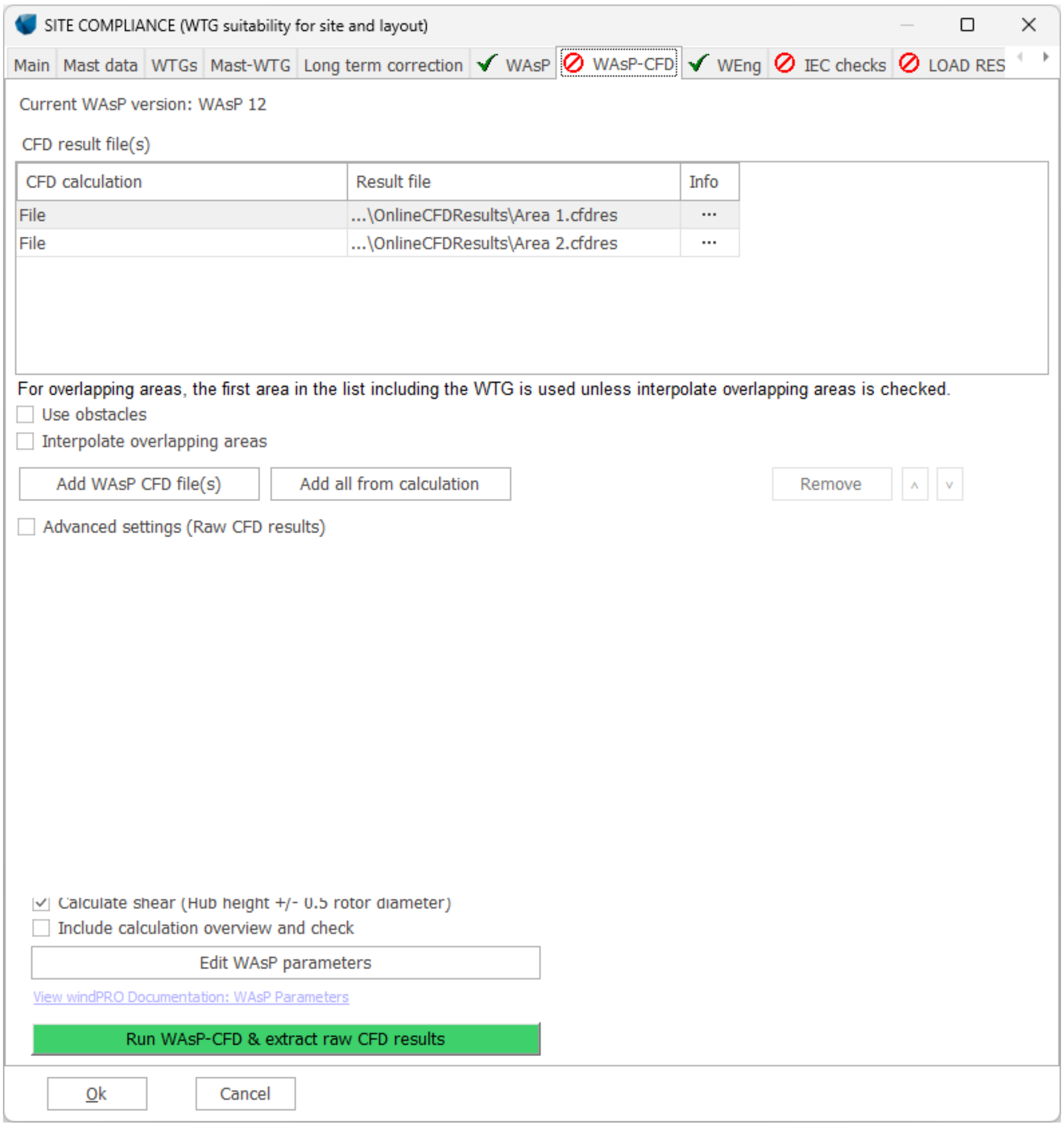
First step is to add the ‘raw’ CFD results by pressing the button *Add WAsP-CFD file(s)* or *Add all from calculation* and then, in the file browsing window which pops up, select the relevant *cfdres* files. The *cfdres* files are generally situated in a project folder named *OnlineCFDResults*.



Name	Status	Date modified	Type	Size
Area 1.cfdres.Unpacked	✓	03/08/2023 11.01	File folder	
Area 2.cfdres.Unpacked	✓	02/08/2023 13.00	File folder	
CFD demo	✓	02/08/2023 10.32	File folder	
Area 1.cfdres	✓	15/12/2015 12.27	CFDRES File	50,802 KB
☑ Area 2.cfdres	✓	15/12/2015 12.27	CFDRES File	51,981 KB

File name: Area 2.cfdres
WAsP CFD result files (*.CFDRE

Figure 14. Pop-up menus to select WAsP-CFD result files. Left: menu for selecting individual files. Right: menu for selecting all results of an entire calculation.



Current WAsP version: WAsP 12

CFD result file(s)

CFD calculation	Result file	Info
File	...\OnlineCFDResults\Area 1.cfdres	...
File	...\OnlineCFDResults\Area 2.cfdres	...

For overlapping areas, the first area in the list including the WTG is used unless interpolate overlapping areas is checked.

☐ Use obstacles
☐ Interpolate overlapping areas

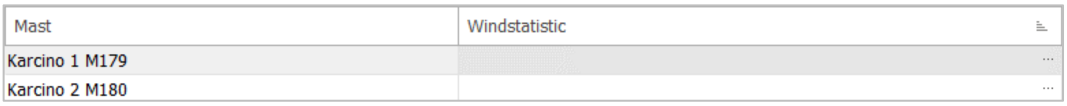
☐ Advanced settings (Raw CFD results)

☑ Calculate shear (Hub height +/- 0.5 rotor diameter)
☐ Include calculation overview and check

View windPRO Documentation: WAsP Parameters

Figure 15. WAsP-CFD tab in Mast directly mode.

If SITE COMPLIANCE is run in the modes *Long-term corrected wind statistics* or *No mast data,* it is also necessary to select the appropriate wind statistics. In the *Long-term corrected wind statistics* mode, a wind statistics must be selected explicitly for each on-site mast.



Mast	Windstatistic
Karcino 1 M179	...
Karcino 2 M180	...

Figure 16. Additional part of WAsP-CFD tab which is shown in the mode: long-term corrected wind statistics.

Once appropriate selection of CFD result files and, if required, also wind statistics has been done, the calculation can be performed by clicking the green *Run WAsP-CFD & extract raw CFD results* button. The calculation may take several minutes and will first call WAsP with the CFD results and wind data or wind statistics to predict the sector-wise Weibull distributions and frequencies at each WTG position, at hub height, and hub height +/- ½ rotor diameter. The last option is default and may be deactivated. After that, SITE COMPLIANCE will extract the additionally required flow parameters like vertical inflow angle, speed-up and veer directly from the raw CFD flow.

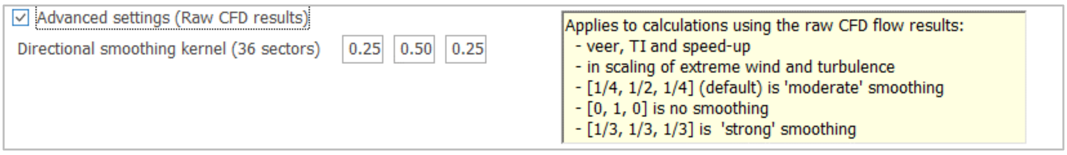
Figure 17. WAsP-CFD tab before and after successful calculation.

Displacement height

See section Displacement height.

Advanced setup

On the WAsP-CFD tab, the tick box *Advanced settings (Raw CFD results)* will give access to additional options for using the raw CFD flow results. The options relate to the how the information in all 36 directions in the flow results may be used to smoothen the flow results. The reason is that each of the 36 directions is run as an independent numerical simulation. When comparing the results of all sectors, "numerical noise" from the solutions is obvious as a scattering or high frequency variation in the results, such as speed-up. To limit this "noise" and improve the robustness of, e.g., propagation models in extreme wind, applying a smoothing filter is good solution. Per default, a smoothing kernel of [0.25, 0.5, 0.25] is applied to the raw CFD parameters veer, TI and speed-up. This means that each directional result is replaced by the weighted average of itself and its two neighbouring simulations using the weights of the chosen "kernel". Inside WAsP, a smoothing kernel of [1/3, 1/3, 1/3] is used for predicting Weibull distributions when using 12 sectors of 30 degrees. Setting the smoothing kernel to [0,1,0] corresponds to no smoothing.



☑ Advanced settings (Raw CFD results)

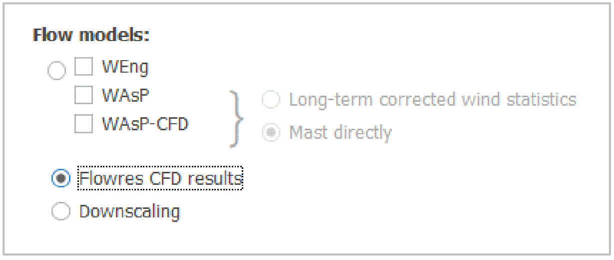
Directional smoothing kernel (36 sectors) 0.25 0.50 0.25

Applies to calculations using the raw CFD flow results:
- veer, TI and speed-up
- in scaling of extreme wind and turbulence
- [1/4, 1/2, 1/4] (default) is 'moderate' smoothing
- [0, 1, 0] is no smoothing
- [1/3, 1/3, 1/3] is 'strong' smoothing

Figure 18. WAsP-CFD tab, Advanced settings (Raw CFD results).

5.2.1.9 Flowres

From windPRO 3.1, it is possible to load and utilize the results of any external flow model, typically CFD models. The required data format is called "Flowres" and is defined here[6]. This format contains a more complete set of the basic flow results from the "raw" simulation output than, e.g., the wrg/rsf (resource) format. Figure 19 shows how the Flowres option is selected on the main tab of SITE COMPLIANCE as an alternative to WAsP, WEng and WASP-CFD. In many regards, Flowres is very similar to the underlying flow data format of WAsP-CFD (called .cfdres). Both formats are zip files, which contain an xml file defining the overall simulation setup. File names of the result data files are also included in the zip file as a number of grid files, one for each simulation direction and for each result parameter, such as turbulence intensity for direction 170° or speed-up for 20°.



Flow models:

○ ☐ WEng
☐ WAsP
☐ WAsP-CFD
○ Long-term corrected wind statistics
● Mast directly
● Flowres CFD results
○ Downscaling

Figure 19. Selection of Flowres on the main tab, which activates the Flowres tab.

Figure 20 shows the Flowres tab, where the first step is to select the relevant Flowres files by pressing the button "Add Flowres file(s)" and selecting the relevant files in the pop-up menu. Once the Flowres files are selected, the "Run calculation" button will turn green and when clicked it starts the "calculation" and the processing of the files. Depending on the file size and number of turbines, this may take several minutes.

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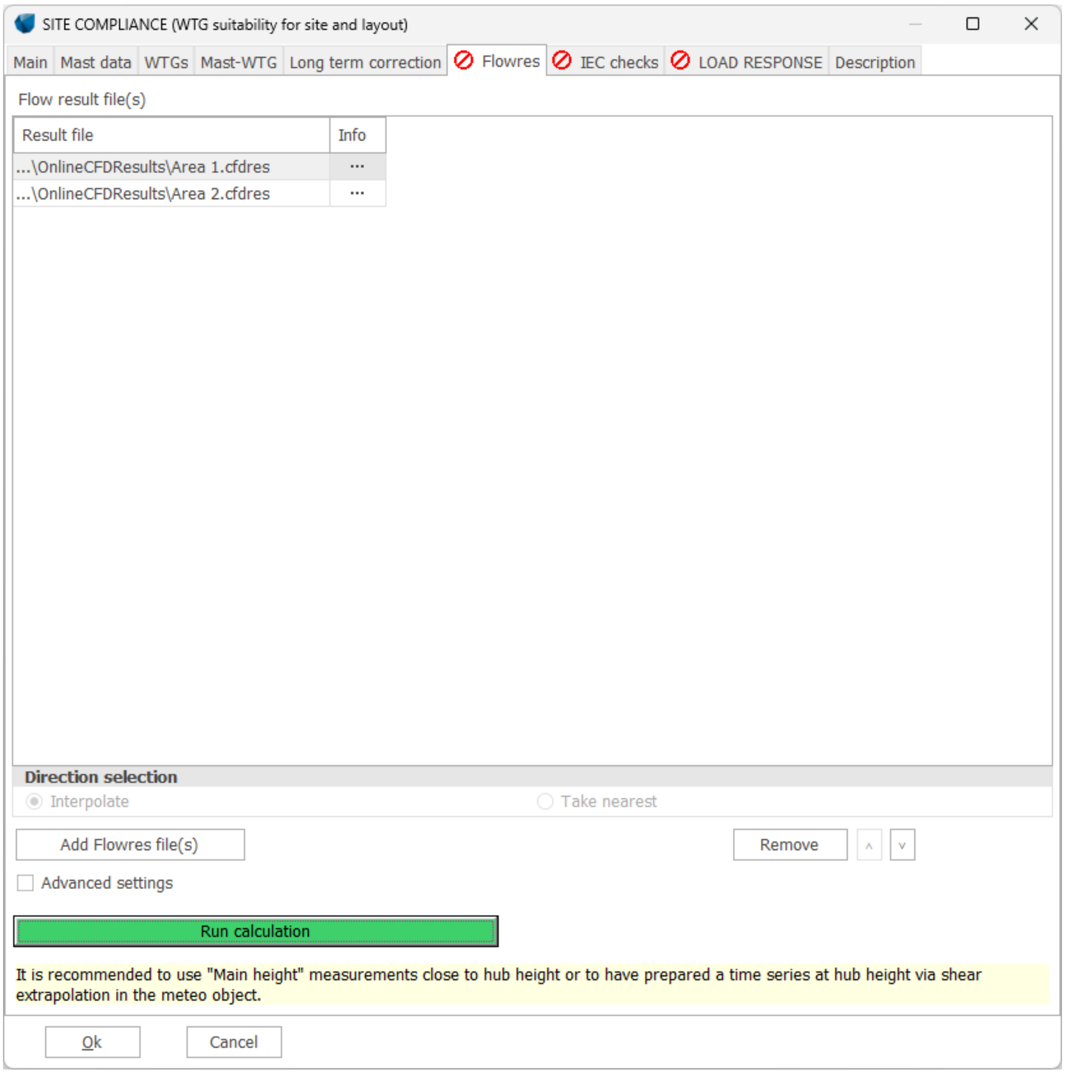
[6] Flowres format: http://www.emd.dk/files/flow/EMD_technote_Generalized_Flow_Request_Result.pdf



Flow result file(s)

Result file	Info
...\OnlineCFDResults\Area 1.cfdres	···
...\OnlineCFDResults\Area 2.cfdres	···

Direction selection

● Interpolate ○ Take nearest

☐ Advanced settings

It is recommended to use "Main height" measurements close to hub height or to have prepared a time series at hub height via shear extrapolation in the meteo object.

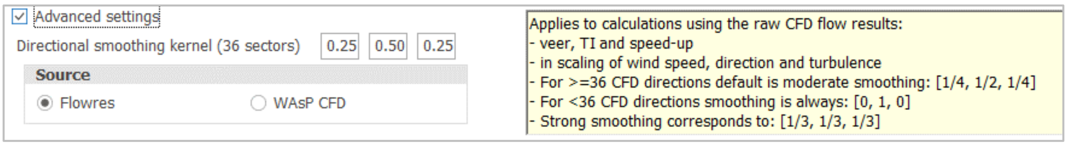
Figure 20. Flowres setup and calculation tab.

Once the loading, calculation and processing of the Flowres files is completed, the “Run calculation“ button turns grey, and the red stop sign on the tab becomes a green tick mark (see Figure 21).

Figure 21. Flowres tab before and after completed loading/calculation/processing.

Advanced setup

By checking “Advanced settings”, the advanced option shown in Figure 22 becomes available. These parameters relate to the smoothing of the CFD results across direction to reduce the numerical noise. See Advanced setup for WAsP-CFD for further details.



☑ Advanced settings

Directional smoothing kernel (36 sectors) 0.25 0.50 0.25

Source

● Flowres ○ WAsP CFD

Applies to calculations using the raw CFD flow results:
- veer, TI and speed-up
- in scaling of wind speed, direction and turbulence
- For >=36 CFD directions default is moderate smoothing: [1/4, 1/2, 1/4]
- For <36 CFD directions smoothing is always: [0, 1, 0]
- Strong smoothing corresponds to: [1/3, 1/3, 1/3]

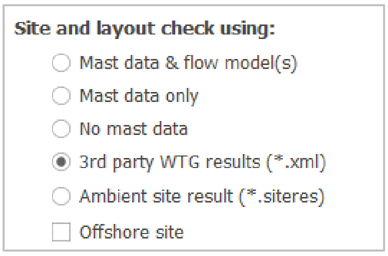
Figure 22. Advanced setup options for Flowres.

Displacement height

See section Displacement height.

5.2.1.10 "3rd party results" mode

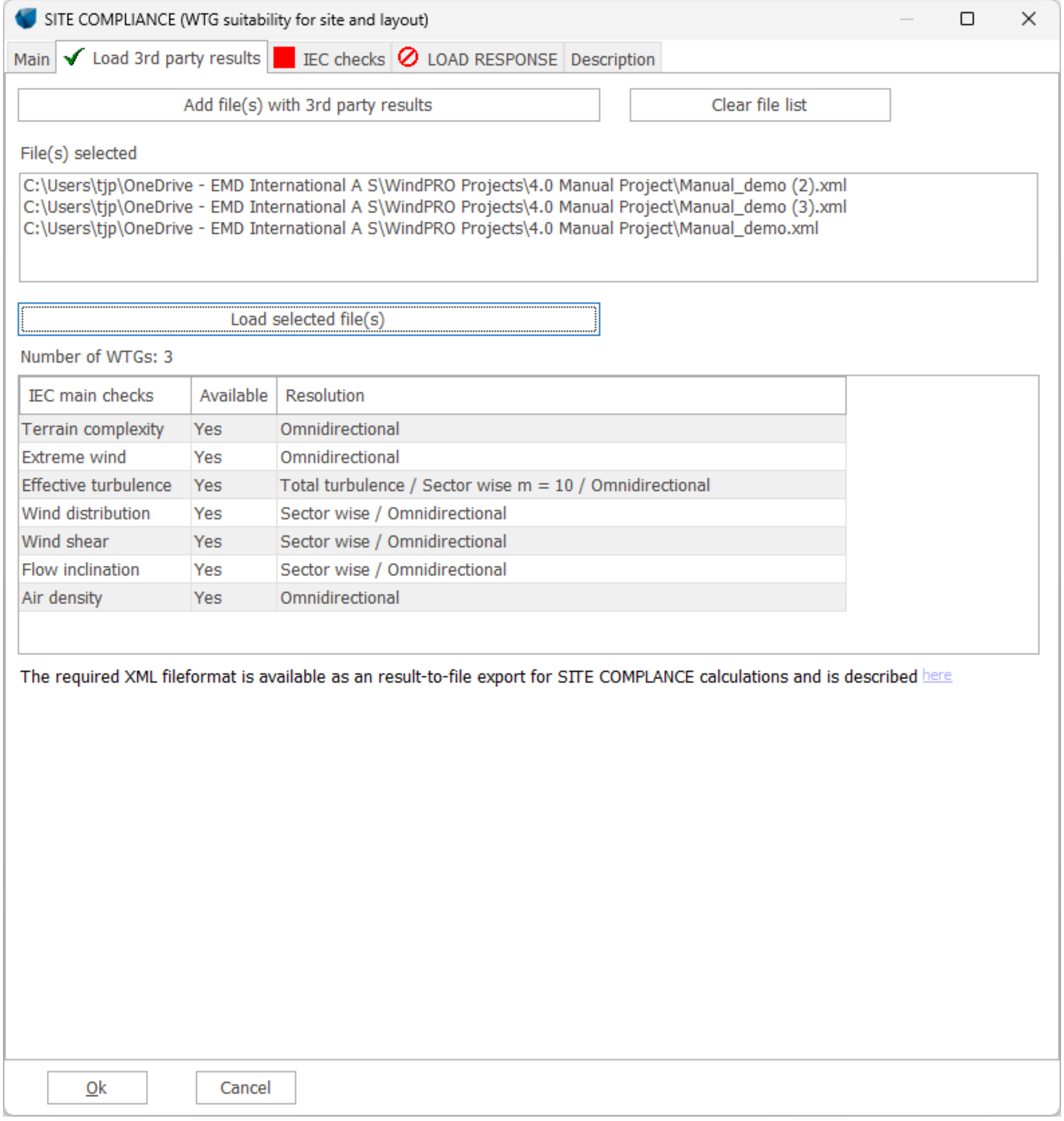
From windPRO 3.1, it is possible to load pre-calculated results of the main IEC checks to allow use of LOAD RESPONSE by users with in-house calculation procedures for the main IEC checks. The 3rd party file format[7] is xml and is also used as result-to-file export option for ordinary SITE COMPLIANCE calculations. It is optional whether to have results for several turbines in one 3rd party xml file or to have one xml file per turbine.



Site and layout check using:

○ Mast data & flow model(s)
○ Mast data only
○ No mast data
● 3rd party WTG results (*.xml)
○ Ambient site result (*.siteres)
☐ Offshore site

Figure 23. Selection of 3rd party on the SITE COMPLIANCE Main tab.



File(s) selected

C:\Users\tjp\OneDrive - EMD International A S\WindPRO Projects\4.0 Manual Project\Manual_demo (2).xml
C:\Users\tjp\OneDrive - EMD International A S\WindPRO Projects\4.0 Manual Project\Manual_demo (3).xml
C:\Users\tjp\OneDrive - EMD International A S\WindPRO Projects\4.0 Manual Project\Manual_demo.xml

Number of WTGs: 3

IEC main checks	Available	Resolution
Terrain complexity	Yes	Omnidirectional
Extreme wind	Yes	Omnidirectional
Effective turbulence	Yes	Total turbulence / Sector wise m = 10 / Omnidirectional
Wind distribution	Yes	Sector wise / Omnidirectional
Wind shear	Yes	Sector wise / Omnidirectional
Flow inclination	Yes	Sector wise / Omnidirectional
Air density	Yes	Omnidirectional

The required XML fileformat is available as an result-to-file export for SITE COMPLANCE calculations and is described here

Figure 24. 3rd party tab with xml files selected and loaded.

Note the summary column named "Resolution" of the loaded IEC main check results in the table in Figure 24, which indicates whether the loaded results for each IEC check are omnidirectional or sectorwise. For Effective

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[7] 3rd party format description: http://www.emd.dk/files/windpro/windPRO_third_party_Load_Response.pdf

turbulence, there is also a third option called “Total turbulence” which represents turbulence results at a resolution of 1 degree, prior to integration using the Wöhler exponent (m). The resolution of the loaded results will determine which calculations options are available in a subsequent LOAD RESPONSE calculation.

In third party mode, all calculation options and settings are disabled in the IEC checks since the result is loaded from the xml files. Only abs with result plots and tables are shown in 3rd party mode. In addition, to close the window of an opened IEC check after viewing the results is only possible by pressing “Cancel” – this is to indicate that no calculations have been performed.

5.2.1.11 “Ambient Site results” mode

From windPRO 3.5, it is possible to load pre-calculated resource and site parameter files as basis for the main IEC checks. The required format is called .siteres and may also be used in PARK calculations for AEP assessments. For most checks the use of siteres overrides all calculation options as it defines the ambient climate. However, for the turbulence checks the wake effects are calculated on top of the ambient climate and wake related calculation options are available. See Appendix IX - Siteres ambient climate files (from Resource, GASP, etc.) for further details of the siteres format.

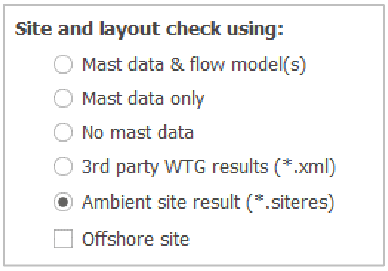

Site and layout check using:
○ Mast data & flow model(s)
○ Mast data only
○ No mast data
○ 3rd party WTG results (*.xml)
● Ambient site result (*.siteres)
☐ Offshore site

Figure 25. Selection of siteres-file on the SITE COMPLIANCE main tab.

5.2.1.12 Curtailment

The *Curtailment* tab is available if “Apply Sector curtailment” is checked on the SITE COMPLIANCE main tab (see Figure 26).

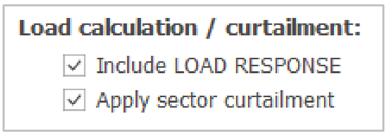
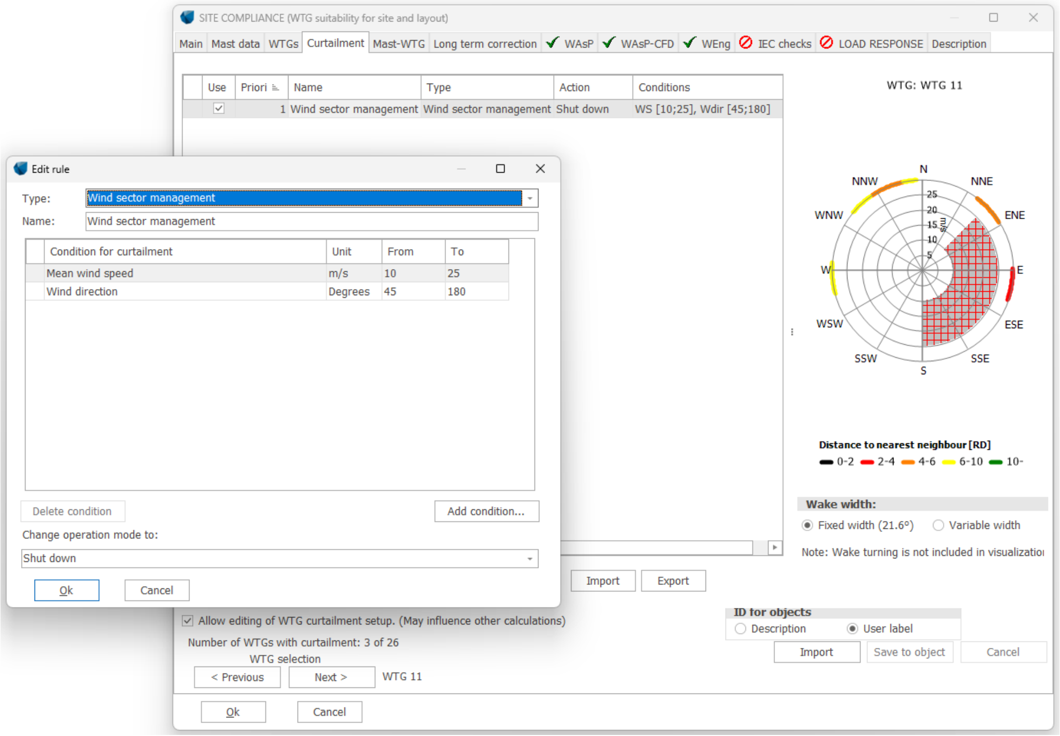

Load calculation / curtailment:
☑ Include LOAD RESPONSE
☑ Apply sector curtailment

Figure 26. Selection of Curtailment on the main tab.

This tab simply provides an overview of the curtailment settings defined on each individual WTG, and the possibility to change these settings. If curtailment settings on WTG objects are adjusted from within this tab, it is important to be aware that this might influence other calculations which use the objects. The details of how the curtailment setting influences the results is described in Appendix V - Curtailment. However, it is important to understand that only results in the Effective turbulence check and in LOAD RESPONSE are affected by the curtailment.



SITE COMPLIANCE (WTG suitability for site and layout)

Use	Priori	Name	Type	Action	Conditions
☑	1	Wind sector management	Wind sector management	Shut down	WS [10;25], Wdir [45;180]

Edit rule

Type: Wind sector management

Name: Wind sector management

Condition for curtailment	Unit	From	To
Mean wind speed	m/s	10	25
Wind direction	Degrees	45	180

Change operation mode to: Shut down

☑ Allow editing of WTG curtailment setup. (May influence other calculations)

Number of WTGs with curtailment: 3 of 26

WTG: WTG 11

Wake width: ● Fixed width (21.6°) ○ Variable width

Note: Wake turning is not included in visualizatio

ID for objects: ○ Description ● User label

Figure 27. The Curtailment tab, with one curtailment line added for one WTG.

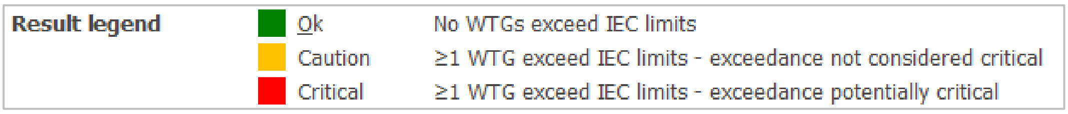
5.2.2 IEC Checks - Main checks

Subsections:

Once all the setup steps have been completed and chosen flow models have been run, the actual IEC calculations can be performed on the *IEC checks* tab. To start the calculation of the *Main IEC checks,* mark the relevant checkboxes in the *Include* column. It is recommended to include all *Main checks*. If any steps in the setup are incomplete or missing this is indicated with a *Missing:……..* text in the *Setup/Calculate* of the affected checks.

Some checks will be shown as "*Missing*" until connected calculations have been completed. *Effective turbulence* always requires the *Terrain complexity* to be calculated first. If no WEng calculation result is available, the *Flow inclination* also requires the *Terrain complexity* to be completed first.

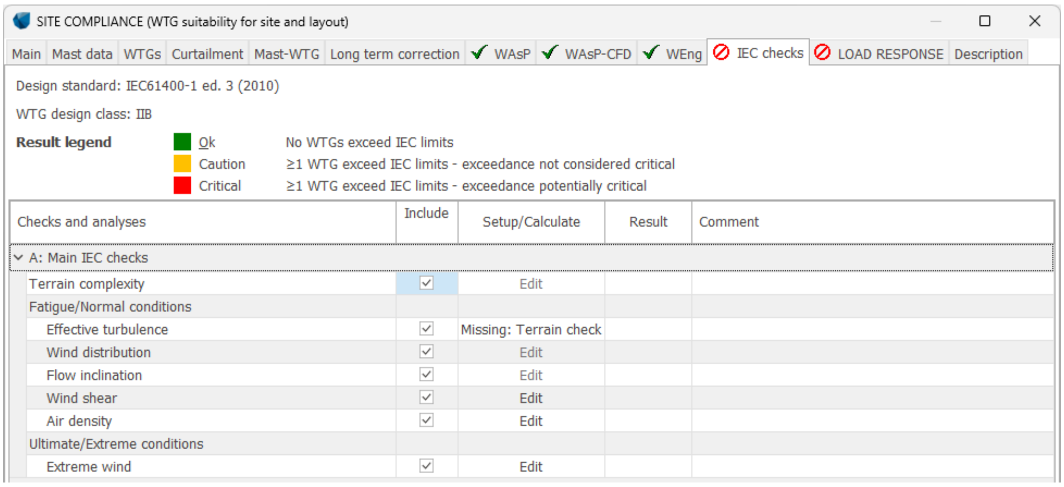
Note also the *Result legend* as this is used extensively as a clear visual evaluation of all calculation results.



Result legend			
	🟩	Ok	No WTGs exceed IEC limits
	🟨	Caution	≥1 WTG exceed IEC limits - exceedance not considered critical
	🟥	Critical	≥1 WTG exceed IEC limits - exceedance potentially critical

Figure 28. The result legend from the Calculations tab.

The overall wind farm evaluation is shown in the *Result* column when then calculation of a check is completed, and it is determined by the evaluation of the worst WTG of the wind farm. Inside each check, the evaluation is presented for each WTG.



Design standard: IEC61400-1 ed. 3 (2010)

WTG design class: IIB

Result legend			
	🟩	Ok	No WTGs exceed IEC limits
	🟨	Caution	≥1 WTG exceed IEC limits - exceedance not considered critical
	🟥	Critical	≥1 WTG exceed IEC limits - exceedance potentially critical

Checks and analyses	Include	Setup/Calculate	Result	Comment
A: Main IEC checks				
Terrain complexity	☑	Edit		
Fatigue/Normal conditions				
Effective turbulence	☑	Missing: Terrain check		
Wind distribution	☑	Edit		
Flow inclination	☑	Edit		
Wind shear	☑	Edit		
Air density	☑	Edit		
Ultimate/Extreme conditions				
Extreme wind	☑	Edit		

Figure 29. The IEC checks tab with the Main checks expanded and checked, ready for calculation.

To start the calculation of each *Main IEC check,* click the *Edit* button. It is recommended first to calculate the *Terrain complexity* check.

Note: A single or a few CRITICAL exceedances for a project may not always mean that a wind turbine class can be fully excluded as suitable. CRITICAL issues should always be addressed with the relevant turbine manufacturer. A turbine manufacturer knows the load margins and detailed aeroelastic model of their WTGs and can perform detailed load calculations for the particular model to evaluate if the buffer present for the OK checks or in the design can balance the identified CRITICAL issues.

5.2.2.1 Terrain complexity

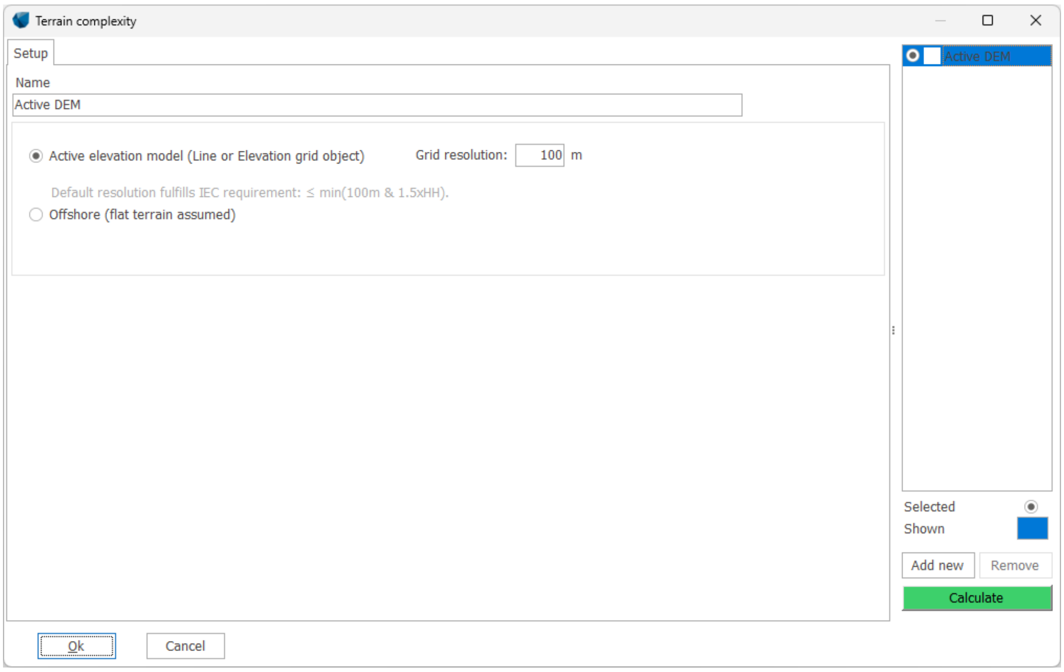
Description and limit

The IEC standard describes, in quite elaborate detail, the Terrain complexity check. The check evaluates the terrain steepness and variability in the vicinity of each WTG position. A number of circular and “pizza slice” planes must be fitted to the terrain and the inclination and terrain variation from each plane must be evaluated. These requirements are described in detail below.

The Terrain complexity check is not a binary “GO” / “NO GO” check that may kill a project in itself. Instead, the check serves to identify complex sites / WTG positions, mainly to enable an appropriate correction referred to as *Turbulence structure correction* to the measured turbulence. This correction is to compensate for the fact that cup-anemometers only measure the horizontal component of turbulence, whereas, in complex terrain, a significant fraction of the turbulent kinetic energy may be transferred to the vertical component of turbulence.

Setup, Calculation and Results

Setup and calculation of the IEC Terrain complexity check is very simple in SITE COMPLIANCE. The module uses the active elevation model (i.e. the Digital Elevation Model) defined for the project. This model can be either a contour file in a Line object, referred to as the “TIN”, or can be defined by an Elevation grid data object.



Name: Active DEM

● Active elevation model (Line or Elevation grid object)   Grid resolution: 100 m

Default resolution fulfills IEC requirement: ≤ min(100m & 1.5xHH).

○ Offshore (flat terrain assumed)

Figure 30. Setup and calculation of Terrain complexity check.

The only user option is the *Grid resolution*, which defines the resolution of a suitable quadratic grid of point elevations extracted from the elevation model to be used in the required terrain fits. The IEC states that the resolution may not be greater than the smaller of 100m or 1.5xHH. The default resolution automatically fulfils this criterion. However, often the quality of the available elevation data does not grant the use of a finer resolution.

Click the green *Calculate* button to perform the Terrain complexity check. Calculation may take longer if the full TIN has not already been calculated by the user. After successful calculation of the check, several new tabs emerge presenting the results. The module jumps directly to the tab *Results (Graphics)* giving the main result overview. On this tab, the so-called *Terrain complexity index,* as defined in the IEC standard, is illustrated for each WTG position. A WTG position is complex if the index equals 1 and not complex if it equals 0. An index between 0 and 1 indicates a partly complex WTG position.

Note also that, in the case shown, a green square has emerged beside the calculation name in the “calculation list” to the upper right. This indicates that the result of this check is *OK*, and that no problems or risks are expected relating to the Terrain complexity.

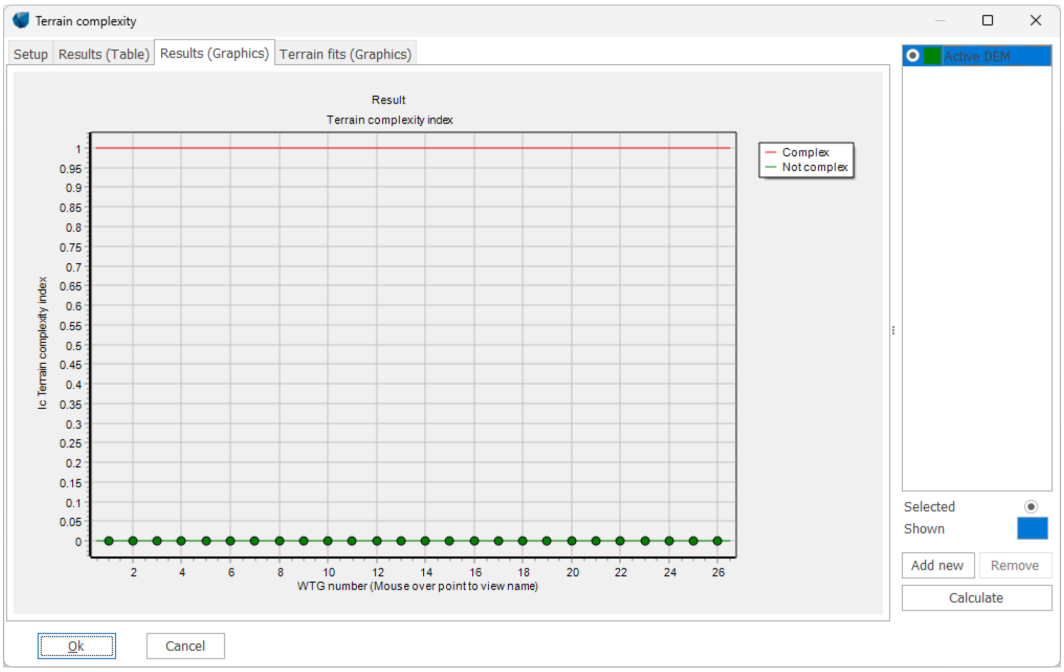


Figure 31. Results (Graphics) tab presents the Terrain complexity results as a simple overview.

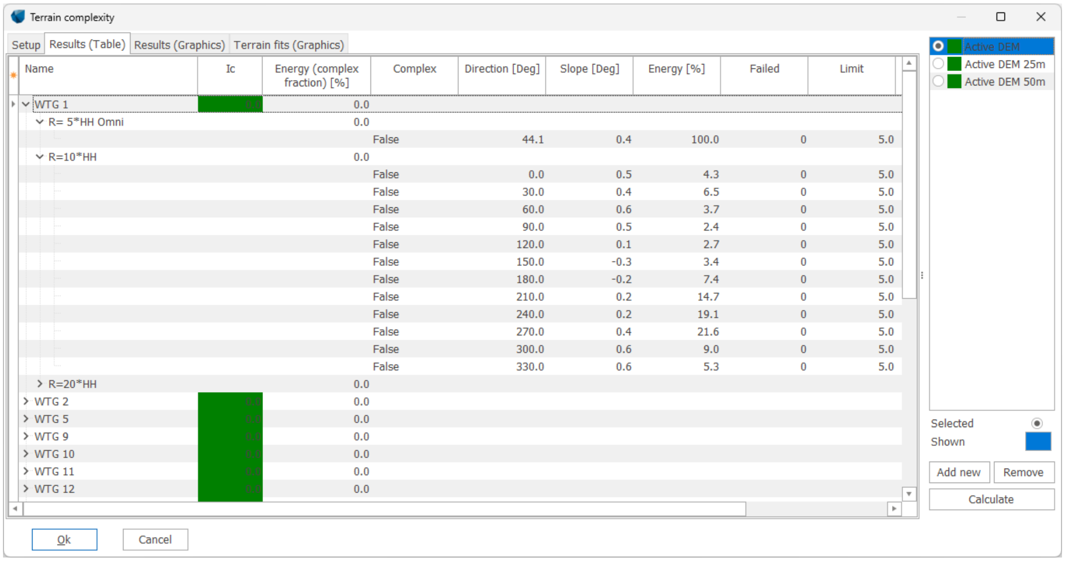
SITE COMPLIANCE allows the user to *Add new* additional calculations with a different setup (in this case, grid resolution). This is done by clicking the *Add new* button selecting the required new setup and clicking the green *Calculate* button again. In this way, several supplementary calculations may be added to check how strongly the results depend on the setup/assumptions. It is recommended to adjust the names of each calculation on its *Setup* tab – this may also be done after calculation. The setup and result tabs of a calculation may be viewed by clicking on that calculation in the calculation list. The shown calculation is highlighted in blue.

Before finalising the check by clicking the OK button, one of the performed calculations must be *Selected* as the final result.

Figure 32. Left: The “calculation list” with multiple calculation setups and the upper one selected (marked) but the lower one is viewed (blue highlight). Right: the “view legend” defining shown and selected calculations in the calculation list.

The *Results (Table)* tab summarizes the results in terms of the Terrain complexity index for each WTG. A colour code highlights complexity indices in green if they are 0 (i.e., OK) and in yellow (i.e., CAUTION) if an index exceeds zero.

Expand the results of a WTG by clicking the “>”, this reveals the three sub-levels: “R=5xHH”, “R=10xHH” and “R=20xHH”. Expanding one these levels reveal the results of the fit(s) with that radius in terms of the slope and its direction, and the energy that is available in the directional span represented by that fit. Further details of how these fits are performed are shown in the following.



Name	Ic	Energy (complex fraction) [%]	Complex	Direction [Deg]	Slope [Deg]	Energy [%]	Failed	Limit
WTG 1	0.0	0.0						
R= 5*HH Omni		0.0						
			False	44.1	0.4	100.0	0	5.0
R=10*HH		0.0						
			False	0.0	0.5	4.3	0	5.0
			False	30.0	0.4	6.5	0	5.0
			False	60.0	0.6	3.7	0	5.0
			False	90.0	0.5	2.4	0	5.0
			False	120.0	0.1	2.7	0	5.0
			False	150.0	-0.3	3.4	0	5.0
			False	180.0	-0.2	7.4	0	5.0
			False	210.0	0.2	14.7	0	5.0
			False	240.0	0.2	19.1	0	5.0
			False	270.0	0.4	21.6	0	5.0
			False	300.0	0.6	9.0	0	5.0
			False	330.0	0.6	5.3	0	5.0
R=20*HH		0.0						
WTG 2	0.0	0.0						
WTG 5	0.0	0.0						
WTG 9	0.0	0.0						
WTG 10	0.0	0.0						
WTG 11	0.0	0.0						
WTG 12	0.0	0.0						

Figure 33. Results (Table) presents the many details of the fits performed in the Terrain complexity check.

IEC requirement – Terrain complexity

For the Terrain complexity check, the IEC standard describes how a number of planes of varying size and shape must be fitted to the terrain around each WTG position. The following text describes these requirements as defined in [2]. In total 25 planes must be fitted with the following characteristics, all passing the WTG base position:

- A circular plane with radius 5xHH centred on the WTG
- 12 “pizza-slice” fits with a radius of 10xHH, one fit in each sector
- 12 “pizza-slice” fits with a radius of 20xHH, one fit in each sector

The fits are illustrated for a contour file below showing the points used in some of the fits. For the “pizza-slice” fits, all the points are shown, but only the points used within the northern sector are highlighted. The standard requires that the grid resolution must not exceed the smaller of 100m or 1.5xHH.

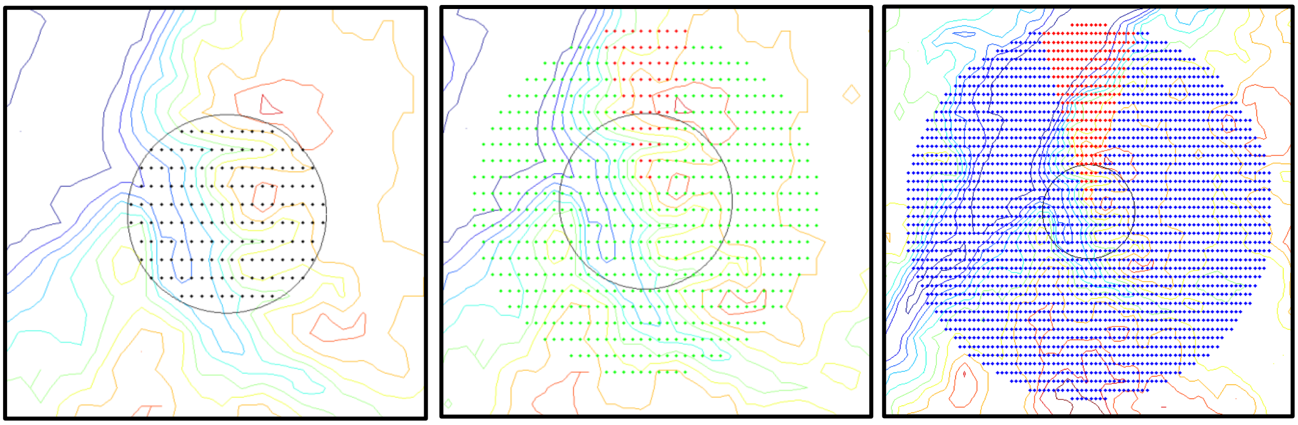


Figure 34. Illustration of the fits required in the Terrain complexity check. Left: outline of the 5xHH omni-directional fit and the included grid points. Middle: the grid points in a 10xHH sectorial fit, with points in the north sector highlighted (5xHH circle shown as scale). Right: the points in a 20xHH sectorial fit with the northern sector highlighted (5xHH circle shown as scale).

For each fit the slope is estimated. For the 5xHH fit, the slope is in the direction of the gradient (i.e. max slope); for the 2x12 “pizza-slice” fits, (10 and 20xHH) the slope is estimated along the sector median. If the estimated slope exceeds +/-10°, the fit is considered ”failed”.

In addition to the slope, a “check area” must be estimated for each of the 25 fitted planes. This check is the area that has a vertical deviation from the fitted plane exceeding a certain threshold. The vertical thresholds for each radius as well as the slope demand as defined in the standard are summarized in the table below:

Fit radius	Count	Fit type	Max slope	Max vertical deviation	Max allowed area exceeding deviation
5xHH	1	Omni. (360°)	10°	0.3xHH	$5xHH^2$
10xHH	12	Sector (30°)	10°	0.6xHH	$5xHH^2$
20xHH	12	Sector (30°)	10°	1.2xHH	$5xHH^2$

Figure 35. Summary of the checks applied to each of the fits required in the Terrain complexity check [2].

The standard defines a Complexity Index, I_c, which is calculated based on the outcome of the fits. For each fit, the relative energy fraction is estimated based on the relevant sector-wise Weibull parameters. The omni-directional fit (5xHH) represents 100% of the energy. If less than 5% of the energy is in the sectors which fail either the slope or the vertical deviation check, the WTG position is regarded *not complex*, and the complexity index I_c=0. If more than 15% of the energy is in sectors which fail either of the checks, the WTG position is regarded complex and I_c=1. In the interval when 5%-15% energy is in sectors which fail, the complexity index is interpolated linearly between 0 and 1.

If the complexity index is larger than 0, extra caution is required. The standard requires that a correction is applied in the turbulence calculation. This is to compensate that cup anemometers only measure the horizontal component of turbulence and not the vertical. In complex terrain, part of the turbulent kinetic energy is transferred from the horizontal component to the vertical component and, hence, not accounted for by the measurements made by a cup anemometer. The standard defines a *Turbulence Structure Correction Parameter,* C_{CT}, which may be calculated from the complexity index. This correction parameter must be applied to the measured turbulence when the complexity index is larger than zero. This information is automatically transferred to the Effective turbulence check.

As a foot note, the standard mentions that the inclination angle of the plane from the omni-directional fit with a radius of 5xHH may be used as the inflow angle estimate. We allow this option in SITE COMPLIANCE module and the relevant inflow angles are automatically transferred from the Terrain complexity check to the Flow inclination check.

Note: If both WAsP and WAsP-CFD have been run in the setup of SITE COMPLIANCE, the WAsP-CFD results will always take preference to define sector energy fractions used in the terrain complexity check.

5.2.2.2 Extreme wind

Description and limit

The extreme wind speed check is one of the most important and potentially most critical checks in a SITE COMPLIANCE calculation. The reasons are the very high uncertainty associated with most extreme wind estimates and that the check represents an extreme load, which may not be compensated by a buffer in the results of other checks relating to fatigue.

In the context of the IEC standard, extreme wind refers to a 10-minute averaged wind speed event with a recurrence period of 50 years. Recurrence period (T) is a statistical term derived from the more stringent statistical term “annual risk of exceedance” (R) via the simple relation $T = 1/R$. So, by definition, a 50-year wind speed estimate has an annual risk of being exceeded of 2%.

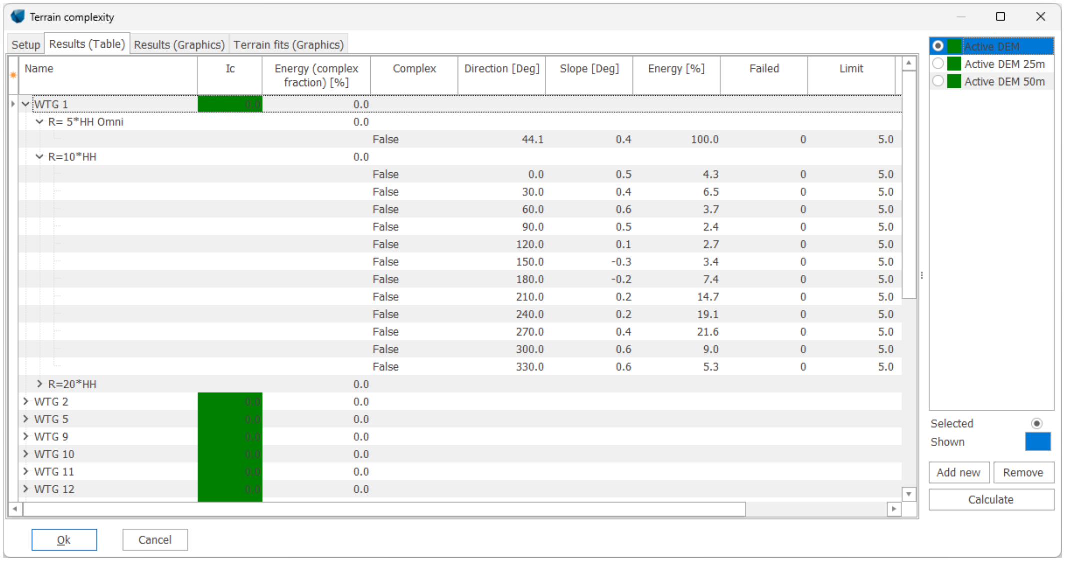
The IEC standard’s design assumption for extreme wind is V_{ref} defined for each wind speed class in Table 1 of the standard (see Table 1 of this manual). So, e.g., a Class I WTG is designed for extreme wind speeds of up to 50m/s at standard air density of 1.225kg/m^3.

Most methods of extreme wind estimation rely in one way or the other on the theory developed by E. Gumbel in [3]. Appendix I describes the fundamentals of this theory and details of the theory relating to the models available in this module.

Setup, Calculation and Results

The following text describes the workflow in setting up, calculating and reviewing the results of a typical Extreme wind calculation. The setup of this check is split in three groups: *Statistical model, Propagation model and*

Additional model settings. Details of the options within each of these groups are described in more detail after this description of the workflow. Figure 36 below shows the *Setup* of the Extreme wind check. There are a number of input parameters with abbreviated names for the different methods.



Name	Ic	Energy (complex fraction) [%]	Complex	Direction [Deg]	Slope [Deg]	Energy [%]	Failed	Limit
WTG 1	0.0	0.0						
R= 5*HH Omni		0.0						
			False	44.1	0.4	100.0	0	5.0
R=10*HH		0.0						
			False	0.0	0.5	4.3	0	5.0
			False	30.0	0.4	6.5	0	5.0
			False	60.0	0.6	3.7	0	5.0
			False	90.0	0.5	2.4	0	5.0
			False	120.0	0.1	2.7	0	5.0
			False	150.0	-0.3	3.4	0	5.0
			False	180.0	-0.2	7.4	0	5.0
			False	210.0	0.2	14.7	0	5.0
			False	240.0	0.2	19.1	0	5.0
			False	270.0	0.4	21.6	0	5.0
			False	300.0	0.6	9.0	0	5.0
			False	330.0	0.6	5.3	0	5.0
R=20*HH		0.0						
WTG 2	0.0	0.0						
WTG 5	0.0	0.0						
WTG 9	0.0	0.0						
WTG 10	0.0	0.0						
WTG 11	0.0	0.0						
WTG 12	0.0	0.0						

● 🟩 Active DEM
○ 🟩 Active DEM 25m
○ 🟩 Active DEM 50m

Figure 36. The Setup tab of the Extreme wind check. Note that the upper most option "Annual Maximum & Gumbel" is greyed out and not available in the case shown because not all site masts hold ≥5 years data.

For *POT-N & Gumbel;*

- *N* is the number of extreme events to extract from the time series
- *Δt* is the minimum time separation between two extreme events to secure independence

For *Weibull parent (EWTS/Bergström):*

- *N* is the assumed number of independent 10-minute wind speed samples per year.

For *Eurocode EN1991-1-4:*

Input 'base values':

- *Wind speed* is the design wind speed at standard conditions from the relevant national annex to the Eurocode (usually available from national standards authorities).
- *Height* and *Roughness* are the standard conditions for the base wind speed, typically 10m and 0.05m.
- *Direction* is needed for the base wind speed to select speed-up factors, if known or given in the national annex this should be input directly.
- *Auto sector* let's SITE COMPLIANCE calculate the most likely extreme wind sector based on the Weibull parameters.
- *Max sector* takes the speed-up from the (worst) sector with the highest speed-up factor.

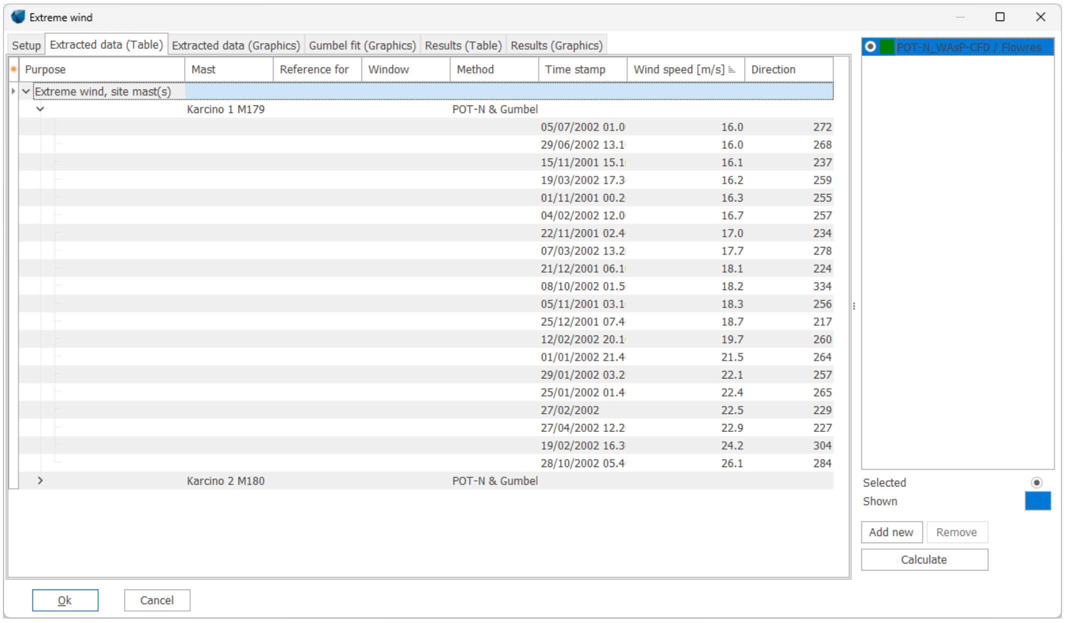
In *Additional model settings:*

- ρ is the air density at high wind speeds.
- K_p is a normalized gust factor, where the default value 3.0 represents a 3 seconds gust.

Note that, for the default setup, no *Additional model settings* are activated. To include any of these additional settings, they must always be activated manually with the appropriate input parameter. If any additional modelling options are not selectable and greyed out, the reason is that a required input source is missing in the general setup as e.g. a Long-term reference mast for the *Index correct POT-N & Gumbel* option.

Click the highlighted *Calculate* button to the lower right to run the Extreme wind calculation using the default setup. When the calculation is complete, several new results tabs emerge:

The *Extracted data (Table)* tab shows a table of the extracted extreme samples from the mast time series.



Purpose	Mast	Reference for	Window	Method	Time stamp	Wind speed [m/s]	Direction
Extreme wind, site mast(s)							
	Karcino 1 M179			POT-N & Gumbel			
					05/07/2002 01.0	16.0	272
					29/06/2002 13.1	16.0	268
					15/11/2001 15.1	16.1	237
					19/03/2002 17.3	16.2	259
					01/11/2001 00.2	16.3	255
					04/02/2002 12.0	16.7	257
					22/11/2001 02.4	17.0	234
					07/03/2002 13.2	17.7	278
					21/12/2001 06.1	18.1	224
					08/10/2002 01.5	18.2	334
					05/11/2001 03.1	18.3	256
					25/12/2001 07.4	18.7	217
					12/02/2002 20.1	19.7	260
					01/01/2002 21.4	21.5	264
					29/01/2002 03.2	22.1	257
					25/01/2002 01.4	22.4	265
					27/02/2002	22.5	229
					27/04/2002 12.2	22.9	227
					19/02/2002 16.3	24.2	304
					28/10/2002 05.4	26.1	284
	Karcino 2 M180			POT-N & Gumbel			

Figure 37. The Extracted data (Table) tab.

On the *Extracted data (Graphics)* tab you see a plot of each of the mast time series with the extracted extreme samples highlighted. Scroll through the masts (if more than one) using the *Next* and *Previous* buttons to the lower left.

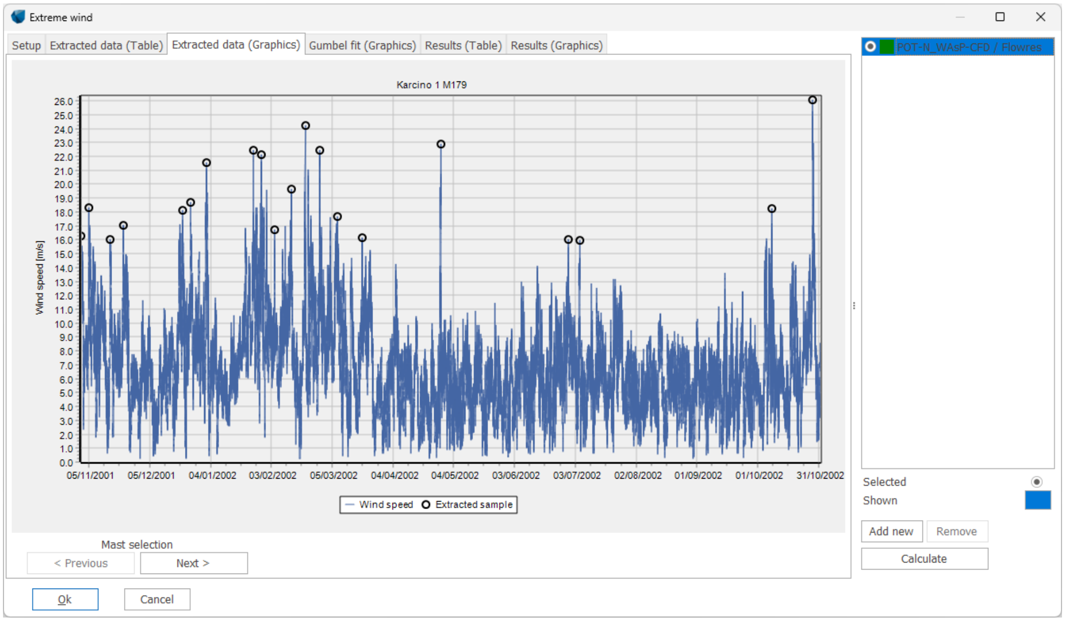


Figure 38. The Extracted data (Graphics) tab.

The Gumbel fit (Graphics) tab shows you the statistical fit for each WTG and the extrapolation to the required return periods (i.e. risk levels), typically 50 years. Click next (lower left) to scan through the WTGs.

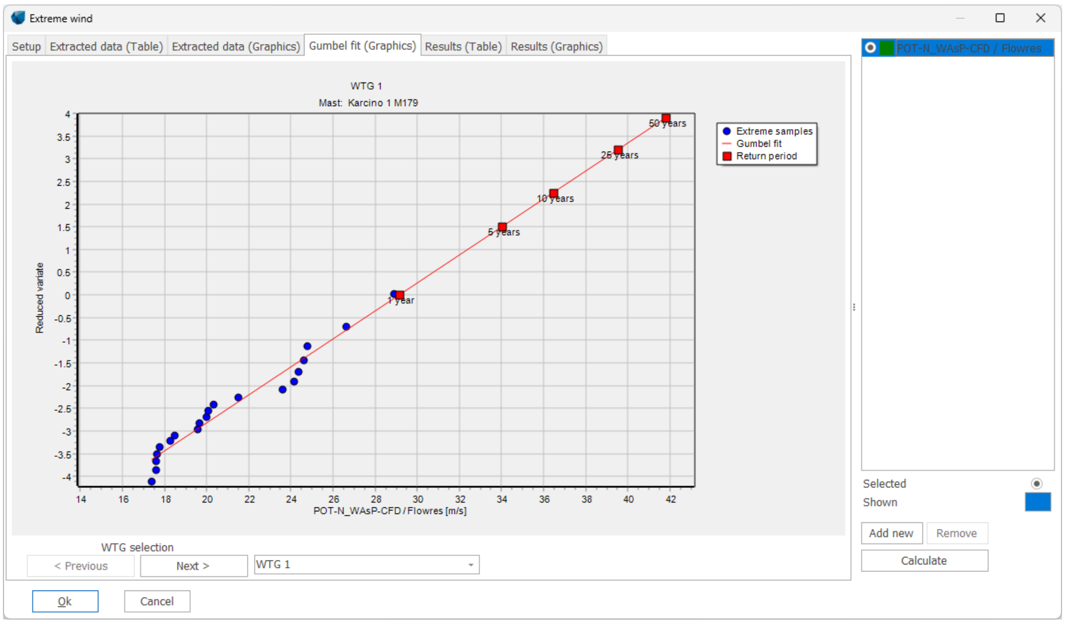
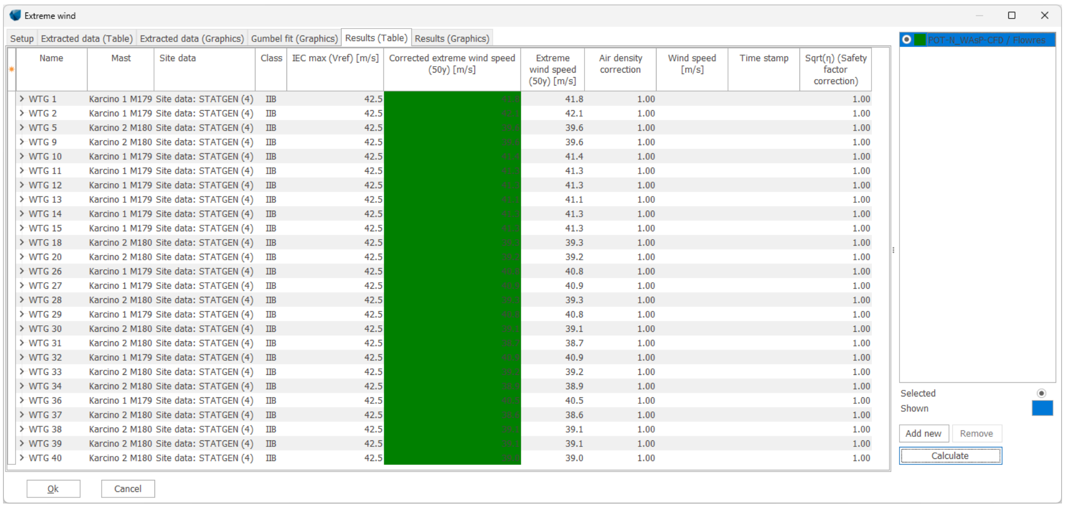


Figure 39. The Gumbel fit (Graphics) tab.

The *Results (Table)* tab gives you the final 50-year extreme wind speed result for each WTG as well as the IEC limit for the WTG class (V_{ref} for the relevant class). In the case shown, all WTGs are OK (green), and hence the overall result for the park (upper right corner) is also green (OK).



Name	Mast	Site data	Class	IEC max (Vref) [m/s]	Corrected extreme wind speed (50y) [m/s]	Extreme wind speed (50y) [m/s]	Air density correction	Wind speed [m/s]	Time stamp	Sqrt(η) (Safety factor correction)
WTG 1	Karcino 1 M179	Site data: STATGEN (4)	IIB	42.5	41.8	41.8	1.00			1.00
WTG 2	Karcino 1 M179	Site data: STATGEN (4)	IIB	42.5	42.1	42.1	1.00			1.00
WTG 5	Karcino 2 M180	Site data: STATGEN (4)	IIB	42.5	39.6	39.6	1.00			1.00
WTG 9	Karcino 2 M180	Site data: STATGEN (4)	IIB	42.5	39.6	39.6	1.00			1.00
WTG 10	Karcino 1 M179	Site data: STATGEN (4)	IIB	42.5	41.4	41.4	1.00			1.00
WTG 11	Karcino 1 M179	Site data: STATGEN (4)	IIB	42.5	41.3	41.3	1.00			1.00
WTG 12	Karcino 1 M179	Site data: STATGEN (4)	IIB	42.5	41.3	41.3	1.00			1.00
WTG 13	Karcino 1 M179	Site data: STATGEN (4)	IIB	42.5	41.1	41.1	1.00			1.00
WTG 14	Karcino 1 M179	Site data: STATGEN (4)	IIB	42.5	41.3	41.3	1.00			1.00
WTG 15	Karcino 1 M179	Site data: STATGEN (4)	IIB	42.5	41.3	41.3	1.00			1.00
WTG 18	Karcino 2 M180	Site data: STATGEN (4)	IIB	42.5	39.3	39.3	1.00			1.00
WTG 20	Karcino 2 M180	Site data: STATGEN (4)	IIB	42.5	39.2	39.2	1.00			1.00
WTG 26	Karcino 1 M179	Site data: STATGEN (4)	IIB	42.5	40.8	40.8	1.00			1.00
WTG 27	Karcino 1 M179	Site data: STATGEN (4)	IIB	42.5	40.9	40.9	1.00			1.00
WTG 28	Karcino 2 M180	Site data: STATGEN (4)	IIB	42.5	39.3	39.3	1.00			1.00
WTG 29	Karcino 1 M179	Site data: STATGEN (4)	IIB	42.5	40.8	40.8	1.00			1.00
WTG 30	Karcino 2 M180	Site data: STATGEN (4)	IIB	42.5	39.1	39.1	1.00			1.00
WTG 31	Karcino 2 M180	Site data: STATGEN (4)	IIB	42.5	38.7	38.7	1.00			1.00
WTG 32	Karcino 1 M179	Site data: STATGEN (4)	IIB	42.5	40.9	40.9	1.00			1.00
WTG 33	Karcino 2 M180	Site data: STATGEN (4)	IIB	42.5	39.2	39.2	1.00			1.00
WTG 34	Karcino 2 M180	Site data: STATGEN (4)	IIB	42.5	38.9	38.9	1.00			1.00
WTG 36	Karcino 1 M179	Site data: STATGEN (4)	IIB	42.5	40.5	40.5	1.00			1.00
WTG 37	Karcino 2 M180	Site data: STATGEN (4)	IIB	42.5	38.6	38.6	1.00			1.00
WTG 38	Karcino 2 M180	Site data: STATGEN (4)	IIB	42.5	39.1	39.1	1.00			1.00
WTG 39	Karcino 2 M180	Site data: STATGEN (4)	IIB	42.5	39.1	39.1	1.00			1.00
WTG 40	Karcino 2 M180	Site data: STATGEN (4)	IIB	42.5	39.0	39.0	1.00			1.00

Figure 40. The Results (Table) tab.

The *Results (Graphics)* tab gives a graphical overview of the results relative to the IEC limit. In the shown case, the results are within the IEC limit.

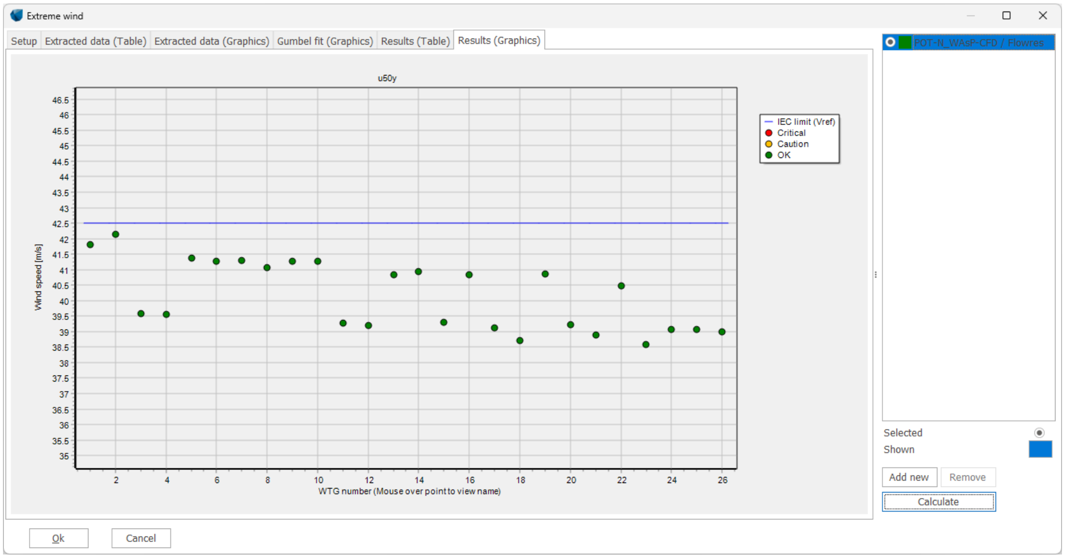


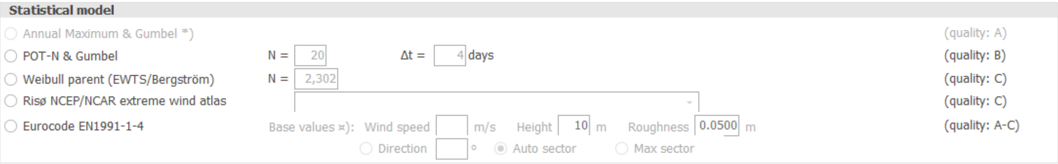
Figure 41. The Results (Graphics) tab.

You may click the *Add new* button (lower right corner) to add another calculation setup for extreme wind using a different method or different parameters for the same method. E.g., select *Weibull parent (EWTS/Bergström)* and press *Calculate*. Now, you have two result options you can compare. If you have run a WEng calculation, you may also try the *Risø NCEP/NCAR extreme wind atlas* which covers most of Europe and US. Each calculation adds a line in the right pane. Click on a calculation in the pane to highlight it and view its setup and results.

IMPORTANT: The results of the calculation which is marked with the ⦿ will be used in the final evaluation.

Statistical model

The setup in this group defines the statistical model used to extract the extreme wind data and how this data is fitted to the Gumbel statistical model, if required in the method. The different models are described in the following text.


Statistical model

○ Annual Maximum & Gumbel *) (quality: A)
○ POT-N & Gumbel N = 20 Δt = 4 days (quality: B)
○ Weibull parent (EWTS/Bergström) N = 2,302 (quality: C)
○ Risø NCEP/NCAR extreme wind atlas (quality: C)
○ Eurocode EN1991-1-4 Base values ¤): Wind speed m/s Height 10 m Roughness 0.0500 m (quality: A-C)
○ Direction ° ● Auto sector ○ Max sector

Figure 42. The Setup of the Statistical model in the Extreme wind check. Note that the uppermost option is only available with at least 5 years of measurements for all site masts.

Annual maximum & Gumbel (requires ≥5 years for all site masts)

This method is only available if all masts have at least 5 years of data, because only the single most extreme wind speed measurement is extracted from each year from the time series. With less than five years and hence less than five data points, the linear fit to the Gumbel model becomes very vulnerable to the individual data points. General recommendations suggest at least seven years of data for the annual maximum (AM) method to obtain reliable results for this method. The AM method is the classical method proposed by Gumbel and is still considered the most accurate, provided that sufficient data is available, which, unfortunately, is rarely the case in wind energy project development.

Once the annual maxima data points are extracted they are processed according to the classical Gumbel method of extremes, resulting in the so-called Gumbel plot. The fit of the Gumbel asymptote is performed using the Probability Weighted Moments (PWM). (See [4] or Appendix I for further details of the theory).

POT-N & Gumbel

This method is available when at least one site mast with time series data was selected in the general setup. The name abbreviates *Peak-Over-Threshold* and the *N* signifies the modification that the threshold is not defined in terms of wind speed as is usually the case, but, instead, in terms of a fixed number (*N*) of samples. Often, this method is also referred to as "Method of Independent Storms (MIS)" (see [5] and Appendix I) although the original MIS method [5] uses a slightly different approach for data extraction.

There is no lower limit to the length of the time series needed for this method, but it is strongly recommended to use an integer number of full years, i.e., at least one full year. *N* defines the total number of storms to be extracted (default is 20) and *Δt* the minimum time separation required for storms to be independent (default is 4 days). The default time separation is chosen to match the typical time scale of synoptic storm events.

Once extracted, the samples are processed according to Gumbels method with the additional step of correcting for the annual storm rate (see [5] or Appendix I for further details). The model fit to the Gumbel asymptote is performed based on the classical plotting positions (see [6]) and a traditional least squares fit with wind speed as the independent variable.

Weibull parent (EWTS/Bergström)

The European Wind Turbine Standard (EWTS) [7] describes an extreme wind method based on the tail characteristics of the Weibull mean wind speed distribution (*parent distribution*). A fundamental principle is that sites which exhibit wind distributions with a low Weibull k-factor have heavier tails and, thus, a higher likelihood of extreme events and, hence, higher extreme wind speeds.

This methodology relies on two main assumptions:

1) The wind distribution is a Weibull
2) The number of statistically independent wind samples per year is known (and equal for all sites)

The EWTS publication uses the number 23037 10-min independent events per year with a reference to a 1992 publication by Bergström [8]. However, there is typographical error in the EWTS publication and the number is incorrect. In Bergström's original paper [8], the correct number is 2302.
For the Weibull distribution shape parameter, we use the so-called "combined Weibull" [18] which results from combining the sector-wise Weibull distributions, typically resulting from the WAsP calculation, to a resulting omni-directional Weibull with the same first (mean wind speed) and third (energy) moments.

Risø NCEP/NCAR extreme wind atlas

The Risø NCEP/NCAR extreme wind atlas method uses a database of *Regional Extreme Wind Climate* (REWC) files established for WEng 2 as part of a research project at Risø [9]. These atlases are based on the NCEP/NCAR global reanalysis data with some ad hoc corrections established as part of the project to compensate for the coarse temporal and spatial nature of the NCEP/NCAR data.

This method requires that a WEng calculation has been performed in SITE COMPLIANCE. The user may select one of the nearest four REWC files. Each REWC file contains 12x30 reduced geostrophic wind speeds, one for each of twelve direction sectors in each of thirty reference years. The wind speed samples are adjusted for each WTG position using the predicted sector-wise flow corrections established by WEng to obtain the annual maximum samples for each reference year. From this point, the method progresses identically to the Annual Maximum method described above.

Eurocode EN1991-1-4

During the past decade or so, all national building codes within the European Community have been standardized into the Euro Codes (EN). The Euro Code EN1991-1-4 treats wind loads and defines the guidelines for handling of design extreme wind speeds. Each country has a national annex to EN1991-1-4 that describes the *Base wind speed* to be used in different regions of the country as well as appropriate corrections at high altitude and other exceptions or corrections. Thus, national codes like DIN (Germany), BS6399 (UK), DS (Denmark), SS (Sweden), PN (Poland), SFS (Finland) are now referred to as e.g. DS-EN1991-1-4.

The input *Base wind speed, height* and *roughness* is to be found in the relevant national annex. The wind speed is defined as a 50-year extreme wind speed at reduced geostrophic conditions. The typical standard conditions are: 10m agl. (flat terrain) and a uniform roughness of z_0= 0.05m (roughness class 2,).

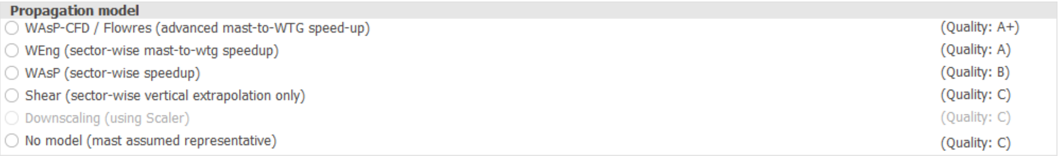
A simple example is Denmark where the 50-year base wind speed is defined as 24m/s for all inland positions, except in a 25km wide belt along the Danish west coast. In this belt, the base wind increases linearly from 24m/s to 27m/s at the west coast. In countries with mountainous areas such as Poland or Germany, the national annex specifies base wind speeds but also adjustment factors to these base wind speeds for altitudes above a certain threshold.

In the calculation, the base wind speed is propagated from the standardized reduced geostrophic conditions (10m, flat terrain and uniform roughness) to the specific terrain and roughness conditions of each WTG using the flow results of WEng, WAsP or WAsP-CFD.

Several countries outside Europe have also adopted or are in the process of adopting the Euro Codes (or selected parts of them) as design standards. At the time of writing (2012), these countries include Singapore, South Africa, New Zeeland and Australia.

Propagation models

Once the extreme samples have been extracted from the measurement series, either using the Annual Maximum method or the Peak-Over-Threshold method (POT-N), they are scaled to better represent the conditions at the WTG positions. This scaling using a *Propagation model* may be based on the methods summarized in the figure below.



Propagation model

○ WAsP-CFD / Flowres (advanced mast-to-WTG speed-up) (Quality: A+)
○ WEng (sector-wise mast-to-wtg speedup) (Quality: A)
○ WAsP (sector-wise speedup) (Quality: B)
○ Shear (sector-wise vertical extrapolation only) (Quality: C)
○ Downscaling (using Scaler) (Quality: C)
○ No model (mast assumed representative) (Quality: C)

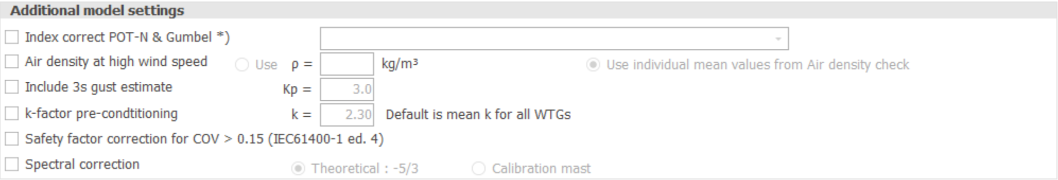
Figure 43. Setup of the Propagation model in the Extreme wind check.

For the option *WAsP-CFD* / Flowres, an advanced scaling method is used which accounts for the potentially strong turning (veer) of the wind from a mast to the WTG in complex terrain. For *WEng* and *WAsP,* the scaling is performed using the sector-wise mast-to-WTG speed-up factors predicted in the WEng and WAsP calculations respectively. In the *Shear* option, the measured sector-wise shear is used to calculate the sector-wise speed-up factors from mast height to WTG hub height. For the choice *No model,* no scaling is performed of the measured extremes.

The Gumbel fitting is always performed after the chosen scaling is applied to the extracted extreme samples.

Additional model settings

The *Extreme wind* check offers several *Additional model settings* as shown in the figure below. These are described in the following.



Additional model settings

☐ Index correct POT-N & Gumbel *)
☐ Air density at high wind speed ○ Use ρ = kg/m³ ● Use individual mean values from Air density check
☐ Include 3s gust estimate Kp = 3.0
☐ k-factor pre-condtitioning k = 2.30 Default is mean k for all WTGs
☐ Safety factor correction for COV > 0.15 (IEC61400-1 ed. 4)
☐ Spectral correction ● Theoretical : -5/3 ○ Calibration mast

Figure 44. Setup of Additional model settings for the Extreme wind check.

Index correct POT-N & Gumbel

This long-term index correction method for extreme wind estimates is only available for the POT-N method. It is based on work published at the EWEA conference 2010 [10]. The fundamental basis of this method is the observation that two main sources of error dominate in extreme wind estimation:

1) Too short a time-series (resulting in a statistical uncertainty)
2) Bias introduced by the method of the Gumbel model fit.

In addition to this, we know that the Annual maximum method with the PWM fit is virtually free of error source two: bias from the Gumbel fit [11].

The idea of this index correction is based on calculating an extreme wind index for the period of the site measurements by using an overlapping long-term reference series which is representative in regards to the storm events. The index is estimated by applying the same POT-N setup to the concurrent part of the reference series and the Annual maximum (AM) method and PWM fit to the full length of the reference series. The index is then defined as the ratio of the concurrent POT-N estimate to the full AM estimate for the reference. The appropriate correction, which is applied to the extreme wind estimate using the site mast, equals the inverse of the extreme wind index.

As a validation, an index is calculated for each year of the site series and for the reference series. This allows a visual validation to check if the extreme wind climate is properly accounted for by the reference series. If this is the case, the index curves will have the same shape.

Note: The Extreme wind index correction should be used with great caution if only one year of site/reference overlap is available. This prevents evaluation of the mast and reference index trends that can be prevalent in such short periods, e.g., if an evaluation based on several years overlap reveals very different trends than using only one year.

Air density at high wind speed

The aerodynamic force is proportional to the square of the wind speed and to the air density. Thus, a decrease of air density results in a decreased thrust. The IEC limit for extreme wind is defined at standard air density of 1.225kg/m^3. Extreme wind estimates at other air densities may be corrected to standard air density assuming that the thrust force is unchanged but that the site air density is replaced by the standard value.

The air density inserted by the user should represent the air density expected at high speeds. Often the expected mean air density is used as an approximation.

Include 3s gust estimate

Gust values may be estimated from measurements using the max of each 10-minute interval which is often logged. However, the averaging period of such estimates is unknown. The IEC standard requires 3-second averages to be used for gust estimates. Instead of maximum 10-minute measurements, 3-second gust estimates may be based on a simple model, originally introduced by Davenport. The method uses the formula below to estimate the gust at averaging time t.

$$u_t = u_{10min}(1 + k_p(t)TI)$$

Where k_p is a normalized peak factor equal to 3.0 for t=3s according to Cook (1990) in [12], TI is the expected turbulence intensity (10-minute averaging) which is calculated as the mean turbulence intensity for the extracted extreme samples. No adjustment is made to the turbulence; hence the gust factor estimated at each mast is used directly for the relevant WTG positions.

k-factor pre-conditioning

The Gumbel model is an asymptotic model - it assumes that the number of independent events per year is infinite. In [5], Cook demonstrates that the error due to this assumption depends on the Weibull k-factor of the wind speed distribution. If the k-factor is one (also called the exponential distribution), the error is zero no matter the real sample size. For k larger than 1, the error increases with k. The error introduced by this assumption makes the Gumbel plot of the extracted extreme samples curve slightly down. The curvature introduces an overestimation (conservatism) in the Gumbel fitting.

To reduce this error, the wind speeds may be transformed prior to Gumbel fitting to turn the distribution into a Weibull with a k-factor of one. This is done by raising the wind speeds to the power of k. After the fit has been performed and extrapolated to obtain the 50-year estimate, the wind speeds are transformed back taking the kth root. Often a factor of two is used as a general estimate of the k-factor. The default value in this setup is the mean “combined” k-factor for WTGs [18]. The typical effect of the k-factor pre-conditioning is to reduce the extreme wind estimates by 5-10%.

Thus, the use of k-factor preconditioning rests on a solid statistical argument. See the *Extreme wind* appendix for further details.

Safety factor correction for COV>0.15

In the ed. 4 of the IEC standard, it was identified that further safety is needed for particular distribution parameters of the extreme wind Gumbel distribution, in the case when the coefficient of variation of the distribution exceeds 0.15. See further details in Appendix VII.

5.2.2.3 Effective turbulence

Description and design limit

The Effective turbulence check is together with the Extreme wind check - one of the most important IEC checks. Where Extreme wind represents the extreme loads, the Effective turbulence mainly represents the fatigue loads, a more long-term degradation of structural integrity of the turbine. Calculation of the Effective turbulence is described in a revised version in the 2010 Amendment to IEC61400-1 ed. 3 [2]. The Effective turbulence model is based on the publication [13] by the late Sten Frandsen from Risø/DTU, hence the model is also known as the “Frandsen model”.

The design limit for Effective turbulence is called the “Normal turbulence model” in the IEC standard and is calculated from the basic parameter I_{ref} in Table 1 (see section 5.1.1). I_{ref} has the values 0.12, 0.14 and 0.16 for the standard turbulence classes A, B and C, respectively. The calculated Effective turbulence is based on the 90th percentile of measured ambient turbulence and must be compared against the Normal turbulence model (the design limit) for a range of wind speeds. When the power curve is known, the range is from 60% of the wind speed at rated power to the cut out wind speed. In SITE COMPLIANCE, a WTG object, and hence a power curve, is always defined prior to calculating Effective turbulence. Appendix II describes further theoretical details of the Effective turbulence model.

Effective turbulence is calculated as a function of wind speed only. This is done by integrating the directional variation of turbulence over all directions for each wind speed bin. However, effective turbulence is NOT a measurable quantity as it combines the directional contributions with a special weighting that accounts for material fatigue via use of the material parameter, the Wöhler exponent, hence the name Effective turbulence. Prior to the integration over all directions for each wind speed, the estimated wake added contribution is combined with the 90th percentile of the ambient turbulence at each WTG. The normal turbulence model is illustrated below for each of the three turbulence classes.

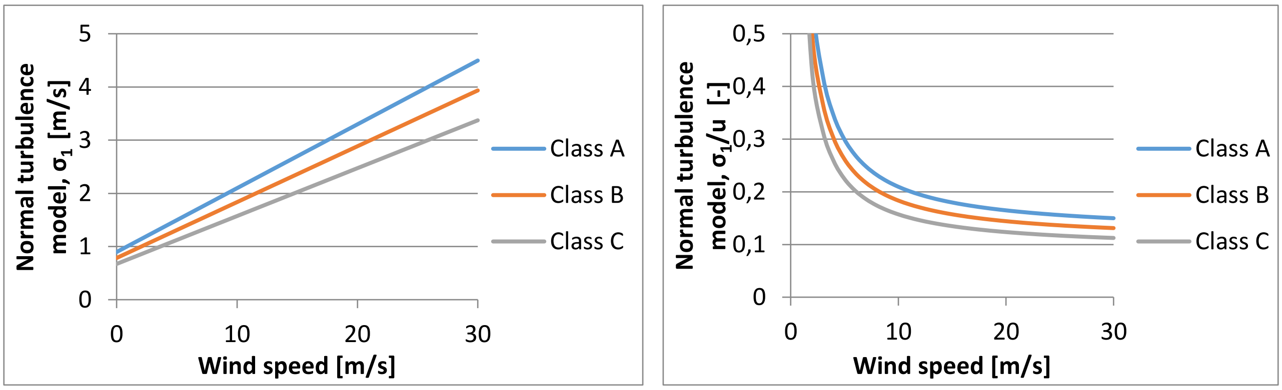
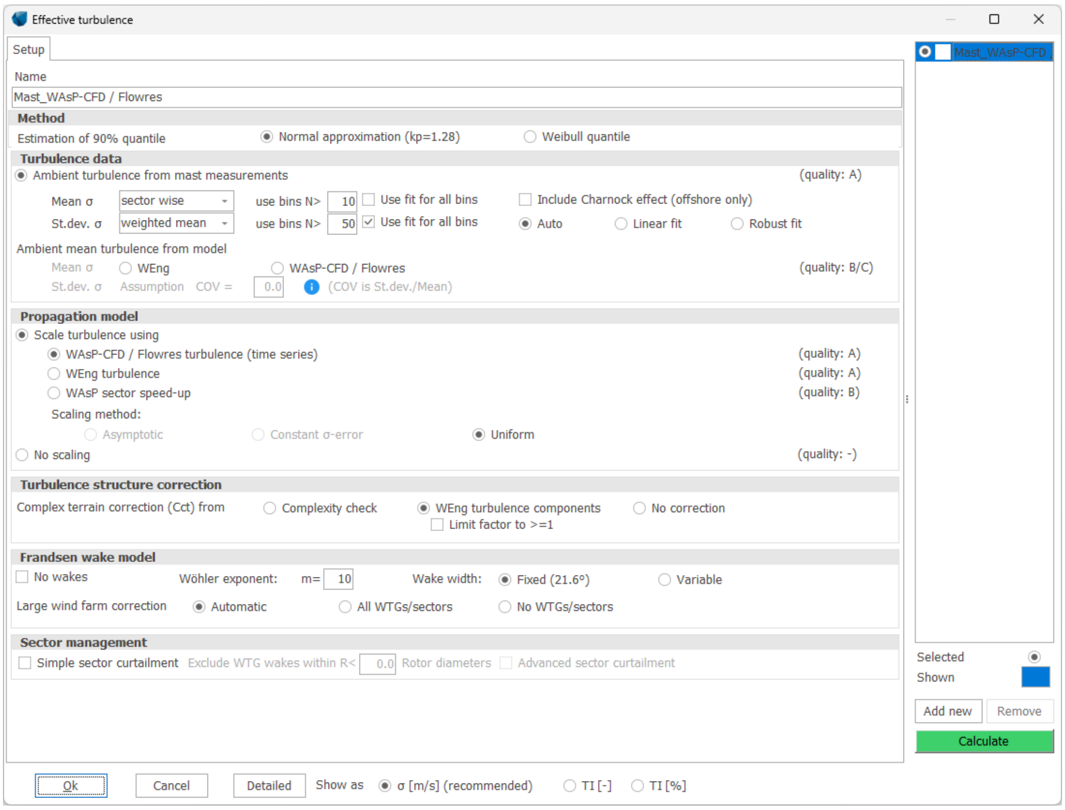


Figure 45. Illustration of the IEC “Normal turbulence model” which is the IEC design limit for the Effective turbulence check. Left: plotted as standard deviation of wind speed. Right: plotted as turbulence intensity.

Setup, Calculation and Results

Note:
Please be aware that the Terrain complexity check must always be completed before the Effective turbulence calculation can be initiated. The reason is that the results of the Terrain complexity check are used in the Effective turbulence calculation via a correction factor called turbulence structure correction factor which is required by the IEC standard.

The following text describes the workflow in setting up, calculating and reviewing the results of a typical effective turbulence calculation. The setup of this check is split in five groups: *Turbulence data, Propagation model, Turbulence structure correction, Frandsen model* and *Sector management*. Details of the options within each of these groups are described after this description of the workflow and various tabs. The figure below shows the *Setup* tab of the Effective turbulence check.



Name: Mast_WAsP-CFD / Flowres

Method

Estimation of 90% quantile ● Normal approximation (kp=1.28) ○ Weibull quantile

Turbulence data

● Ambient turbulence from mast measurements (quality: A)

Mean σ: sector wise; use bins N> 10 ☐ Use fit for all bins ☐ Include Charnock effect (offshore only)

St.dev. σ: weighted mean; use bins N> 50 ☑ Use fit for all bins ● Auto ○ Linear fit ○ Robust fit

Ambient mean turbulence from model

Mean σ ○ WEng ○ WAsP-CFD / Flowres (quality: B/C)

St.dev. σ Assumption COV = 0.0 (COV is St.dev./Mean)

Propagation model

● Scale turbulence using

● WAsP-CFD / Flowres turbulence (time series) (quality: A)

○ WEng turbulence (quality: A)

○ WAsP sector speed-up (quality: B)

Scaling method: ○ Asymptotic ○ Constant σ-error ● Uniform

○ No scaling (quality: -)

Turbulence structure correction

Complex terrain correction (Cct) from ○ Complexity check ● WEng turbulence components ☐ Limit factor to >=1 ○ No correction

Frandsen wake model

☐ No wakes Wöhler exponent: m= 10 Wake width: ● Fixed (21.6°) ○ Variable

Large wind farm correction ● Automatic ○ All WTGs/sectors ○ No WTGs/sectors

Sector management

☐ Simple sector curtailment Exclude WTG wakes within R< 0.0 Rotor diameters ☐ Advanced sector curtailment

Selected ●

Shown

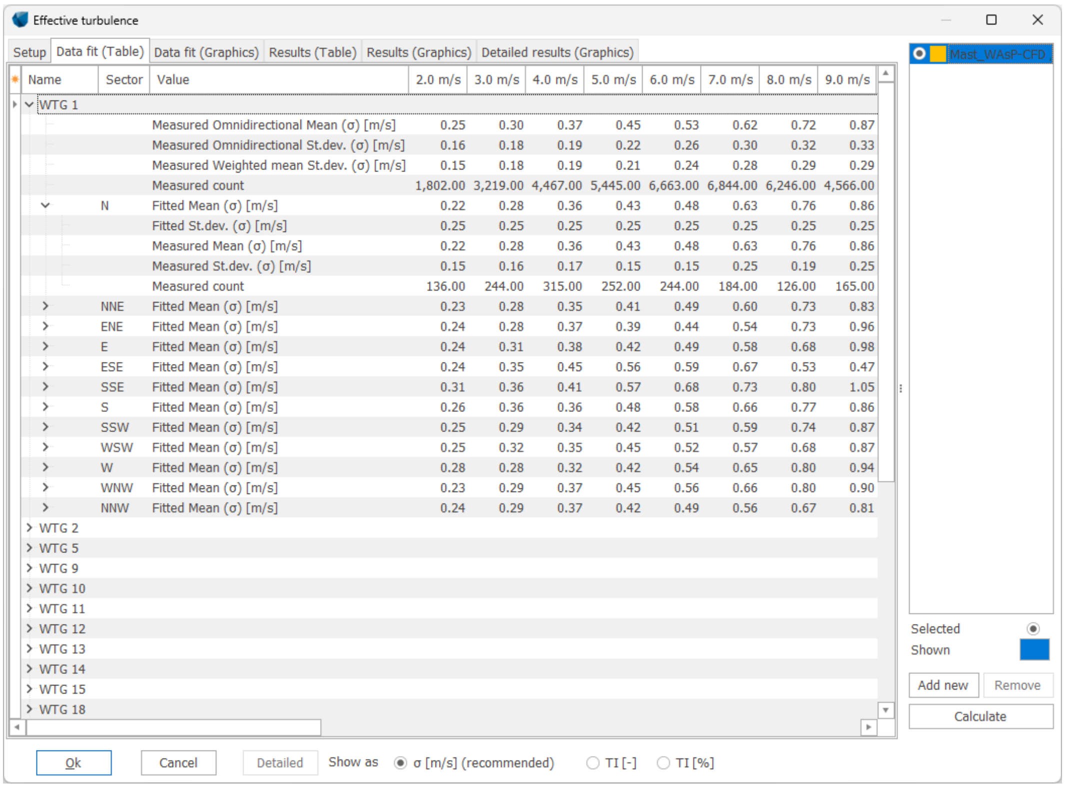
Show as ● σ [m/s] (recommended) ○ TI [-] ○ TI [%]

Figure 46. Setup tab of the Effective turbulence check.

Click the highlighted *Calculate* button to the lower right to run the Effective turbulence calculation using the default setup. When calculation is done, several new results tabs emerge, which are described in the following.

When measured turbulence data from a *Site mast* is used in the calculation, this data must be analysed. A model must be fitted to the mean turbulence and to its standard deviation to fill in gaps in the data and to extrapolate them to the required wind speed bins without data. The *Data fit (Table)* summarizes the omnidirectional and sector-wise outcome of the procedure in a tabular form.

Note that at the bottom of the tab it is possible to toggle between viewing the table as standard deviation in m/s and as turbulence intensity. The standard deviation is recommended throughout as this is the measured quantity, and because the fundamental assumption in the Frandsen model is that loads are proportinal to the standard deviation. Using turbulence intensity tends to move focus to low wind speeds where loads are not as significant. Viewing turbulence data as TI also tends to overemphasize small insignificant deviations of the fits at low wind speeds.



Name	Sector	Value	2.0 m/s	3.0 m/s	4.0 m/s	5.0 m/s	6.0 m/s	7.0 m/s	8.0 m/s	9.0 m/s
WTG 1										
		Measured Omnidirectional Mean (σ) [m/s]	0.25	0.30	0.37	0.45	0.53	0.62	0.72	0.87
		Measured Omnidirectional St.dev. (σ) [m/s]	0.16	0.18	0.19	0.22	0.26	0.30	0.32	0.33
		Measured Weighted mean St.dev. (σ) [m/s]	0.15	0.18	0.19	0.21	0.24	0.28	0.29	0.29
		Measured count	1,802.00	3,219.00	4,467.00	5,445.00	6,663.00	6,844.00	6,246.00	4,566.00
	N	Fitted Mean (σ) [m/s]	0.22	0.28	0.36	0.43	0.48	0.63	0.76	0.86
		Fitted St.dev. (σ) [m/s]	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25
		Measured Mean (σ) [m/s]	0.22	0.28	0.36	0.43	0.48	0.63	0.76	0.86
		Measured St.dev. (σ) [m/s]	0.15	0.16	0.17	0.15	0.15	0.25	0.19	0.25
		Measured count	136.00	244.00	315.00	252.00	244.00	184.00	126.00	165.00
	NNE	Fitted Mean (σ) [m/s]	0.23	0.28	0.35	0.41	0.49	0.60	0.73	0.83
	ENE	Fitted Mean (σ) [m/s]	0.24	0.28	0.37	0.39	0.44	0.54	0.73	0.96
	E	Fitted Mean (σ) [m/s]	0.24	0.31	0.38	0.42	0.49	0.58	0.68	0.98
	ESE	Fitted Mean (σ) [m/s]	0.24	0.35	0.45	0.56	0.59	0.67	0.53	0.47
	SSE	Fitted Mean (σ) [m/s]	0.31	0.36	0.41	0.57	0.68	0.73	0.80	1.05
	S	Fitted Mean (σ) [m/s]	0.26	0.36	0.36	0.48	0.58	0.66	0.77	0.86
	SSW	Fitted Mean (σ) [m/s]	0.25	0.29	0.34	0.42	0.51	0.59	0.74	0.87
	WSW	Fitted Mean (σ) [m/s]	0.25	0.32	0.35	0.45	0.52	0.57	0.68	0.87
	W	Fitted Mean (σ) [m/s]	0.28	0.28	0.32	0.42	0.54	0.65	0.80	0.94
	WNW	Fitted Mean (σ) [m/s]	0.23	0.29	0.37	0.45	0.56	0.66	0.80	0.90
	NNW	Fitted Mean (σ) [m/s]	0.24	0.29	0.37	0.42	0.49	0.56	0.67	0.81
WTG 2										
WTG 5										
WTG 9										
WTG 10										
WTG 11										
WTG 12										
WTG 13										
WTG 14										
WTG 15										
WTG 18										

Figure 47. Data fit (Table) tab of the Effective turbulence check. Note that only when WAsP-CFD is the propagation model the fit is also shown for each WTG in addition to each mast.

The *Data fit (Graphics)* presents the turbulence measurements and fits them into a graphical form. Use the buttons in the lower left corner to change to another mast (if available) or to skip through the sectors. It is worth noting that in the plots the…:

- asterisk illustrates the measurements
- open circles show the chosen value
- red lines are the fitted data model

If the asterisk and the open circles coincide, it means that the measurements in the bin are accepted as the bin fullfills the selection criteria (minimum number of samples in each bin) defined on the *Setup* tab. If the asterisks and open circles deviate for a bin, the open circle will always fall on the redline, indicating that the fitted value was selected because the bin failed the selection criteria.

Note that for the default setup, the standard deviation of turbulence (σ_σ) is the same for all sectors. This is due to the fact that this quantity (the standard deviation of the standard deviation) is ususally not well determined sector-wise with only one year of data. The IEC standard allows this use the weighted mean σ_σ instead of sector-wise values to stabilize the estimation.This is introduced in a footnote in [2].

If the data selection or the fits are not satisfactory, press the *Add* button to the lower right to try another setup where the data selection criteria have been changed. This setup is described in more detail below.

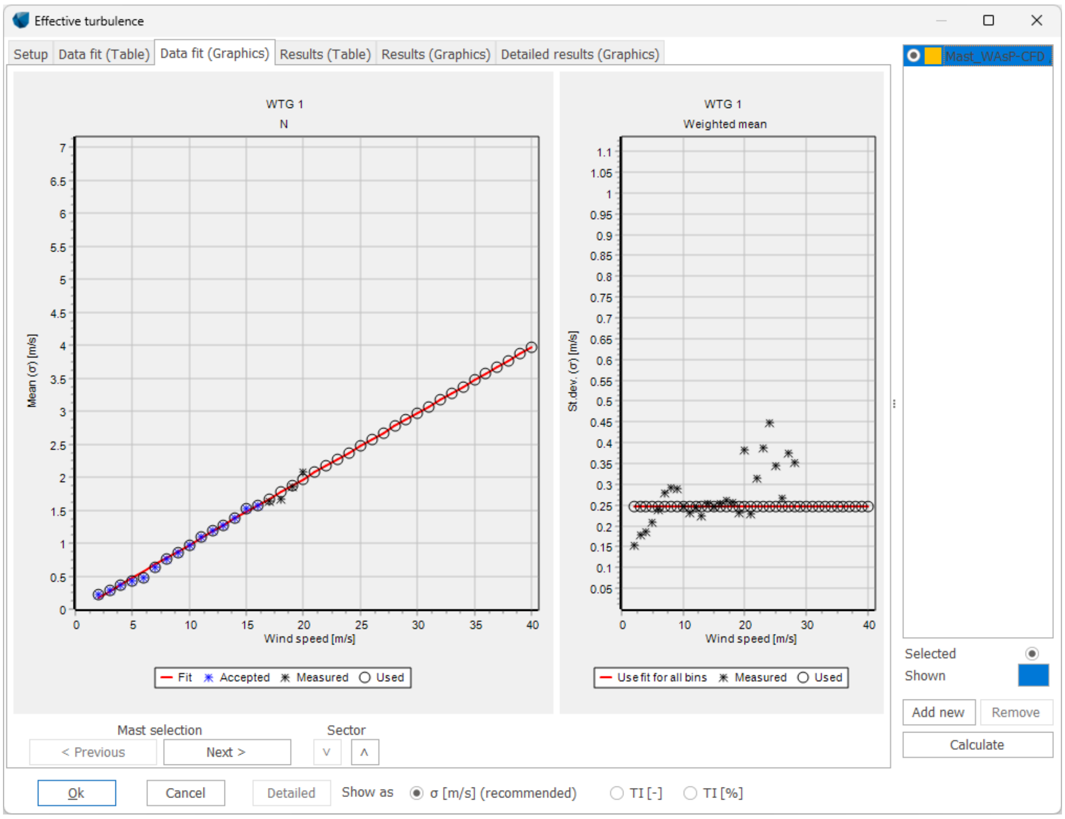
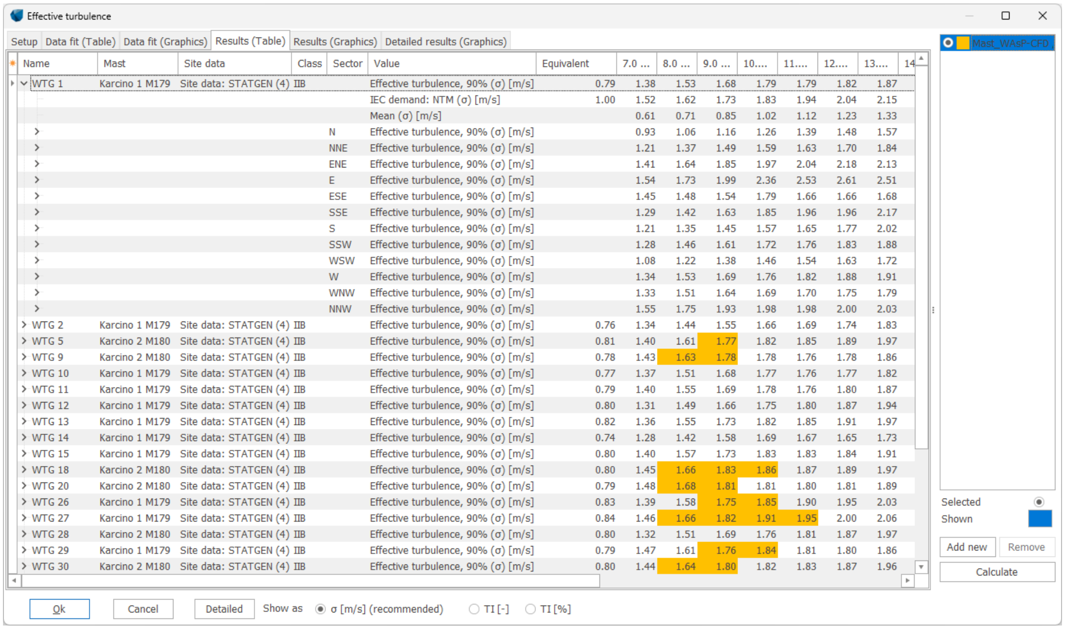


Figure 48. Data fit (Graphics) tab of the Effective turbulence check. Note the three highest samples on the left plot. These are measurements with too few samples in their bin to be selected for use. Thus, the asterisks (measurements) do not coincide with the circles (selected value) for those four bins. Instead those circles fall on the red line (the fit) as the fit is used for bins with too few samples. Sample thresholds are defined in the setup.

Results of the Effective turbulence calculation are summarized on the tab *Results (Table)* showing the results for each wind speed bin within the required check interval by the IEC standard. This check interval is described above (in *Description and limit*) and is relative to the wind speed at rated power, which is estimated from the power curve defined for each particular WTG object in the calculation.

Any bins exceeding the IEC limit are highlighted in the table, so that a WTG with no highlighting is fully within the IEC limit for all required wind speeds. Yellow highlighting is used for *Caution*, i.e. when the exceedances for the particular WTG are not considered critical and, thus, are compensated by the buffer at other wind speeds. Red highlighting is used when overall the exceedances for the WTG are expected to accumulate to a critical exceedance.

For each WTG, the first line in the table shows the result of the Effective turbulence calculation for each wind speed bin. The second line shows the relevant IEC limit for the same bins. In the column *Equivalent*, the equivalent accumulated effective turbulence normalized to the IEC design climate is shown. Thus, the value of *Equivalent* is always one for the row *IEC demand* (second line). The threshold between *Caution* (yellow) and *Critical* (red) is reached at value of *Equivalent* exceeding 1. Third line shows the omnidirectional mean turbulence, and the lines below summarize the sector-wise part results and scaling factors used for each WTG.



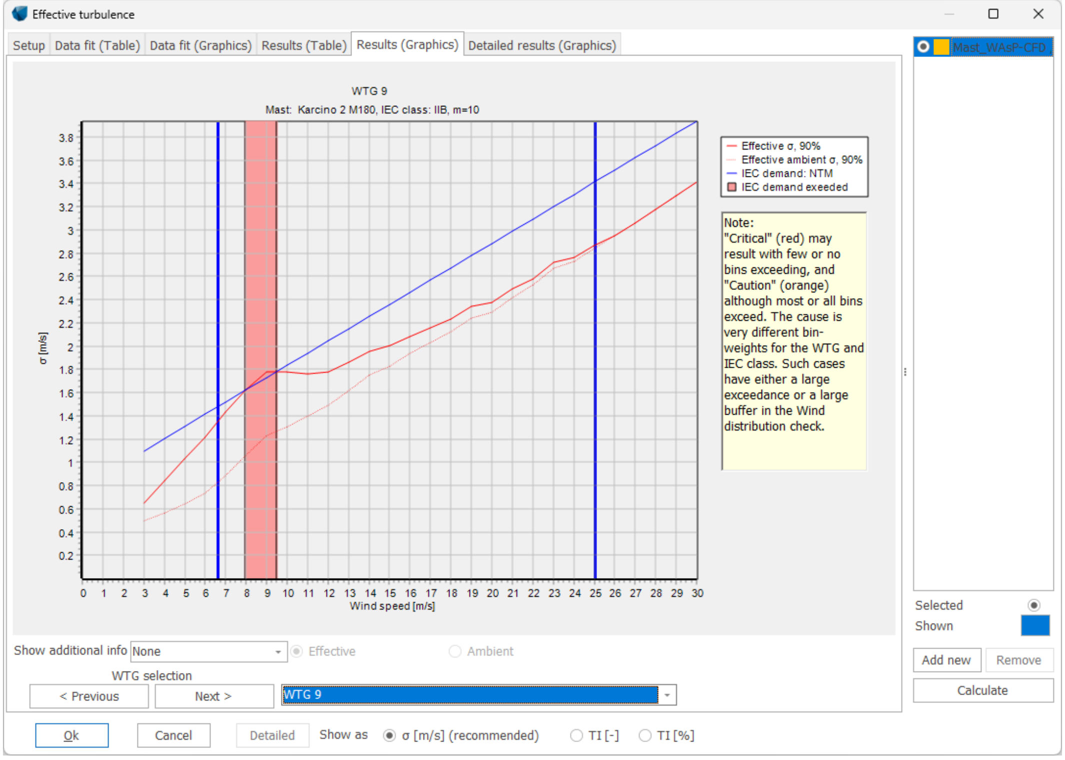
Name	Mast	Site data	Class	Sector	Value	Equivalent	7.0 ...	8.0 ...	9.0 ...	10....	11....	12....	13....	14
WTG 1	Karcino 1 M179	Site data: STATGEN (4)	IIB		Effective turbulence, 90% (σ) [m/s]	0.79	1.38	1.53	1.68	1.79	1.79	1.82	1.87	
					IEC demand: NTM (σ) [m/s]	1.00	1.52	1.62	1.73	1.83	1.94	2.04	2.15	
					Mean (σ) [m/s]		0.61	0.71	0.85	1.02	1.12	1.23	1.33	
				N	Effective turbulence, 90% (σ) [m/s]		0.93	1.06	1.16	1.26	1.39	1.48	1.57	
				NNE	Effective turbulence, 90% (σ) [m/s]		1.21	1.37	1.49	1.59	1.63	1.70	1.84	
				ENE	Effective turbulence, 90% (σ) [m/s]		1.41	1.64	1.85	1.97	2.04	2.18	2.13	
				E	Effective turbulence, 90% (σ) [m/s]		1.54	1.73	1.99	2.36	2.53	2.61	2.51	
				ESE	Effective turbulence, 90% (σ) [m/s]		1.45	1.48	1.54	1.79	1.66	1.66	1.68	
				SSE	Effective turbulence, 90% (σ) [m/s]		1.29	1.42	1.63	1.85	1.96	1.96	2.17	
				S	Effective turbulence, 90% (σ) [m/s]		1.21	1.35	1.45	1.57	1.65	1.77	2.02	
				SSW	Effective turbulence, 90% (σ) [m/s]		1.28	1.46	1.61	1.72	1.76	1.83	1.88	
				WSW	Effective turbulence, 90% (σ) [m/s]		1.08	1.22	1.38	1.46	1.54	1.63	1.72	
				W	Effective turbulence, 90% (σ) [m/s]		1.34	1.53	1.69	1.76	1.82	1.88	1.91	
				WNW	Effective turbulence, 90% (σ) [m/s]		1.33	1.51	1.64	1.69	1.70	1.75	1.79	
				NNW	Effective turbulence, 90% (σ) [m/s]		1.55	1.75	1.93	1.98	1.98	2.00	2.03	
WTG 2	Karcino 1 M179	Site data: STATGEN (4)	IIB		Effective turbulence, 90% (σ) [m/s]	0.76	1.34	1.44	1.55	1.66	1.69	1.74	1.83	
WTG 5	Karcino 2 M180	Site data: STATGEN (4)	IIB		Effective turbulence, 90% (σ) [m/s]	0.81	1.40	1.61	1.77	1.82	1.85	1.89	1.97	
WTG 9	Karcino 2 M180	Site data: STATGEN (4)	IIB		Effective turbulence, 90% (σ) [m/s]	0.78	1.43	1.63	1.78	1.78	1.76	1.78	1.86	
WTG 10	Karcino 1 M179	Site data: STATGEN (4)	IIB		Effective turbulence, 90% (σ) [m/s]	0.77	1.37	1.51	1.68	1.77	1.76	1.77	1.82	
WTG 11	Karcino 1 M179	Site data: STATGEN (4)	IIB		Effective turbulence, 90% (σ) [m/s]	0.79	1.40	1.55	1.69	1.78	1.76	1.80	1.87	
WTG 12	Karcino 1 M179	Site data: STATGEN (4)	IIB		Effective turbulence, 90% (σ) [m/s]	0.80	1.31	1.49	1.66	1.75	1.80	1.87	1.94	
WTG 13	Karcino 1 M179	Site data: STATGEN (4)	IIB		Effective turbulence, 90% (σ) [m/s]	0.82	1.36	1.55	1.73	1.82	1.85	1.91	1.97	
WTG 14	Karcino 1 M179	Site data: STATGEN (4)	IIB		Effective turbulence, 90% (σ) [m/s]	0.74	1.28	1.42	1.58	1.69	1.67	1.65	1.73	
WTG 15	Karcino 1 M179	Site data: STATGEN (4)	IIB		Effective turbulence, 90% (σ) [m/s]	0.80	1.40	1.57	1.73	1.83	1.83	1.84	1.91	
WTG 18	Karcino 2 M180	Site data: STATGEN (4)	IIB		Effective turbulence, 90% (σ) [m/s]	0.80	1.45	1.66	1.83	1.86	1.87	1.89	1.97	
WTG 20	Karcino 2 M180	Site data: STATGEN (4)	IIB		Effective turbulence, 90% (σ) [m/s]	0.79	1.48	1.68	1.81	1.81	1.80	1.81	1.89	
WTG 26	Karcino 1 M179	Site data: STATGEN (4)	IIB		Effective turbulence, 90% (σ) [m/s]	0.83	1.39	1.58	1.75	1.85	1.90	1.95	2.03	
WTG 27	Karcino 1 M179	Site data: STATGEN (4)	IIB		Effective turbulence, 90% (σ) [m/s]	0.84	1.46	1.66	1.82	1.91	1.95	2.00	2.06	
WTG 28	Karcino 2 M180	Site data: STATGEN (4)	IIB		Effective turbulence, 90% (σ) [m/s]	0.80	1.32	1.51	1.69	1.76	1.81	1.87	1.97	
WTG 29	Karcino 1 M179	Site data: STATGEN (4)	IIB		Effective turbulence, 90% (σ) [m/s]	0.79	1.47	1.61	1.76	1.84	1.81	1.80	1.86	
WTG 30	Karcino 2 M180	Site data: STATGEN (4)	IIB		Effective turbulence, 90% (σ) [m/s]	0.80	1.44	1.64	1.80	1.82	1.83	1.87	1.96	

Show as ● σ [m/s] (recommended) ○ TI [-] ○ TI [%]

Figure 49. Results (Table) tab of the Effective turbulence check. Note that the Effective turbulence is exceeded for some WTGs at some wind speeds in the table. Those bins are highlighted in yellow as the exceedance is not expected to be critical.

The tab *Results (Graphics)* illustrates the Effective turbulence results as a function of wind speed for each WTG. Use the buttons to the lower left to shift to next WTG. Any exceedance within the relevant IEC check interval is highlighted by light red shading of the wind speed bin.

Note that also the *Effective ambient turbulence* is shown as the dashed curve, which illustrates the result of the Effective turbulence calculation disregarding all wake-added turbulence contributions. The difference between the full and the dashed curve clearly illustrates the wake contribution of the wind farm to the effective turbulence. The difference is usually highest up to 8-12 m/s, because at higher wind speeds, the thrust coefficient decreases quickly for most WTGs and lower thrust results in less wake turbulence.



Note:
"Critical" (red) may result with few or no bins exceeding, and "Caution" (orange) although most or all bins exceed. The cause is very different bin-weights for the WTG and IEC class. Such cases have either a large exceedance or a large buffer in the Wind distribution check.

Show additional info None ● Effective ○ Ambient

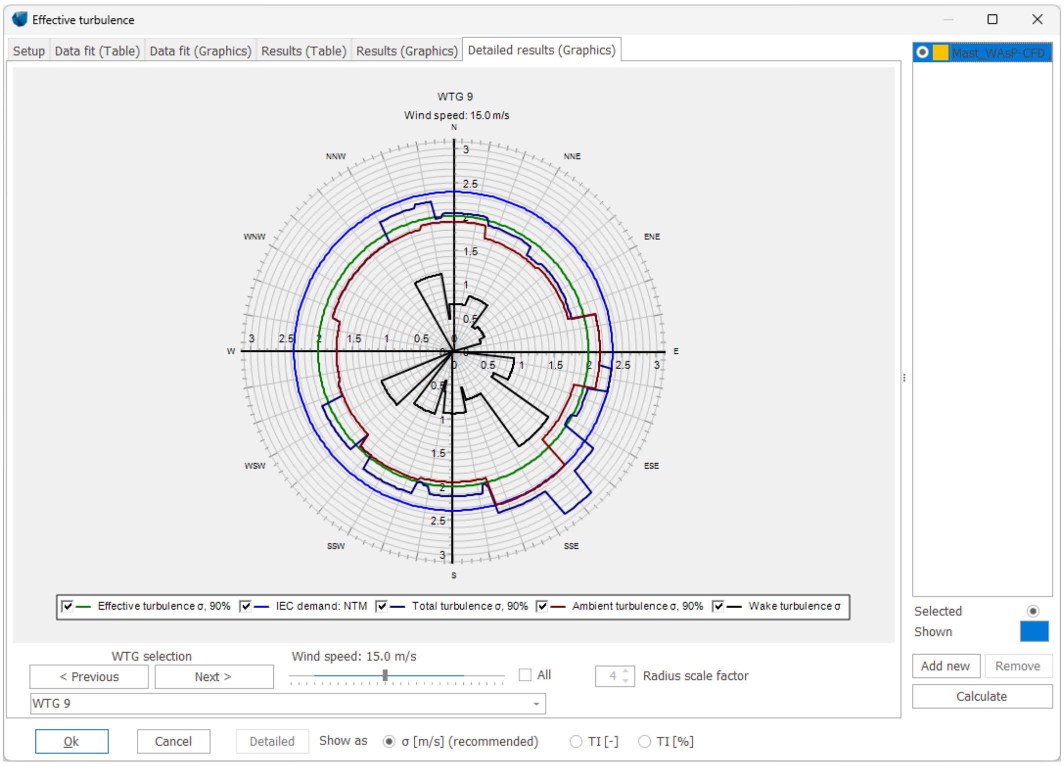
WTG selection: WTG 9

Show as ● σ [m/s] (recommended) ○ TI [-] ○ TI [%]

Figure 50. Results (Graphics) tab of the Effective turbulence check.

The rightmost tab *Detailed results (Graphics)* illustrates all the contributions and part results in the calculation of effective turbulence as a function of wind speed. Each contribution may be de-activated in the menu below the graph. The wind speed is adjusted using the slide bar. To scroll through the graphs for the WTGs use the *Previous/Next* buttons to the lower left. If the box *All* is ticked, all WTGs are plotted together with their relative positions. Use the mouse-over-effect to see the label of each WTG. If all contributions are unchecked except *Wake turbulence,* this graph is particularly useful to identifying which neighbour WTG is the cause of a too high Effective turbulence level.

The graphics on this tab are also very useful to help better understand the calculation of Frandsen's Effective turbulence but also to analyse and help understand the cause of turbulence-related problems of a wind farm design. Is it the ambient turbulence or is it the wake-added turbulence that is causing the problem? And from which sector/directions are the problems caused?



☑ Effective turbulence σ, 90% ☑ IEC demand: NTM ☑ Total turbulence σ, 90% ☑ Ambient turbulence σ, 90% ☑ Wake turbulence σ

Wind speed: 15.0 m/s ☐ All 4 Radius scale factor

WTG 9

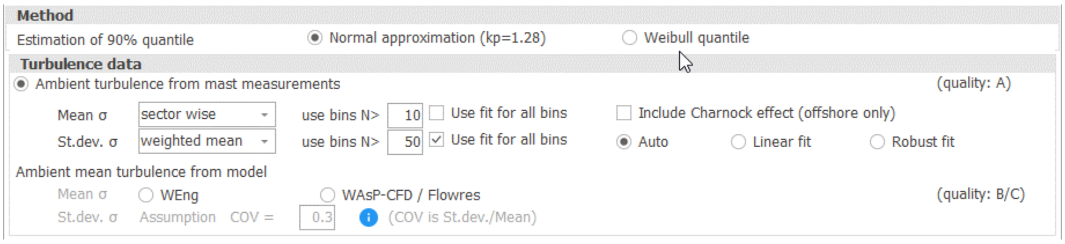
Show as ● σ [m/s] (recommended) ○ TI [-] ○ TI [%]

Figure 51. Detailed results (Graph) tab of the Effective turbulence check.

The following sub sections describe the setup options of the Effective turbulence check in more detail.

Turbulence data (ambient)

The starting point of an Effective turbulence calculation is the ambient turbulence on the site.



Method

Estimation of 90% quantile ● Normal approximation (kp=1.28) ○ Weibull quantile

Turbulence data

● Ambient turbulence from mast measurements (quality: A)

Mean σ sector wise use bins N> 10 ☐ Use fit for all bins ☐ Include Charnock effect (offshore only)

St.dev. σ weighted mean use bins N> 50 ☑ Use fit for all bins ● Auto ○ Linear fit ○ Robust fit

Ambient mean turbulence from model

Mean σ ○ WEng ○ WAsP-CFD / Flowres (quality: B/C)

St.dev. σ Assumption COV = 0.3 (COV is St.dev./Mean)

Figure 52. Setup of ambient turbulence data input and handling.

Ambient turbulence from mast measurements

When the ambient turbulence is measured, it must be treated properly to ensure a robust outcome of the calculation as real data always have outliers, holes and other problems. This is handled by applying selection criteria to the data and by fitting a model to the ambient turbulence measurements and using this for problematic or missing bins.

First setup choice for the mean turbulence (*Mean σ*) is the selection of *Sector-wise* or *Weighted mean*. The first option is default and highly recommended. The latter choice is only to be used experimentally as a very robust estimate for very problematic data, e.g., with a very short time span.
Second choice is the number of samples (*N*) in a bin for the bin-average turbulence to be used. Bins with less than *N* samples will be disregarded; they will not contribute to the fit, and the turbulence of those bins will be replaced by the fit. The default value of *N* has been chosen by testing the methodology on a number of site masts. The fit is performed as a standard least squares fit to the bin values with equal weights. This disregards the fact that there are many more samples in bins at low wind speeds compared to bins at higher wind speeds, thus, effectively increasing the relative weight of bins at higher wind speeds where loads are more critical. If a fit weighting each bin by the number of samples is used, any upward curvature of the σ(u) curve at higher wind speeds, as in forests and off/near shore, tends to be ignored, which can lead to falsely low estimates of turbulence at high wind speeds as illustrated in the figure below.

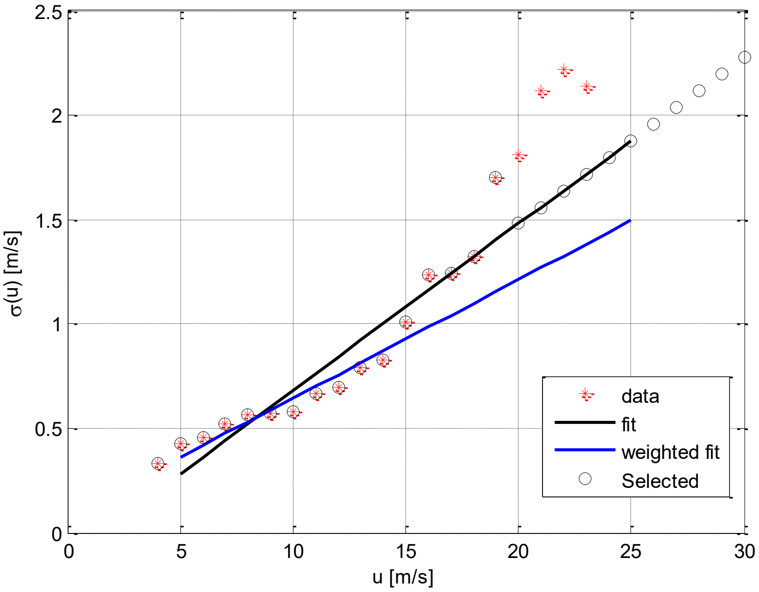


Figure 53. Plot showing the difference between a weighted fit and the fit employed in SITE COMPLIANCE. Note how the weighted fit severely underestimates values of accepted bins between 15 and 20 m/s.

Next choice is activating the *Use fit for all bins* option. If this is activated the fit is used for all bins no matter the number of samples. This is only recommended as a robust approach if the data seems very noisy and oscillatory. The last choice is whether or not Charnock effect should be included by adding a second order term to the turbulence fit. This option should only be activated for offshore sites where the surface roughness increases with wind speed due to the build-up of the wave height. If Charnock effect is included Site Compliance has a built-in extreme wind speed limit of 35m/s for which it is assumed that waves start breaking and the drag coefficient saturates (i.e. the second order growth of turbulence ceases).

Setup for handling of measured standard deviation of turbulence (i.e., σ_σ) has the same three choices as for the mean turbulence (σ), but the defaults are different. By default the weighted mean is used for σ_σ as this is allowed in the standard [2] and ensures a much more stable estimation of this otherwise quite unstable parameter. In addition, a higher default bin acceptance limit of 50 samples is used, as well as using the fit for all bins. These defaults ensure a quite robust estimation of σ_σ. However, our analyses have shown that still, for some sites with only a year of data, an even more robust estimation is required. Therefore, an extra fit criterion is included which controls the type fitting with the options *Auto*, *Linear* or *Robust*. The default setting is *Auto*. In this mode, an ordinary linear fit is used if the R^2 of the fit is above 0.8. When R^2 is below 0.8, a very robust estimator is used, namely the median sample which is very insensitive to outliers. The user may also force the fit to always be a *Linear* fit or a *Robust* fit (i.e. median) no matter the value of R^2 using the last to options.

Ambient turbulence from model (no mast data)

If no measurements of turbulence are available the turbulence must be predicted using a model, which means either WEng or WAsP-CFD or a pre-run flow result in flowres format. In addition, the flow models only predict the mechanically generated contribution to the mean turbulence intensity and not the thermal contribution or the standard deviation of the turbulence intensity. There is just one sub-option '*COV', with default value COV=0.3*, which means that the turbulence intensity from flow model will be used as the mean turbulence, whereas the standard deviation is assumed to equal 30% of the mean, i.e., that the mean has a coefficient of variation (COV) of 0.3. This assumption is chosen to match observations and includes a deliberately slight conservative bias on the 90 percent quantiles of turbulence on average for many masts in simple terrain[8]. A COV of 0.2 yields on average an unbiased result, but has a variation which might lead to underestimation for some sites, which is effectively compensated by using COV=0.3 according to the results in[8].

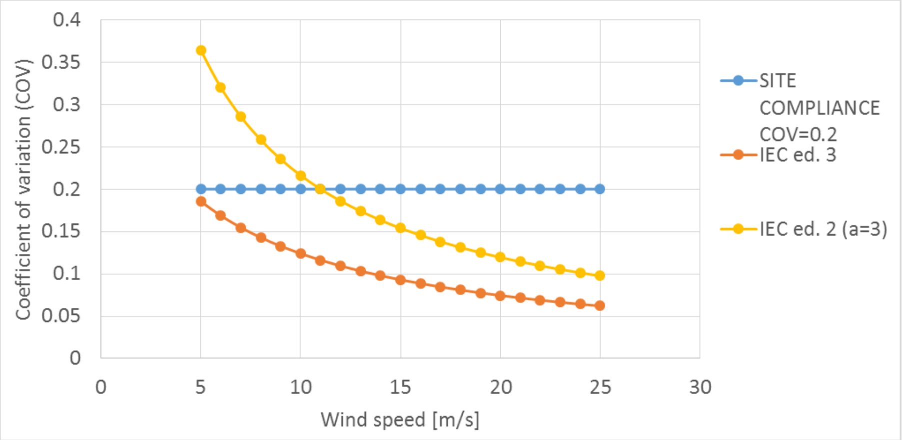
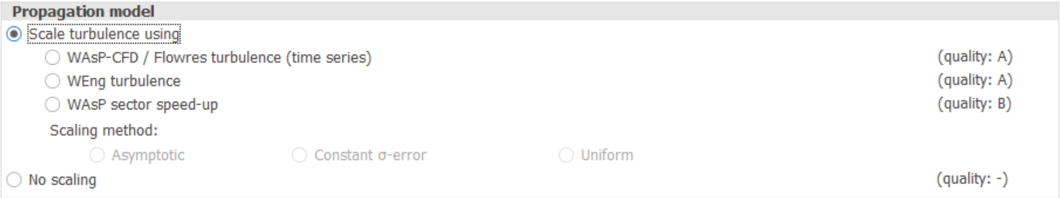


Figure 54. Comparison of COV=0.2 assumption with the assumptions in the IEC standards.

Propagation model

Turbulence measured on a mast only represents the mast position and measuring height. Conditions might be significantly different at other heights and at other locations across a site. To compensate for this SITE COMPLIANCE allows a number of scaling options to adjust measured turbulence to become more representative for each WTG position. This scaling is setup in the *Propagation model* group which also allows the option *No scaling,* which is recommended only for sites where the mast is fully representative for WTG conditions.



Propagation model

● Scale turbulence using

○ WAsP-CFD / Flowres turbulence (time series) (quality: A)

○ WEng turbulence (quality: A)

○ WAsP sector speed-up (quality: B)

Scaling method:

○ Asymptotic ○ Constant σ-error ○ Uniform

○ No scaling (quality: -)

Figure 55. Setup of propagation model, which defines the scaling method of measured turbulence from mast position and height to each WTG position and hub height.

The scaling can be based on predicted turbulence and speed-up from WAsP-CFD / Flowres or WEng or on just sector-wise speed-up factors predicted by WAsP. Additionally, the actual scaling may be done using three different basic assumptions, abbreviated as:

1) Asymptotic
2) Constant σ-error
3) Uniform

For WAsP-CFD / Flowres, the scaling performed for all individual samples so that the complete time series of wind speed and turbulence is scaled out to each WTG position. The tabulation/binning and fitting is then performed for each WTG. This time series approach allows the scaling to properly account for potentially very strong turning (veer) of the wind from mast to WTG, which is likely in complex terrain. With the WAsP-CFD time

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[8] For details see: http://help.emd.dk/knowledgebase/content/WindEuropeSummit2016_Paper_L_Svenningsen_annex.pdf

series approach only the scaling option *Uniform* is possible. Scaling based on WEng turbulence is applied to the binned turbulence table at the mast and allows all three scaling assumptions, which are described in the following.

Asymptotic scaling using WEng turbulence

This method relies on two assumptions:

a) That WEng, as a neutral model, captures the variation of mechanically generated turbulence well. Hence, WEng turbulence ratios must approach the ratios of site turbulence in the high wind speed limit.

$$\sigma^t_{mast}(u,\theta)/\sigma^t_{WTG}(u,\theta) \overset{\square}{\rightarrow} \sigma^p_{mast}(u,\theta)/\sigma^p_{WTG}(u,\theta) \qquad \text{for } u \overset{\square}{\rightarrow} \infty$$

b) That thermally-generated turbulence dominates at wind speeds approaching zero and is a general feature across the site (i.e. a constant).

$$\sigma^t_{mast}(u,\theta)/\sigma^t_{WTG}(u,\theta) \overset{\square}{\rightarrow} 1 \qquad \text{for } u \overset{\square}{\rightarrow} 0$$

Where index *t* indicates “true” which for the mast is the measured turbulence and for the WTG the quantity we want to estimate. Index *p* abbreviates “predicted” and represents WEng predictions.

The resulting scaling factor is a function of direction sector and wind speed.

Constant σ-error scaling using WEng

In this method it is assumed that the error of the WEng predicted turbulence (σ) is constant across the site, related to, e.g., thermal or larger scale turbulence contributions not captured by the WEng micro-scale model.

$$\sigma^t_{WTG}(u,\theta) - \sigma^p_{WTG}(u,\theta) = \sigma^t_{mast}(u/c,\theta) - \sigma^p_{mast}(u/c,\theta)$$

Speed-up across the site is accounted for via the predicted WEng mast-to-WTG speed-up factor $c = u_{WTG}/u_{mast}$ (in the above equation, u is used for u_{WTG}). Indices on sigmas are used as in the previous scaling method and the resulting scaling factor, in this case, is also a function of direction sector and wind speed.

Uniform scaling using WEng

The uniform scaling relies on the very simplifying assumption that the “true” ratio of mast-to-WTG turbulence equals the ratio predicted by WEng, which is constant for all wind speeds within a sector. The scaling factor depends on the sector.

$$\sigma^t_{WTG}(u,\theta)/\sigma^t_{mast}(u,\theta) = \sigma^p_{WTG}(u,\theta)/\sigma^p_{mast}(u,\theta)$$

No speed-up is included and the scaling factor does not vary with wind speed. This scaling assumption is coarser than the other WEng based methods, but on the other hand the simplicity of the underlying assumptions also makes this method quite robust.

Constant σ-error scaling using WAsP

This scaling approach is related to the *Constant σ-error* scaling using WEng (see above) but, in a simplified form as no predicted turbulence values are available. If the predicted turbulence values are set to zero in the equivalent WEng equation, the corresponding WAsP version is obtained.

$$\sigma^t_{WTG}(u,\theta) = \sigma^t_{mast}(u/c,\theta)$$

The fundamental assumption is that, for a certain flow condition (wind speed and direction) at the mast, the turbulence in terms of σ is constant across the site. But, as wind speed varies across the site due to roughness and terrain speed-ups, the turbulence intensity will vary.

Uniform scaling using WAsP

The uniform scaling based on WAsP relies on a similar simple assumption as the uniform WEng scaling is based on. The scale factor is assumed constant for all wind speeds and simply equal to the inverse of the mast-to-WTG speed-up factor predicted by WAsP.

$$\sigma^t_{WTG}(u,\theta) = 1/c\ \sigma^t_{mast}(u,\theta)$$

No scaling

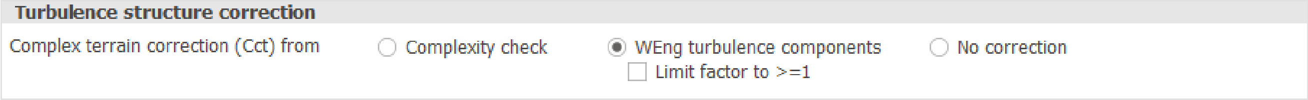
This last option is to assume that the mast measurements are representative for all WTG positions, implying no scaling at all. The underlying assumption is rather trivial.

$$\sigma_{WTG}^{t}(u,\theta) = \sigma_{mast}^{t}(u,\theta)$$

This assumption is only recommended for simple and small sites with little variation in terrain or from mast to WTG or if the scaling options, for some reason, perform poorly. For offshore sites this setting may also be most appropriate depending on the mast setup.

Turbulence structure correction

The IEC standard specifies that if a WTG position is estimated to be complex or partly complex in the terrain complexity check, i.e., the complexity index is I_C>0, then a correction should be applied to turbulence values. The argument is that in complex terrain turbulent kinetic energy is transferred from the horizontal component to the vertical component. Cup anemometers measure only the horizontal component. To compensate for the transferred turbulence, the IEC standard introduces a correction factor C_{CT}, the *Turbulence structure correction parameter*. This correction has its own setup group with several options as shown below.



Turbulence structure correction

Complex terrain correction (Cct) from ○ Complexity check ● WEng turbulence components ○ No correction

☐ Limit factor to >=1

Figure 56. Setup of the Turbulence structure correction requirement of the IEC standard.

The setup allows the following three options.

Complexity check

The IEC standard describes how C_{CT} may be calculated from the terrain complexity index (I_C) for each WTG position using the following equation.

$$C_{CT} = 1 + 0.15 I_C$$

The IEC standard [2] states that this equation is to be used when no measurements or modelling is available for the three components of turbulence.

So far, experience from several complex sites has shown that this *Complexity check* option is quite conservative when compared to modelled components of turbulence. This is the case even when the modelling of these components is using a linearized model, such as WEng, expected to over-estimate inflow angles and, hence, over-estimate transfer of horizontal turbulent kinetic to the vertical/transverse component.

WEng turbulence components

When measurements or modelling of the three components of turbulence are available, the IEC standard states that the following equation for the turbulence structure correction parameter (C_{CT}) may be used.

$$C_{CT} = \frac{\sqrt{1 + \left(\sigma_w/\sigma_u\right)^2 + \left(\sigma_v/\sigma_u\right)^2}}{1.375}$$

Where σ_u, σ_v and σ_w are the three components of turbulence (longitudinal, vertical and transverse). These three components are predicted for each WTG position in a WAsP Engineering calculation and are used when the setting *WEng turbulence components* is chosen. This setting is default when a WEng calculation is available.

The current release of SITE COMPLIANCE does not support the use of three-component measurements.

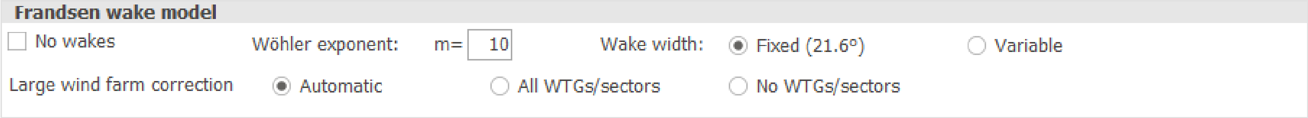
No correction

This option should only be selected if terrain complexity indices for all WTGs equal zero, i.e., for not complex sites. The only exception is when ambient turbulence is predicted using WAsP Engineering. In this case, No correction is the default setting, because WEng models the longitudinal component and not the horizontal component as measured by a cup anemometer. This decision is in-line with the comparable use of WEng calculation results in Risø/DTU's own software tools e.g. WAT.

Frandsen model

The Frandsen Effective turbulence model plays a central role in the IEC context and the model is described in detail in Annex D of the Standard [1, 2]. The theoretical details of the model are summarized in Appendix II of this manual.

In very brief terms, the Frandsen model consists of several sub components. The first component is a model that predicts the wake-generated turbulence downstream of a WTG at a certain wind speed and for a given thrust coefficient. The second component is a model for combining wake-generated turbulence with ambient turbulence into a “total” turbulence for each direction and each wind speed bin. The third component is a special integral over all directions that accounts for frequency of each direction but also includes a non-linear weighting relating to the accumulation of material fatigue in different materials. Hence, a material parameter called the Wöhler exponent is needed as input. The integration is performed for each wind speed bin and the resulting integral is the Effective turbulence as a function of wind speed.



Frandsen wake model

☐ No wakes

Wöhler exponent: m= 10

Wake width: ● Fixed (21.6°) ○ Variable

Large wind farm correction ● Automatic ○ All WTGs/sectors ○ No WTGs/sectors

Figure 57. Setup of the Frandsen model also referred to as the Effective turbulence model.

Wöhler exponent

The general material parameter which is used in weighting according to fatigue accumulation, as described above for the Frandsen Effective turbulence model. Usually, the value m=10 is assumed as it represents glass fibre and thus the WTG blades. A m value of 3-5 represents welded steel and e.g. the tower. Generally, using a high value e.g. m=10 will be a conservative assumption for materials with a lower Wöhler exponent.

Wake width

From Frandsens original publication [13] uses so-called ‘view angles’ to quantify the directions with wake effects. In the proposed model for the standard Frandsen used constant view angles of 21.6° independent of the spacing between turbines - this is the default option in SITE COMPLIANCE. However, Frandsen also proposes an alternative view angle estimate ‘Variable’, which depends on spacing, x, in RD via: $\theta = \text{atan}(1/x) + 10°$. Between typical spacings of 4 and 5 RD spacing the two options produce very similar results. For spacings less than 3 RD the variable option results in larger view angles (wake widths), and thus in higher loads, which is likely more realistic.

Large wind farm correction

A fourth and additional component in the Frandsen model is a large wind farm correction which accounts for extra added turbulence levels inside very large wind farms. The original specification of the correction assumes a regular layout not generally applicable to the real world, but this has been generalized in [15]. Our implementation is in line with this generalization; It assess the need for large wind farm correction for each sector and adjusts ambient turbulence levels as requested in the standard. Only the number of neighbour WTGs in the sector decides if a sector is large wind farm or not.

Sector management

There are two options for sector management: the 1) *Simple sector curtailment* and 2) *Advanced sector curtailment*. Option one is described below and can be selected in the calculation without any prerequisites. Option two, described in section 5.2.1.11 Curtailment, requires curtailment rules to be defined directly on the relevant WTG objects and that *Curtailment* has been selected on the SITE COMPLIANCE main tab.

The simple curtailment option allows definition of a distance threshold in rotor diameters (RD), e.g., 3 RD. In the calculation, all wake effects from neighbour WTGs within the set distance for a particular direction will be excluded, assuming, therefore, that those WTGs have been shut down.

This implementation makes it very easy to assess the effect of most manufacturers’ standard requirement of shutting WTGs down in directions where distances are below 3 RD.

Sector management

☐ Simple sector curtailment Exclude WTG wakes within R< 0.0 Rotor diameters ☐ Advanced sector curtailment

Figure 58. Selection of sector management. Note that Advanced sector curtailment is not selectable, as this option is selected on the SITE COMPLIANCE main tab.

5.2.2.4 Wind distribution

Description and limit

The Wind distribution check evaluates the frequency of occurrence at different wind speeds for each WTG by comparing them to the frequency of occurrence assumed in the IEC design limit.

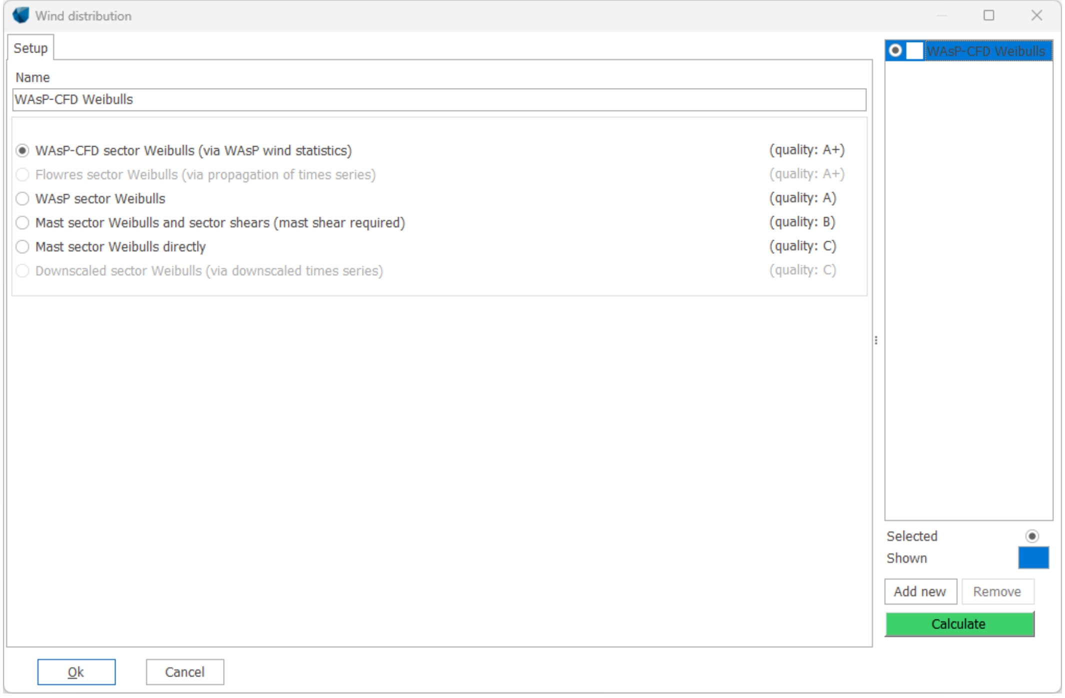
The IEC design limit for the Wind distribution check is a Weibull distribution with a shape factor of k=2. The mean wind speed is defined as 20% of the basic design parameter V_{ref} from Table 1 (see section 5.1.1) which is 10m/s, 8.5m/s and 7.5m/s for the wind speed classes I, II and III, respectively. A range of wind speeds ranging from 20% to 40% of V_{ref} must be checked, i.e. from the mean wind speed to twice the mean wind speed of each WTG class.

In the IEC standard, it is required that the wind distribution estimated for each WTG is long-term representative. Hence, an evaluation of the long-term level and possibly a long-term correction is required. This may be handled in three ways in SITE COMPLIANCE.

1) The first and typical way is by basing the WAsP calculation on a long-term corrected wind statistics saved from windPRO’s MCP module by choosing this WAsP-option in the *Main* setup tab of SITE COMPLIANCE.
2) The second option is to use the mast data directly (either in a WAsP calculation or without) and utilize the simple (MCP supplement) long-term index correction for wind speeds available in SITE COMPLIANCE (see section 5.2.4).
3) The third option is that the data are evaluated to be long-term representative in their own right, and no long-term correction is applied. The last option is not uncommon with around three or more years of site data.

Setup, Calculation and Results

The following text describes the workflow in setting up, calculating and reviewing the results of a typical Wind distribution calculation. The setup of this check is quite simple with few options as illustrated in the figure below showing the *Setup* tab.



Wind distribution

Setup

Name: WAsP-CFD Weibulls

● WAsP-CFD sector Weibulls (via WAsP wind statistics) (quality: A+)
○ Flowres sector Weibulls (via propagation of times series) (quality: A+)
○ WAsP sector Weibulls (quality: A)
○ Mast sector Weibulls and sector shears (mast shear required) (quality: B)
○ Mast sector Weibulls directly (quality: C)
○ Downscaled sector Weibulls (via downscaled times series) (quality: C)

● ☐ WAsP-CFD Weibulls

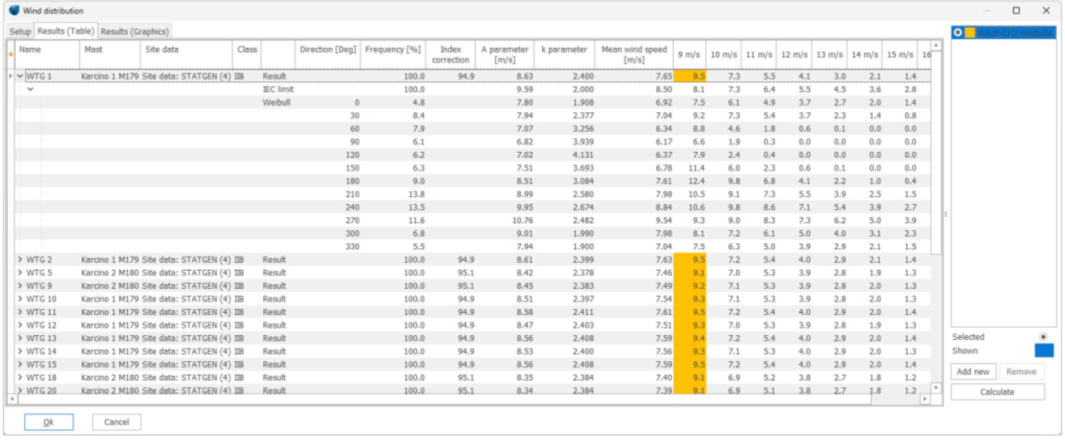
Selected ●
Shown 🟦

Figure 59. Setup tab of the Wind distribution check.

In most cases, a WAsP calculation has been run and using these results predicted at each WTG will then be the default option. In the shown case, a WAsP-CFD calculation has also been performed which then takes preference as default.

The *Results (Table)* summarizes the results for all relevant wind speed bins for each WTG. Bins are highlighted if the frequency within that bin exceeds the IEC limit. If the overall exceedance for the WTG is evaluated to be critical the highlighting is red or if it is only evaluated to be *Caution* highlighting is yellow.

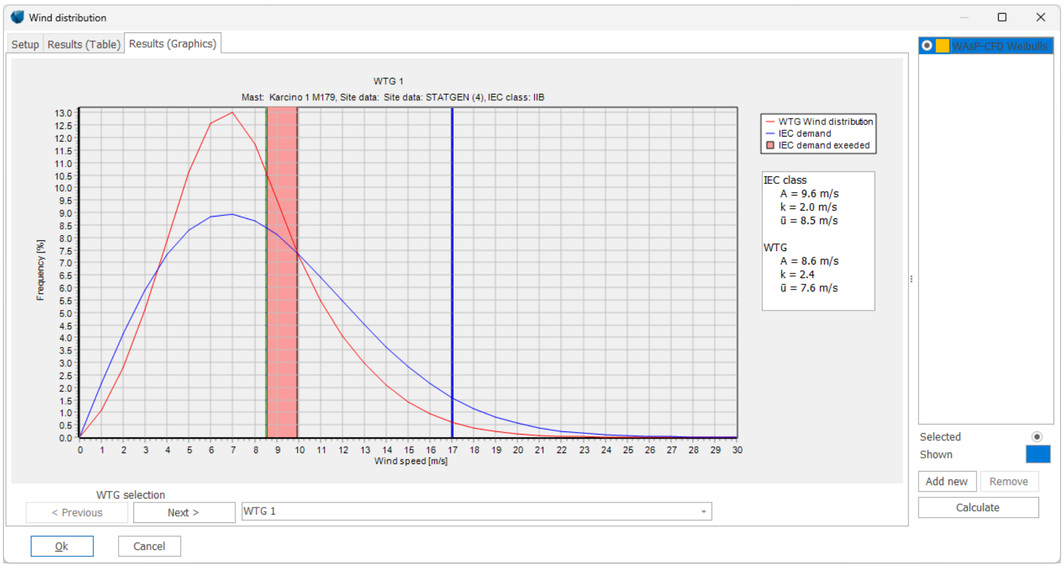
First row for each WTG shows the frequencies of occurrence in each bin predicted for the WTG. Second row shows the IEC limit, i.e., the frequencies of the relevant IEC class. If the sub-levels are expanded, the sector-wise frequencies for the predicted WTG climate are presented.



Name	Mast	Site data	Class		Direction [Deg]	Frequency [%]	Index correction	A parameter [m/s]	k parameter	Mean wind speed [m/s]	9 m/s	10 m/s	11 m/s	12 m/s	13 m/s	14 m/s	15 m/s
WTG 1	Karcino 1 M179	Site data: STATGEN (4)	IIB	Result		100.0	94.9	8.63	2.400	7.65	9.5	7.3	5.5	4.1	3.0	2.1	1.4
				IEC limit		100.0		9.59	2.000	8.50	8.1	7.3	6.4	5.5	4.5	3.6	2.8
				Weibull	0	4.8		7.80	1.908	6.92	7.5	6.1	4.9	3.7	2.7	2.0	1.4
					30	8.4		7.94	2.377	7.04	9.2	7.3	5.4	3.7	2.3	1.4	0.8
					60	7.9		7.07	3.256	6.34	8.8	4.6	1.8	0.6	0.1	0.0	0.0
					90	6.1		6.82	3.939	6.17	6.6	1.9	0.3	0.0	0.0	0.0	0.0
					120	6.2		7.02	4.131	6.37	7.9	2.4	0.4	0.0	0.0	0.0	0.0
					150	6.3		7.51	3.693	6.78	11.4	6.0	2.3	0.6	0.1	0.0	0.0
					180	9.0		8.51	3.084	7.61	12.4	9.8	6.8	4.1	2.2	1.0	0.4
					210	13.8		8.99	2.580	7.98	10.5	9.1	7.3	5.5	3.9	2.5	1.5
					240	13.5		9.95	2.674	8.84	10.6	9.8	8.6	7.1	5.4	3.9	2.7
					270	11.6		10.76	2.482	9.54	9.3	9.0	8.3	7.3	6.2	5.0	3.9
					300	6.8		9.01	1.990	7.98	8.1	7.2	6.1	5.0	4.0	3.1	2.3
					330	5.5		7.94	1.900	7.04	7.5	6.3	5.0	3.9	2.9	2.1	1.5
WTG 2	Karcino 1 M179	Site data: STATGEN (4)	IIB	Result		100.0	94.9	8.61	2.399	7.63	9.5	7.2	5.4	4.0	2.9	2.1	1.4
WTG 5	Karcino 2 M180	Site data: STATGEN (4)	IIB	Result		100.0	95.1	8.42	2.378	7.46	9.1	7.0	5.3	3.9	2.8	1.9	1.3
WTG 9	Karcino 2 M180	Site data: STATGEN (4)	IIB	Result		100.0	95.1	8.45	2.383	7.49	9.2	7.1	5.3	3.9	2.8	2.0	1.3
WTG 10	Karcino 1 M179	Site data: STATGEN (4)	IIB	Result		100.0	94.9	8.51	2.397	7.54	9.3	7.1	5.3	3.9	2.8	2.0	1.3
WTG 11	Karcino 1 M179	Site data: STATGEN (4)	IIB	Result		100.0	94.9	8.58	2.411	7.61	9.5	7.2	5.4	4.0	2.9	2.0	1.4
WTG 12	Karcino 1 M179	Site data: STATGEN (4)	IIB	Result		100.0	94.9	8.47	2.403	7.51	9.3	7.0	5.3	3.9	2.8	1.9	1.3
WTG 13	Karcino 1 M179	Site data: STATGEN (4)	IIB	Result		100.0	94.9	8.56	2.408	7.59	9.4	7.2	5.4	4.0	2.9	2.0	1.4
WTG 14	Karcino 1 M179	Site data: STATGEN (4)	IIB	Result		100.0	94.9	8.53	2.400	7.56	9.3	7.1	5.3	4.0	2.9	2.0	1.3
WTG 15	Karcino 1 M179	Site data: STATGEN (4)	IIB	Result		100.0	94.9	8.56	2.408	7.59	9.5	7.2	5.4	4.0	2.9	2.0	1.4
WTG 18	Karcino 2 M180	Site data: STATGEN (4)	IIB	Result		100.0	95.1	8.35	2.384	7.40	9.1	6.9	5.2	3.8	2.7	1.8	1.2
WTG 20	Karcino 2 M180	Site data: STATGEN (4)	IIB	Result		100.0	95.1	8.34	2.384	7.39	9.1	6.9	5.1	3.8	2.7	1.8	1.2

Figure 60. Results (Table) tab of the Wind distribution check.

On the *Results (Graphics)* tab the WTG probability density function (frequencies of occurrence in each wind speed bin) is graphically compared to that for the IEC class. The IEC wind speed check interval is highlighted by the blue vertical lines, and any exceedance is highlighted by a light red box covering the exceeded interval. Results for *Next* or *Previous* WTG and are viewed using the *WTG selection* buttons to the lower left.



IEC class
A = 9.6 m/s
k = 2.0 m/s
ū = 8.5 m/s

WTG
A = 8.6 m/s
k = 2.4
ū = 7.6 m/s

Figure 61. Results (Graphics) tab for the Wind distribution check.

Calculation options

There are only a few calculation options for the Wind distribution check with the most common being the WAsP-CFD sector Weibulls or WAsP sector Weibulls. The two other options should only be used where the mast position is truly representative for the WTG positions.
It is well known that the WAsP model has limitations in very steep or complex terrain where it may over-estimate the terrain speed-up factor considerably. If the mast position is representative of the WTGs, this should not pose a major problem.

WAsP-CFD sector Weibulls

With this setup, the sector-wise predicted Weibull distributions from WAsP-CFD are used. The so-called Emergent wind speed distribution (WAsP nomenclature) is used in the actual IEC check. It is simply the sector-wise Weibull distributions weighted by their sector frequency and summed to form the omni-directional distribution of wind speeds. The resulting distribution is generally not a Weibull itself and hence may exhibit bi- or multi-modality (i.e., multiple maxima). Finally, the Emergent distribution is compared against the IEC design limit for the wind speed bins required by the IEC standard.

Flowres sector Weibulls

With this setup, the sector-wise Weibulls distribution is calculated by transferring the measured time series from each mast and main height to the relevant WTG positions at hub height using the Flowres flow simulation results. Once transferred, the time series are binned and sectorwise Weibull distributions are fitted. As the Flowres results typically represent neutral stability, it is recommended to use this option with measurements close to hub height. If measurements are much lower than hub height it is recommended first to use the shear extrapolation option “Add synthesized height” in the meteo object Data/Data setup tab to establish a time series at or close to hub height at the mast position.

WAsP sector Weibulls

As described above but using the standard WAsP flow model.

Mast sector Weibulls and sector shears (mast shear required)

Basing the vertical extrapolation on shear measured on the mast relies on the assumption that wind shear is constant with height, which is certainly not the case in areas with strong terrain speed-up effects. It also relies on the assumption that horizontal variations of the wind distribution are negligible.

If no WAsP calculation/license is available, this calculation option may be used if the mast position is considered to be representative of the WTG positions. The calculation will use the fitted sector-wise Weibull parameters for the main height of each mast. The Weibull A parameter for each sector is then scaled from mast main height to WTG hub height using the corresponding sector shear exponents estimated for the mast shear heights. Finally, the Emergent distribution is formed by summing the scaled sector Weibull parameters, weighting them by the sector frequencies.

Mast Weibulls directly

In this option, the Emergent distribution is calculated directly from the mast sector-wise Weibull parameters. This is only advisable if the mast is representative for the WTG positions, both in terms horizontal variations and in terms elevation above ground (i.e. mast main height ≈ hub height).

5.2.2.5 Flow inclination

The Flow inclination check predicts the flow inclination in each sector and identifies the sector with the highest absolute (positive or negative) flow inclination for each WTG. The resulting flow inclinations are compared against the IEC design limit for each WTG.

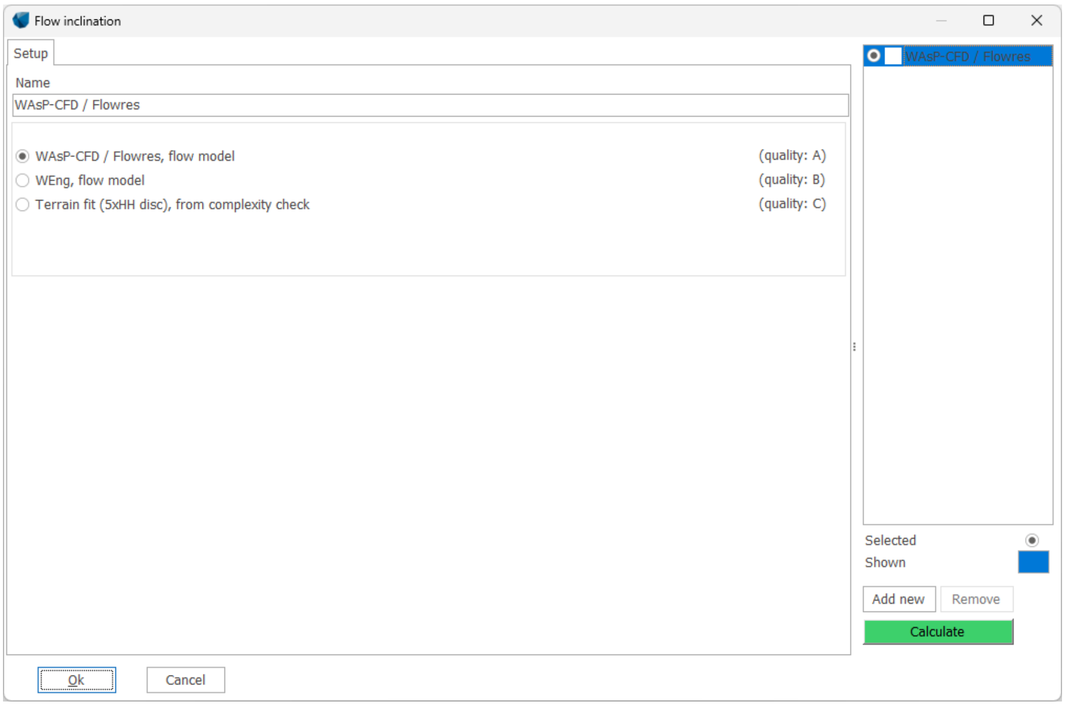
Description and limit

The IEC design limit for the Flow inclination check are flow inclinations of +8° and -8° for the worst direction. Thus, flow inclinations above +8° or below -8° exceed this limit.

The IEC standard mentions that the slope the smallest of the terrain fits (5xHH) required in the Terrain complexity check may be used as an estimate of the flow inclination. We allow this option in SITE COMPLIANCE, and note that, generally, the resulting estimates are not too different from more advanced estimates obtained using flow models.

Setup, Calculation and Results

The following text describes the workflow in setting up, calculating and reviewing the results of a typical Flow inclination calculation. Setup of this check is quite simple with only two options, as illustrated in the figure below showing the *Setup* tab.



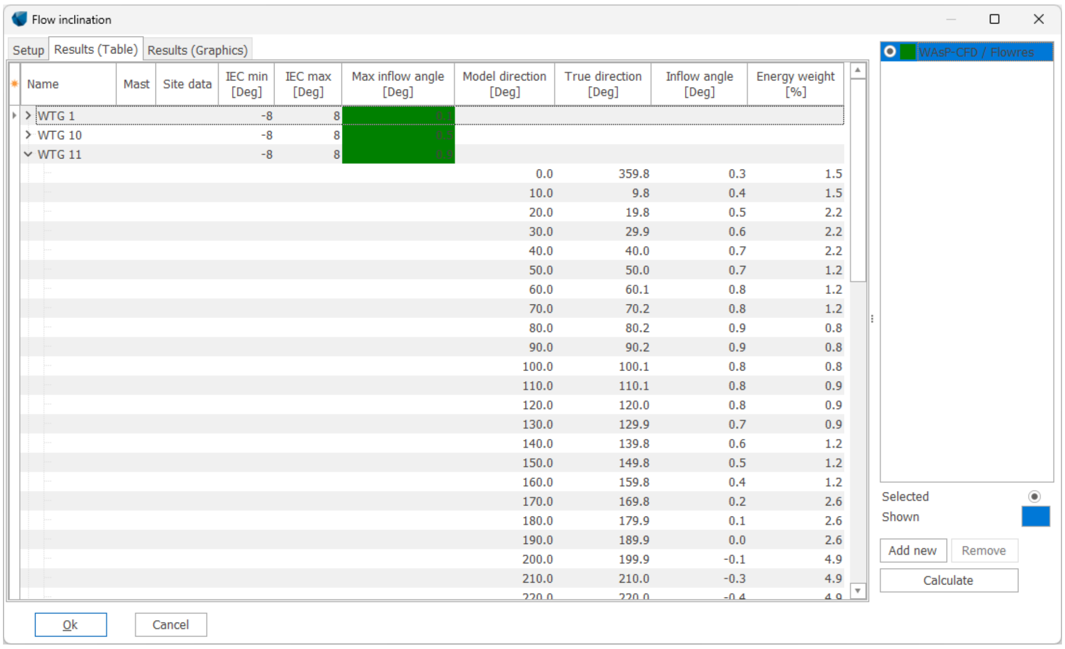
Name: WAsP-CFD / Flowres

- ● WAsP-CFD / Flowres, flow model (quality: A)
- ○ WEng, flow model (quality: B)
- ○ Terrain fit (5xHH disc), from complexity check (quality: C)

Figure 62. Setup tab of the Flow Inclination check.

In cases where WAsP-CFD flow results are available and has been run, the WAsP-CFD flow inclination estimate for each WTG is the default option. Alternatively, WEng flow results or the terrain complexity check may be used.

The *Results (Table)* summarizes the result, i.e., the maximum flow inclination for each WTG and the direction (sector median) in which it occurs. If the table is expanded, the flow inclination for each model sector is shown. The expansion with sector-values is not available for the calculation *Terrain fit (5xHH disc), from complexity check*, as sector-wise results are not available for this calculation.



Name	Mast	Site data	IEC min [Deg]	IEC max [Deg]	Max inflow angle [Deg]	Model direction [Deg]	True direction [Deg]	Inflow angle [Deg]	Energy weight [%]
WTG 1			-8	8	0.1				
WTG 10			-8	8	0.5				
WTG 11			-8	8	0.9				
						0.0	359.8	0.3	1.5
						10.0	9.8	0.4	1.5
						20.0	19.8	0.5	2.2
						30.0	29.9	0.6	2.2
						40.0	40.0	0.7	2.2
						50.0	50.0	0.7	1.2
						60.0	60.1	0.8	1.2
						70.0	70.2	0.8	1.2
						80.0	80.2	0.9	0.8
						90.0	90.2	0.9	0.8
						100.0	100.1	0.8	0.8
						110.0	110.1	0.8	0.9
						120.0	120.0	0.8	0.9
						130.0	129.9	0.7	0.9
						140.0	139.8	0.6	1.2
						150.0	149.8	0.5	1.2
						160.0	159.8	0.4	1.2
						170.0	169.8	0.2	2.6
						180.0	179.9	0.1	2.6
						190.0	189.9	0.0	2.6
						200.0	199.9	-0.1	4.9
						210.0	210.0	-0.3	4.9
						220.0	220.0	-0.4	4.9

Figure 63. Results (Table) tab of the Flow inclination check.

On the *Results (Graphics)* tab the results (i.e., max flow inclination) are summarized for all WTGs. IEC design limits at ±8° are shown as the horizontal blue lines.

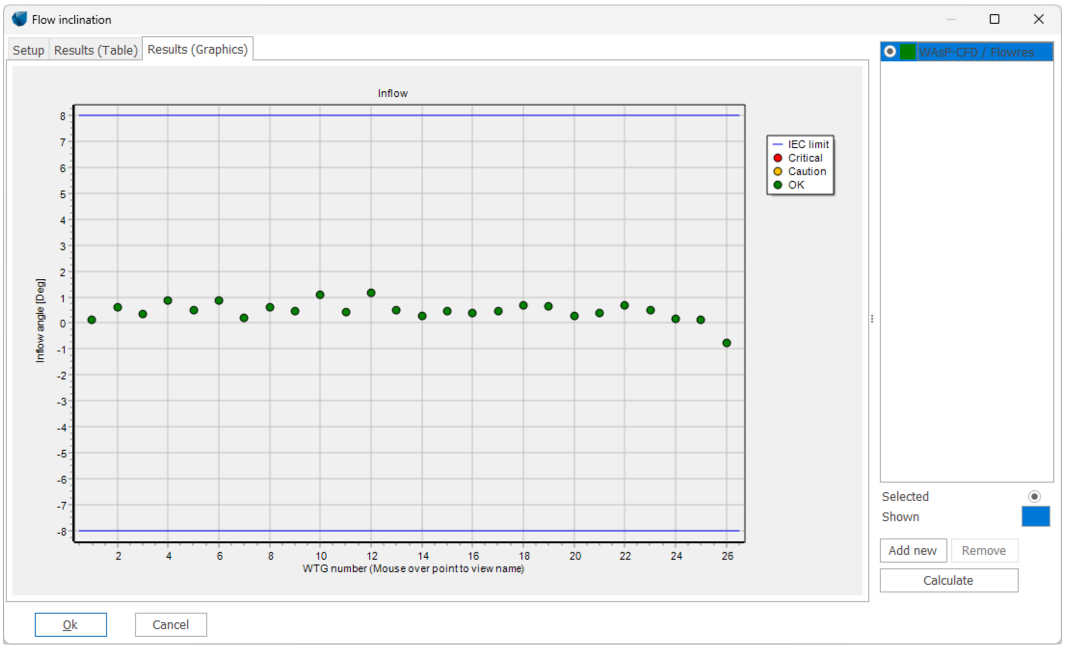


Figure 64. Results (Graphics) tab for the Flow inclination check.

Calculation Options

The following describes the calculation options for the Flow inclination check.

WAsP-CFD / Flowres, flow model

Using this option, flow inclination is extracted directly from the raw WAsP-CFD flow results, which is always run for 36 model directions. WAsP-CFD is the most accurate method for complex terrain sites.

WEng, flow model

WEng is a broadly accepted and used flow model suited for engineering calculations like flow inclination. The advanced setup of the WEng calculation determines the number of sectors in the WEng calculation with a default of 12 sectors. A finer resolution of the inflow angle estimate may be obtained by increasing the number of sectors in the WEng calculation. As a linearized flow model WEng has a tendency to over-estimate inflow angles in steep and complex terrain.

Terrain fitting (5xHH disc) from complexity check

See the section 5.3.1 describing the Terrain complexity check for further details of the terrain fit. Again, it is important to stress that this option is mentioned as acceptable in the IEC standard.

5.2.2.6 Wind shear

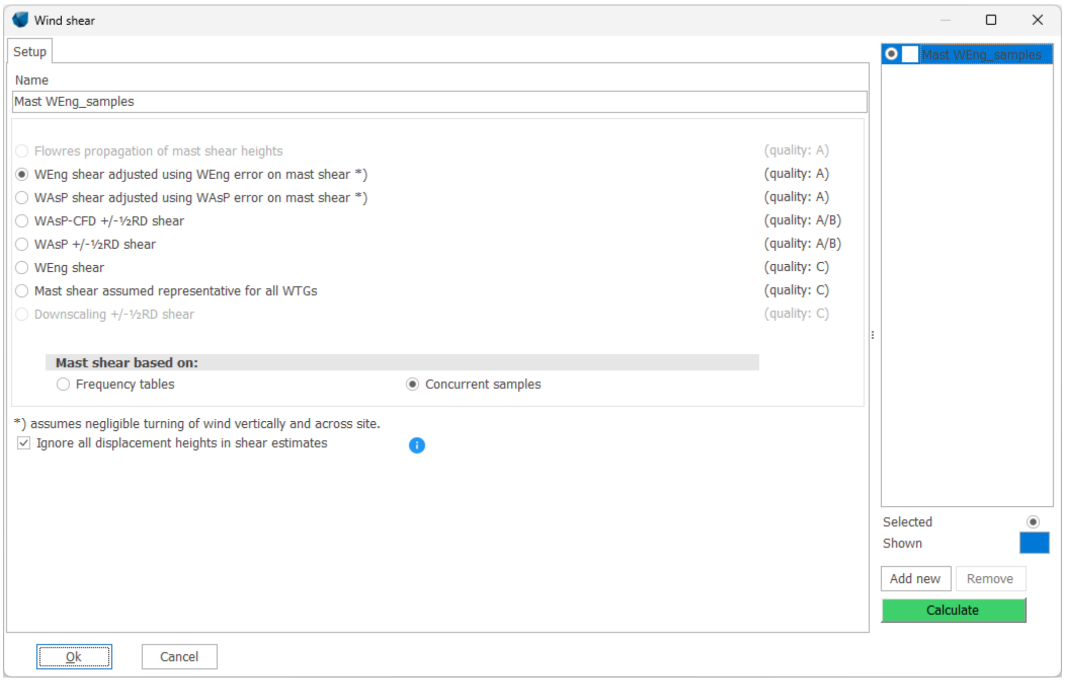
Description and limit

The Wind shear check evaluates the vertical wind shear or, in other words, the vertical variation of wind speed across the rotor for each WTG position. Wind shear is quantified by means of the wind shear power law exponent, α. The IEC design limits for wind shear is an average wind shear above 0 but less than 0.2 for all design classes.

The IEC standard is not clear regarding “the average shear” as it may refer to the shear exponent of the omni-directional mean wind profile or to the average of the sector-wise shear exponents. Since the shear calculation is non-linear (it is based on a log-log fit), these two estimates generally differ - but not drastically. In Section 11.3 of the Standard [1] it is mentioned that the shear must be estimated for at least 30° direction sectors. In SITE COMPLIANCE the shear average is taken to be the weighted average shear of the sector-wise shear exponents. A reason for this is that it enables more detailed adjustments to the sector-wise shear estimates. This interpretation of “average shear” is consistent with the approach adopted in the Risø/DTU WAT tool [15].

Setup, Calculation and Results

There are seven options to select between for the Wind shear check, as illustrated in the *Setup* tab below. The two upper options seek to combine mast measurements of shear with flow predictions to improve the estimation. The next three options are based purely on flow modelling results and the last option is based purely on measurements. From version 3.2 there is also a general option for the methods based on measured shear, to based the shear estimates on the *Frequency tables* in the meteo object (original option) or to base it on *Concurrent samples* (new option), which is more robust for errors in directions across measuring heights.



Wind shear

Setup

Name: Mast WEng_samples

○ Flowres propagation of mast shear heights (quality: A)
● WEng shear adjusted using WEng error on mast shear *) (quality: A)
○ WAsP shear adjusted using WAsP error on mast shear *) (quality: A)
○ WAsP-CFD +/-½RD shear (quality: A/B)
○ WAsP +/-½RD shear (quality: A/B)
○ WEng shear (quality: C)
○ Mast shear assumed representative for all WTGs (quality: C)
○ Downscaling +/-½RD shear (quality: C)

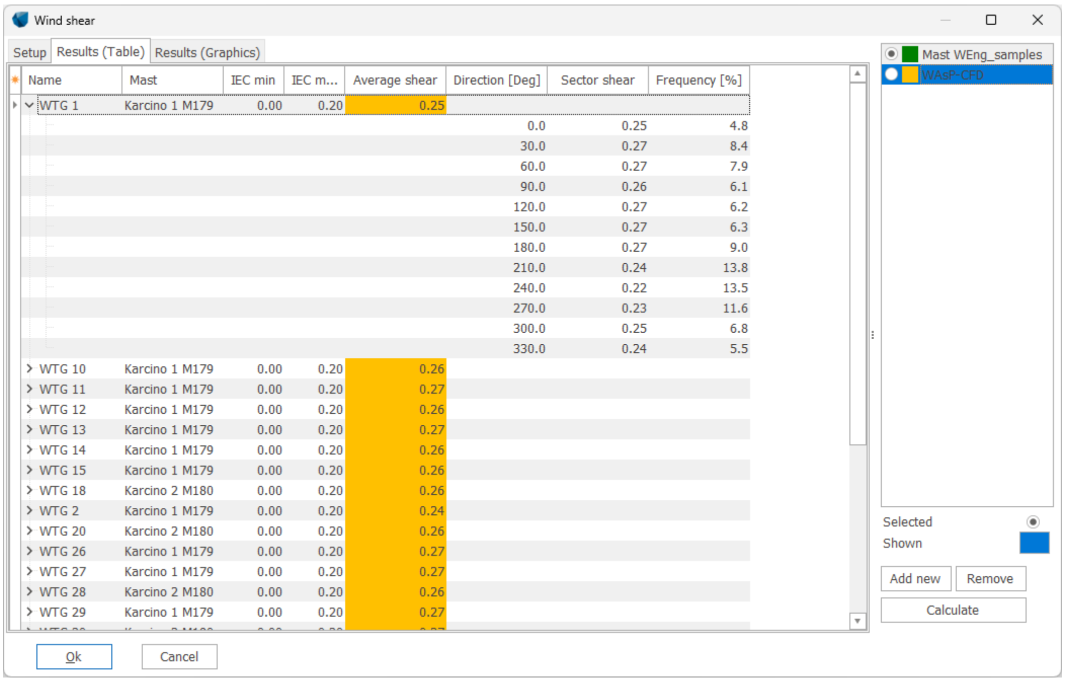
Mast shear based on:
○ Frequency tables ● Concurrent samples

*) assumes negligible turning of wind vertically and across site.
☑ Ignore all displacement heights in shear estimates

● Mast WEng_samples

Figure 65. Setup tab of the Wind shear check.

The *Results (Table)* tab for Wind shear shows the IEC high and low design limits and the wind shear estimate for each WTG. If the table is expanded for a particular WTG, the sector-wise shear estimates and their frequency are presented.



Wind shear

Setup | Results (Table) | Results (Graphics)

Name	Mast	IEC min	IEC m...	Average shear	Direction [Deg]	Sector shear	Frequency [%]
WTG 1	Karcino 1 M179	0.00	0.20	0.25			
					0.0	0.25	4.8
					30.0	0.27	8.4
					60.0	0.27	7.9
					90.0	0.26	6.1
					120.0	0.27	6.2
					150.0	0.27	6.3
					180.0	0.27	9.0
					210.0	0.24	13.8
					240.0	0.22	13.5
					270.0	0.23	11.6
					300.0	0.25	6.8
					330.0	0.24	5.5
WTG 10	Karcino 1 M179	0.00	0.20	0.26			
WTG 11	Karcino 1 M179	0.00	0.20	0.27			
WTG 12	Karcino 1 M179	0.00	0.20	0.26			
WTG 13	Karcino 1 M179	0.00	0.20	0.27			
WTG 14	Karcino 1 M179	0.00	0.20	0.26			
WTG 15	Karcino 1 M179	0.00	0.20	0.26			
WTG 18	Karcino 2 M180	0.00	0.20	0.26			
WTG 2	Karcino 1 M179	0.00	0.20	0.24			
WTG 20	Karcino 2 M180	0.00	0.20	0.26			
WTG 26	Karcino 1 M179	0.00	0.20	0.27			
WTG 27	Karcino 1 M179	0.00	0.20	0.27			
WTG 28	Karcino 2 M180	0.00	0.20	0.26			
WTG 29	Karcino 1 M179	0.00	0.20	0.27			

● Mast WEng_samples
○ WAsP-CFD

Figure 66. Results (Table) tab of the Wind shear check.

Finally, the *Results (Graphics)* presents the overview of all the WTG results with the IEC limits highlighted as blue lines.

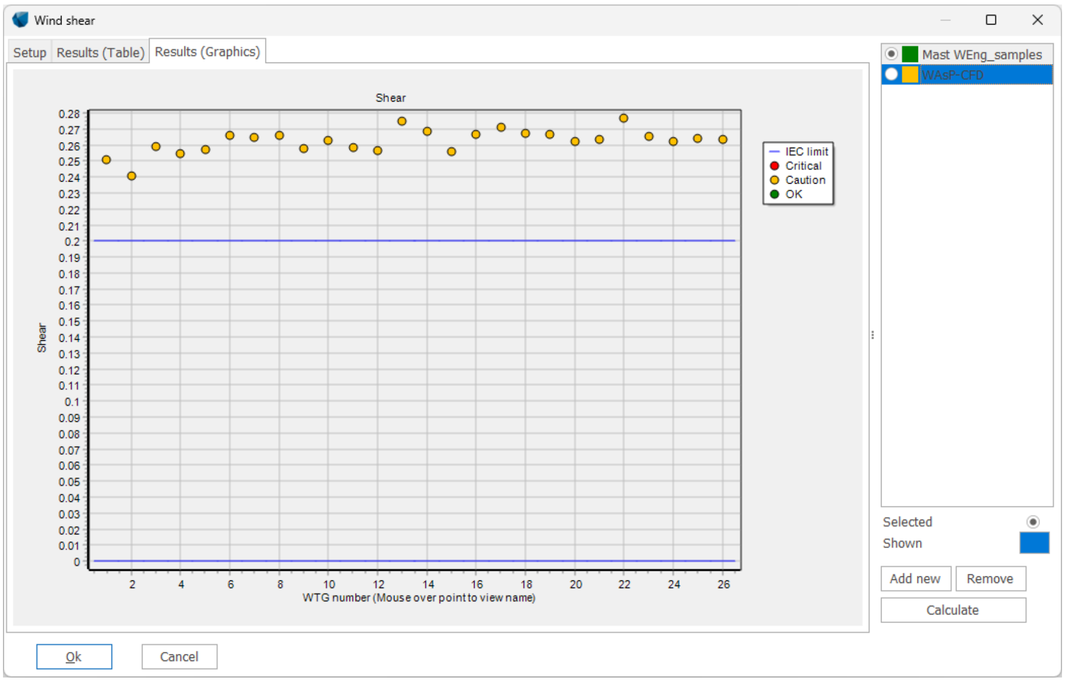
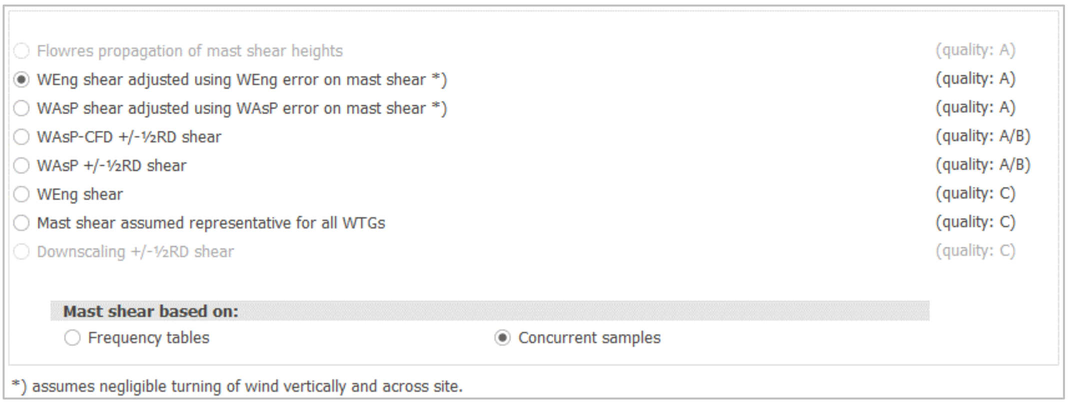


Figure 67. Results (Graphics) tab for the Wind shear check.

Calculation Options

The following text describes the detailed calculation options of the Wind shear check and their main assumptions. The figure below shows the options.



○ Flowres propagation of mast shear heights	(quality: A)
● WEng shear adjusted using WEng error on mast shear *)	(quality: A)
○ WAsP shear adjusted using WAsP error on mast shear *)	(quality: A)
○ WAsP-CFD +/-½RD shear	(quality: A/B)
○ WAsP +/-½RD shear	(quality: A/B)
○ WEng shear	(quality: C)
○ Mast shear assumed representative for all WTGs	(quality: C)
○ Downscaling +/-½RD shear	(quality: C)

Mast shear based on:

○ Frequency tables ● Concurrent samples

*) assumes negligible turning of wind vertically and across site.

Figure 68. Calculation options in the Wind shear check.

Flowres propagation of mast shear heights

In this option, the selected Shear heights on each mast are transferred as time series to the same heights on the relevant WTG positions, and, then, the sectorwise wind shears are estimated based on these heights. This approach ensures that the stability information in the profile measurements is retained and only the effects of roughness and terrain variations on the profile are accounted for. It is recommended to use this option with measurements close to hub height where the shear heights cover a significant part of the rotor to ensure that the shear estimates are represent the rotor area.

WEng shear adjusted using WEng error on mast shear

The sector-wise shear estimates based directly on WEng results are usually quite biased to the low side as WEng assumes neutral stability. This bias may be estimated for each sector of the mast and applied as a correction to the WEng shear estimated for each sector at the WTG positions. After applying the bias-correction, the corrected sector-wise shear exponents are averaged using the sector frequencies for the turbine position to obtain the final average shear estimate.

This method seeks to combine the best from measurements with the best from the flow modelling. Measurements accurately represent the shear at a single position, namely the mast, but may not be representative for the site as such. Flow modelling has its strength in resolving the relative variation of shear across the site, although generally with a constant bias, which may be considerable.

The method relies on the assumption that wind does not turn significantly across the site or vertically, i.e,. flow conditions in one sector at the mast are assumed not to have turned significantly when they reach the WTG positions. The larger the sector width the better this assumption is. Turning across a site and vertically is usually much less than the 30° of standard sectors, however, in very complex terrain turning may be very significant. It is also important to validate that all direction sensors used on a mast are consistent, because such errors might mess up this calculation option considerably.

WAsP shear adjusted using WAsP error on mast shear

This method is similar to the adjusted WEng method described above. The only difference is that the relative variation of shear is extracted from the results of WAsP flow modelling. The WAsP profile is quite different from the WEng profile as WAsP has a built-in stability model that has a very strong effect on the predicted profiles.

WAsP-CFD +/-½RD shear

As for WAsP, the default setup of WAsP-CFD includes modelling of wind conditions at HH and at HH+½RD and HH-½RD, which allows estimation of the shear across the rotor. The WAsP-CFD model combines the “raw” CFD based (Ellipsys model) flow perturbations with the WAsP modelling setup and stability model which only affects the wind profile. The WAsP stability is rather simplified and has a very strong influence of the wind shear. With default WAsP stability settings, WASP-CFD results are likely to result in conservative estimates of the wind shear.

The quality of this calculation option depends on how well the WAsP stability parameters have been adapted to match the observed profile at the site. The quality may be high if WAsP stability settings have been adjusted appropriately and the WAsP-CFD profile matches well with the observed profile at the mast position.

WAsP +/-½RD shear

The default setup of the WAsP calculation includes modelling of wind conditions at HH (hub height), but also at HH+½RD and HH-½RD, where RD is the rotor diameter. Having the flow conditions modelled at these three heights allows the estimation of the wind shear across the rotor for each sector and, hence, definition of the “average shear”.

The quality of this calculation option depends on how well the WAsP profile has been validated and adapted for the site. The quality may be high if WAsP stability settings have been adjusted appropriately and the WAsP profile matches well with the observed profile at the mast position.

In tropical and mid-latitudes, the WAsP profile using default stability settings tends to over-estimate wind shear. The reason is that WAsP defaults are calibrated using the measurements from Northern Europe.

WEng (WAsP engineering) shear

Flow results from WAsP Engineering include the derivatives of the flow field and bases the calculation of wind shear on these derivatives. Hence, the estimated shear represents the hub height exactly. However, as WEng assumes neutral stability, the wind shear is usually under-estimated significantly using WEng results. This method is not generally recommended. It is included to allow comparison with the more suitable estimation methods as it is not common to see that WEng shear is used directly.

Mast shear assumed representative for all WTGs

This calculation is only recommended if the mast is representative for all the WTG positions and for the WTG hub height, both in terms of terrain and roughness conditions.

Mast shear based on..

This is a general option for all the methods using measured shear at the mast(s). Shear estimates can be based either on the *Frequency tables* in the meteo object (original option) or be based on *Concurrent samples* (new option), which is more robust for errors in directions across measuring heights which relatively common.

Ignore all displacement heights in shear estimates.

This option is activated per default and included from windPRO version 3.3. The purpose is to prevent underestimating wind shear when displacement heights are used to predict the wind speed distributions. It is important to stress that this option will not affect the actual wind speeds predicted using the displacement heights, the option simply uses the un-displaced heights together with the predicted wind speeds (including any displacement effects) to get the “real” wind shear exponents relative to the true surface. If the displacement heights are used when calculating the actual shear exponents they will typically be significantly smaller as now the profile is described using two parameters. If such reduced shear exponents are used for load simulations in an aero-elastic model, first step is to simulate turbulent and sheared wind fields. If this model setup does not include displacement heights, but the input shear exponents are calculated using displacement heights the wind shear is significantly underestimated and most likely also the resulting aero-elastic loads.

5.2.2.7 Air density

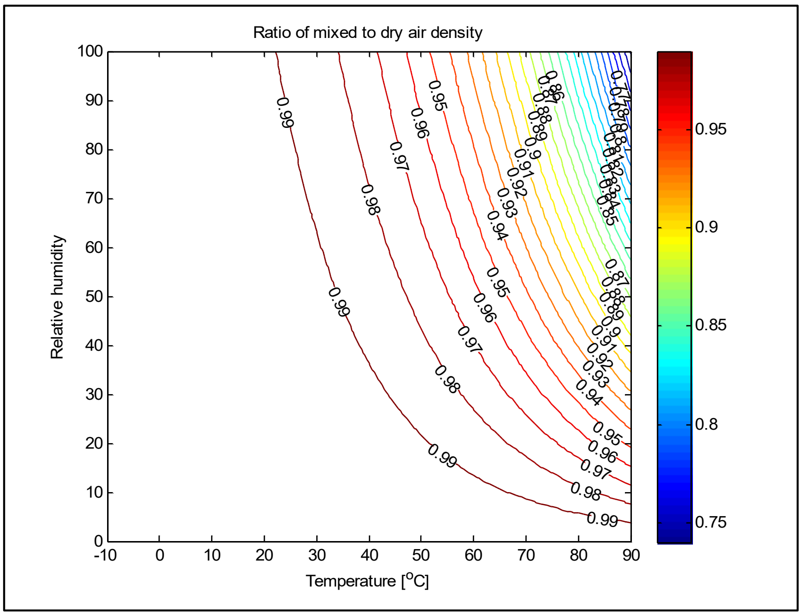
Description and limit

The IEC standard requires an assessment of the air density at hub height. The IEC design assumption for air density is 1.225 kg/m^3. Hence, air densities lower than this limit results in less loading on the WTG and vice versa.

In principle, the IEC standard requires the air density to be averaged only for wind speeds greater than the wind speed at rated power of the WTG. This adds a significant complexity to calculation of this check. However, a number of test cases have shown that the difference between the annual mean air density and the average for wind speeds above U_{rated} are usually within 1-2%. Considering the other uncertainties that affect air density estimates, this small difference is not considered significant. In addition, it is common practice among turbine manufacturers to use the annual mean air density instead. This practice has also been adopted in the SITE COMPLIANCE module.

The model adjustments of temperature (and pressure) from mast height amsl (above mean sea level) to WTG HH amsl are based on the ISO standard atmosphere as mentioned in the IEC standard.

Relative humidity is not an input as it only has a minor effect on air density. This is illustrated in the plot below. For relative humidity to have an effect on air density exceeding 2%, the mean air temperature must exceed 35°C and the mean humidity be close to 100% - it is worth noting that the highest annual mean temperature worldwide is 34°C (in Dalol, Ethiopia[9]). Hence, in most typical locations, the effect of relative humidity is well below 1%. In addition, including the effect of humidity decreases air density and, hence, the aerodynamic loads. Thus, excluding relative humidity is a slightly conservative assumption in regards to wind turbine loads.



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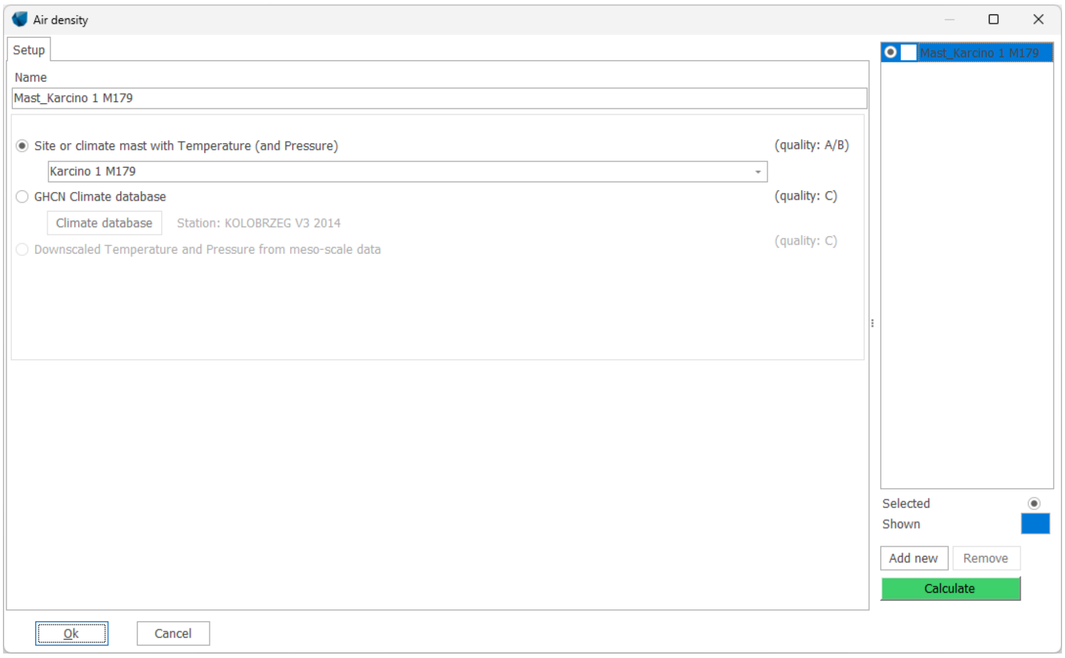
[9] http://www.weatherexplained.com/Vol-1/Record-Setting-Weather.html#b

Figure 69. Plot showing the relative effect on air density of varying mean temperature and relative humidity.

Setup, Calculation and Results

The *Setup* tab for the Air density check requires only the choice of the input data. If a site mast is available with temperature (and pressure, but not required), this option can be chosen. If there are more site masts with temperature, just one has to be chosen. Alternatively, mast, e.g., SYNOP or METAR, data may also be downloaded using the online data option in a Meteo Data Object. The mast must have temperature (and pressure) and have been defined as a *Climate mast* in the general SITE COMPLIANCE setup.

If there are no on-site measurements of temperature (and pressure), climate statistics from the Global Historical Climatological Network (GHCN) may be chosen. By default, this option will choose the nearest station. Sometimes a more distant station may be more appropriate if its elevation above sea level is more representative for the considered site. To review and choose other stations click the *Climate database* button.



Air density

Setup

Name: Mast_Karcino 1 M179

● Site or climate mast with Temperature (and Pressure) (quality: A/B)

Karcino 1 M179

○ GHCN Climate database (quality: C)

Climate database Station: KOLOBRZEG V3 2014

○ Downscaled Temperature and Pressure from meso-scale data (quality: C)

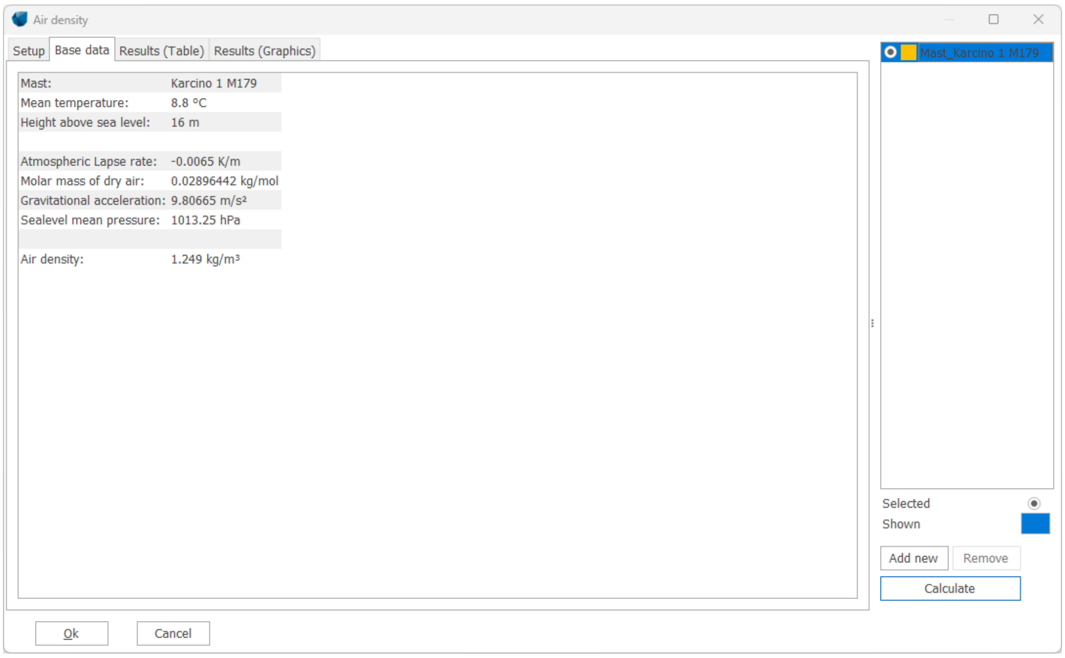
● Mast_Karcino 1 M179

Selected ●

Shown 🟦

Figure 70. Setup tab of the Air density check.

Once the calculation is run by clicking the green “Calculate” button, the results tabs are generated. The tab *Base data* summarizes the selected masts annual mean data and the measuring height above sea level. Below that, all the relevant atmospheric model parameters are listed and, at the end, the air density calculated directly for the mast data is shown.



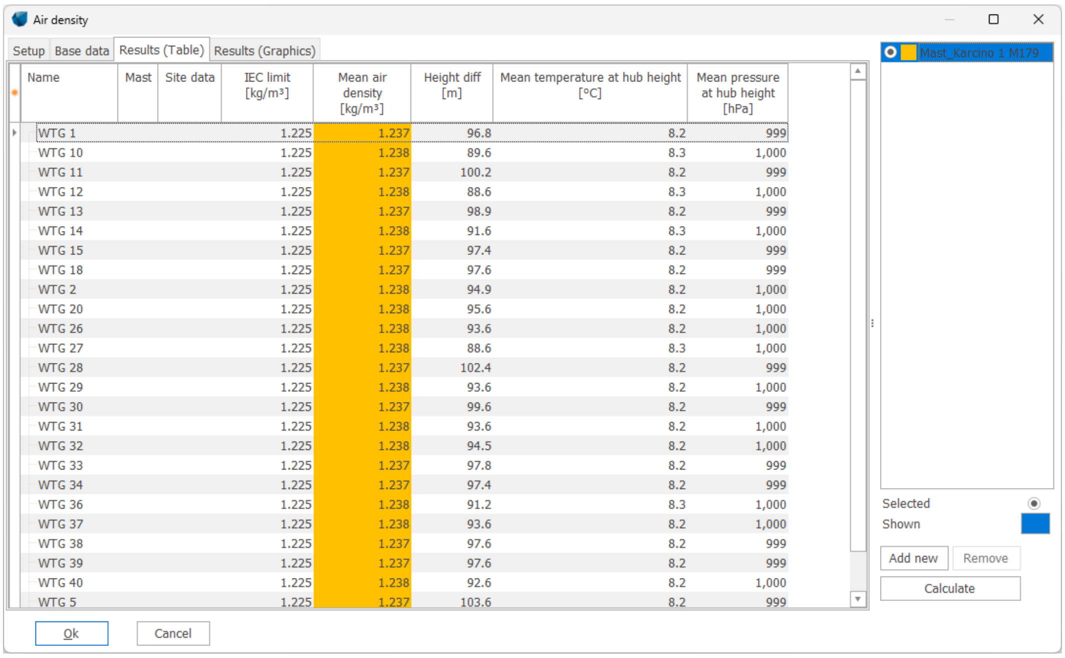
Mast: Karcino 1 M179
Mean temperature: 8.8 °C
Height above sea level: 16 m

Atmospheric Lapse rate: -0.0065 K/m
Molar mass of dry air: 0.02896442 kg/mol
Gravitational acceleration: 9.80665 m/s²
Sealevel mean pressure: 1013.25 hPa

Air density: 1.249 kg/m³

Figure 71. Base data tab of the Air density check.

The *Results (Table)* tab shows the resulting annual mean air density for each WTG. A column shows the height difference to the mast used and another coulumn the predicted annual mean temperature and pressure.



Name	Mast	Site data	IEC limit [kg/m³]	Mean air density [kg/m³]	Height diff [m]	Mean temperature at hub height [°C]	Mean pressure at hub height [hPa]
WTG 1			1.225	1.237	96.8	8.2	999
WTG 10			1.225	1.238	89.6	8.3	1,000
WTG 11			1.225	1.237	100.2	8.2	999
WTG 12			1.225	1.238	88.6	8.3	1,000
WTG 13			1.225	1.237	98.9	8.2	999
WTG 14			1.225	1.238	91.6	8.3	1,000
WTG 15			1.225	1.237	97.4	8.2	999
WTG 18			1.225	1.237	97.6	8.2	999
WTG 2			1.225	1.238	94.9	8.2	1,000
WTG 20			1.225	1.238	95.6	8.2	1,000
WTG 26			1.225	1.238	93.6	8.2	1,000
WTG 27			1.225	1.238	88.6	8.3	1,000
WTG 28			1.225	1.237	102.4	8.2	999
WTG 29			1.225	1.238	93.6	8.2	1,000
WTG 30			1.225	1.237	99.6	8.2	999
WTG 31			1.225	1.238	93.6	8.2	1,000
WTG 32			1.225	1.238	94.5	8.2	1,000
WTG 33			1.225	1.237	97.8	8.2	999
WTG 34			1.225	1.237	97.4	8.2	999
WTG 36			1.225	1.238	91.2	8.3	1,000
WTG 37			1.225	1.238	93.6	8.2	1,000
WTG 38			1.225	1.237	97.6	8.2	999
WTG 39			1.225	1.237	97.6	8.2	999
WTG 40			1.225	1.238	92.6	8.2	1,000
WTG 5			1.225	1.237	103.6	8.2	999

Figure 72. Results (Table) tab of the Air density check.

Finally, the tab *Results (Graphics)* provides the overview plot of all the WTG results and the IEC design limit.

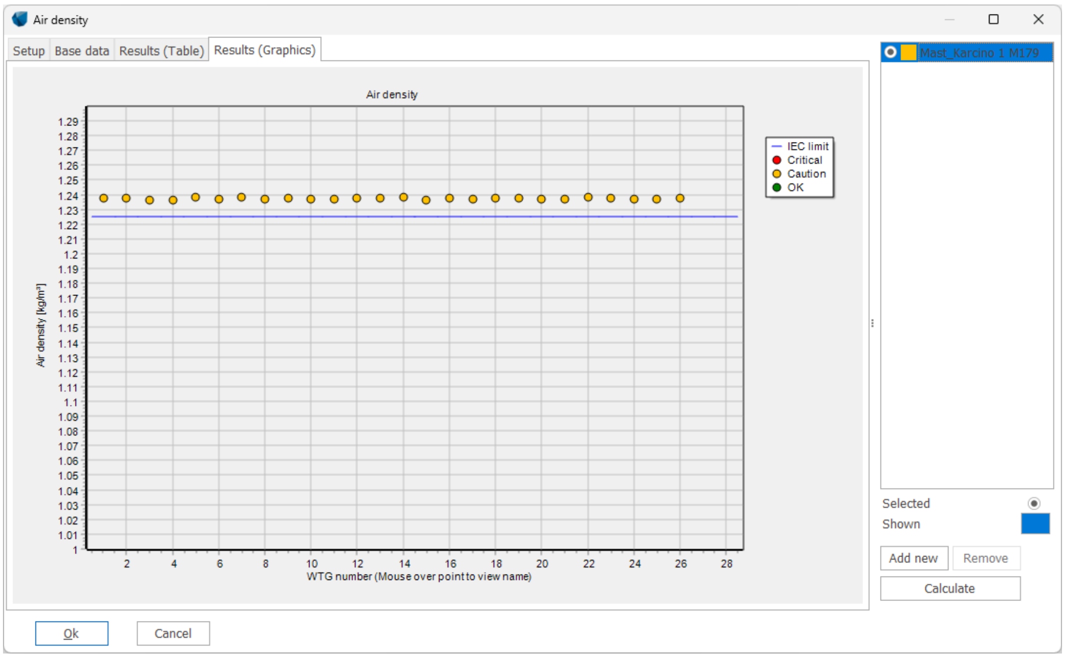


Figure 73. Results (Graphics) tab of the Air density check.

Calculation Options

For both calculation options, the same extrapolation model is used. It corrects the mean temperature using the standard temperature lapse rate of -0.0065 K/m from measuring height to WTG hub height. If pressure measurements are available too, these are corrected using the temperature difference as input and the hydrostatic equation. If no pressure data is available, the sea level pressure is corrected to WTG HH using the standard atmosphere model.

Site or climate mast with Temperature (and Pressure)

If temperature (and pressure) data are available for a site mast, the air density calculation may be based on these - as described above.

GHCN Climate database

GHCN is a database[10] maintained by the US institution NOAA (National Oceanic and Atmospheric Administration). The database contains historic climate statistics for a large number of stations worldwide.

5.2.3 IEC Checks - Other checks

The IEC standard [1] lists a number of *Other environmental conditions* to be assessed and compared with the design assumptions for the WTG. In addition, *Earthquake conditions* must be evaluated to assess if further actions in this regard are needed for the site. The list below summarizes these additional site parameters mentioned in the IEC standard.

- **Earthquake conditions (seismic hazard)**
- **Normal and extreme temperature ranges**
- **Lightning**
- Icing, hail and snow
- Humidity
- Solar radiation
- Chemically-active substances
- Salinity

In SITE COMPLIANCE, we have only included the additional parameters highlighted in bold above. The selection was based on a combination the possibility of allowing a meaningful estimation method and data source and the risk that a specific parameter is critical for a site.

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[10] http://www.ncdc.noaa.gov/ghcnm/

5.2.3.1 Seismic hazard

Description and limit

The IEC standard requires a site estimate of the peak ground acceleration (PGA) with a recurrence period of 475 years for the site area. This recurrence level is equivalent to an annual risk of exceedance of 0.2%. There is no explicit IEC limit for PGA, hence, the general hazard levels of GSHAP have been adopted in SITE COMPLIANCE. “Low hazard” results in *OK*, “Moderate hazard” in *Caution*, and “High” and “Very high hazard” results in *Critical*, emphacizing the need for futher and detailed investigation of seismic loads.

For the PGA site estimate, SITE COMPLIANCE uses a database which results from the UN funded Global Seismic Hazard Assessment program (GSHAP). GSHAP database is compiled from several regional and national sub-projects and summarizes the PGA in m/s^2 at a resolution of 0.1° by 0.1°. The GSHAP data is available via the ETHZ or GeoForschungsZentrum Potsdam homepages. The figure below illustrates the global GSHAP seismic hazard map.

The PGA mapped in GSHAP refers to standard soil conditions which is rock (rock/firm soil in US/Canada). As a consequence very special local conditions which differ significantly from this like a deep and soft sedimentary setting may amplify ground motions significantly, making conditions more severe than mapped in GSHAP. Nevertheless, GSHAP is considered a reliable source of seismic hazard (in terms of PGA) as it compiles numerous local and regional studies made by local experts and authorities.

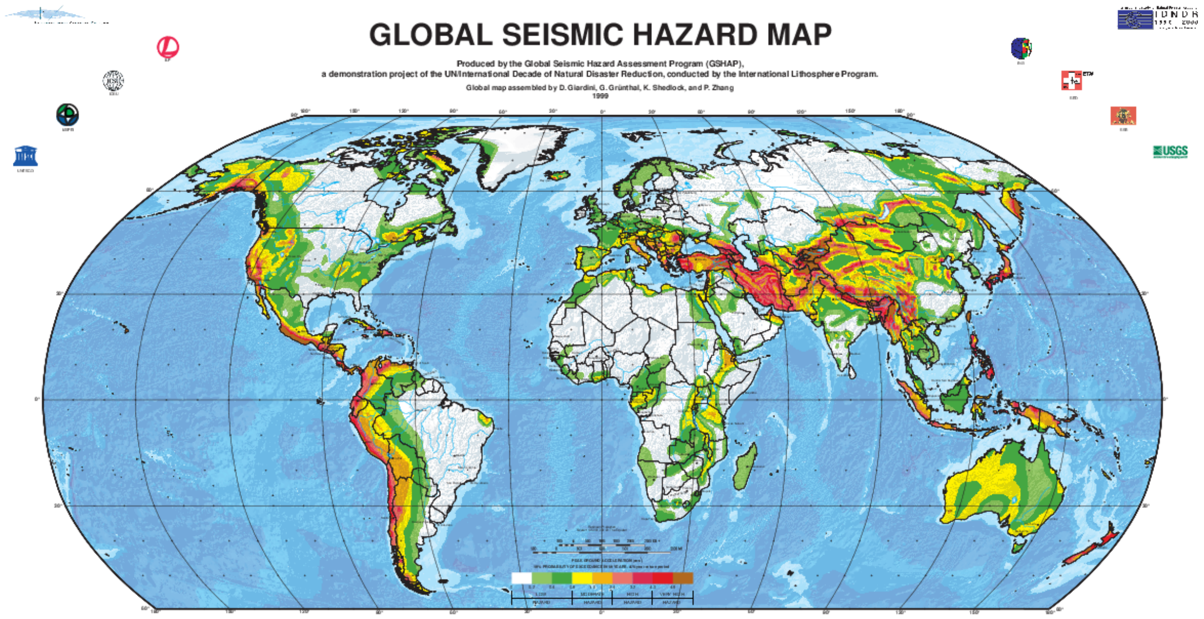
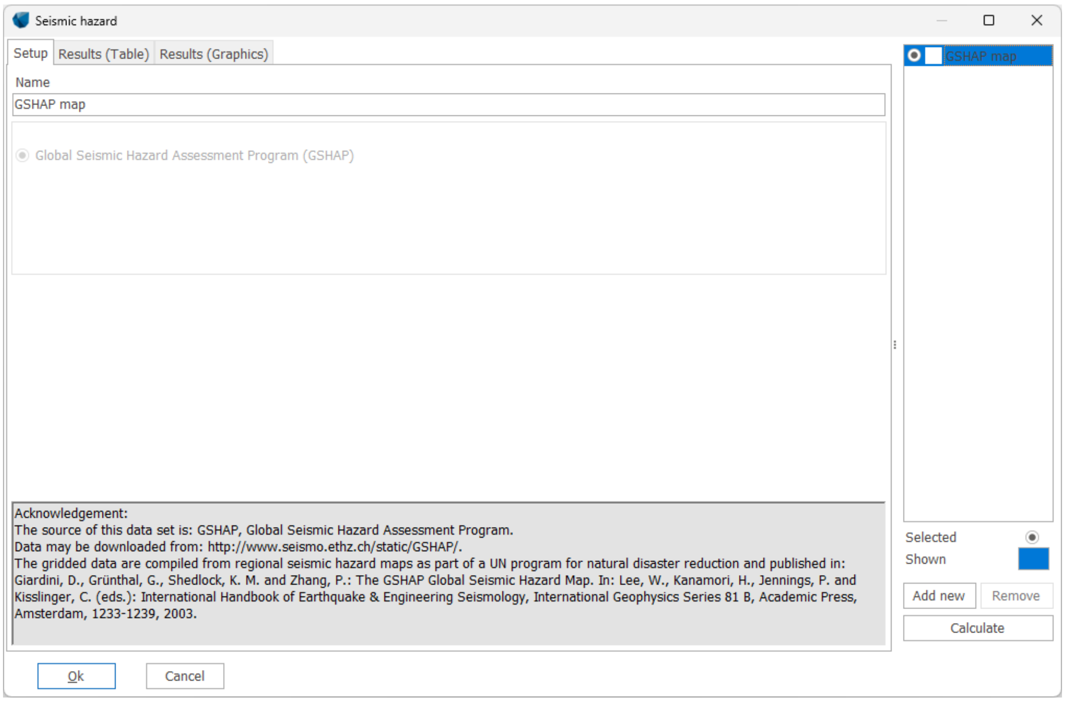


Figure 74. GSHAP seismic hazard map showing global variation of PGA. From [16].

Setup, Calculation and Results

No inputs are required in the Seismic hazard calculation as only the GSHAP database is available.



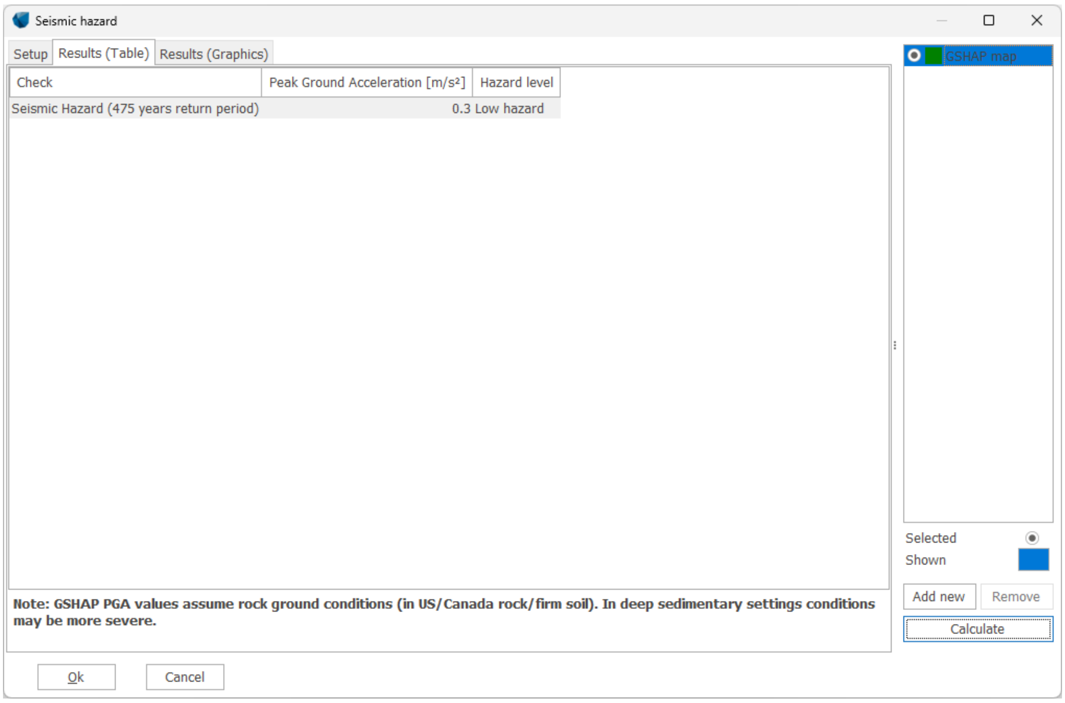
Name: GSHAP map

● Global Seismic Hazard Assessment Program (GSHAP)

Acknowledgement:
The source of this data set is: GSHAP, Global Seismic Hazard Assessment Program.
Data may be downloaded from: http://www.seismo.ethz.ch/static/GSHAP/.
The gridded data are compiled from regional seismic hazard maps as part of a UN program for natural disaster reduction and published in:
Giardini, D., Grünthal, G., Shedlock, K. M. and Zhang, P.: The GSHAP Global Seismic Hazard Map. In: Lee, W., Kanamori, H., Jennings, P. and Kisslinger, C. (eds.): International Handbook of Earthquake & Engineering Seismology, International Geophysics Series 81 B, Academic Press, Amsterdam, 1233-1239, 2003.

Figure 75. Setup tab of the Seismic hazard check.

The *Results (Table)* tab summarizes the site estimated seismic hazard in terms of the PGA level in m/s². It also gives the expected hazard level.



Check	Peak Ground Acceleration [m/s²]	Hazard level
Seismic Hazard (475 years return period)	0.3	Low hazard

Note: GSHAP PGA values assume rock ground conditions (in US/Canada rock/firm soil). In deep sedimentary settings conditions may be more severe.

Figure 76. Results (Table) tab of the Seismic hazard check.

The last tab in the Seismic hazard check provides a map of the seismic hazard in an area of approximately 1000km by 1000km around the site.

Note that since GSHAP is compiled of several national and regional projects, some variations in PGA may not allways be 100% smooth across national borders, as is seen for the U.S. - Canada border (not shown).

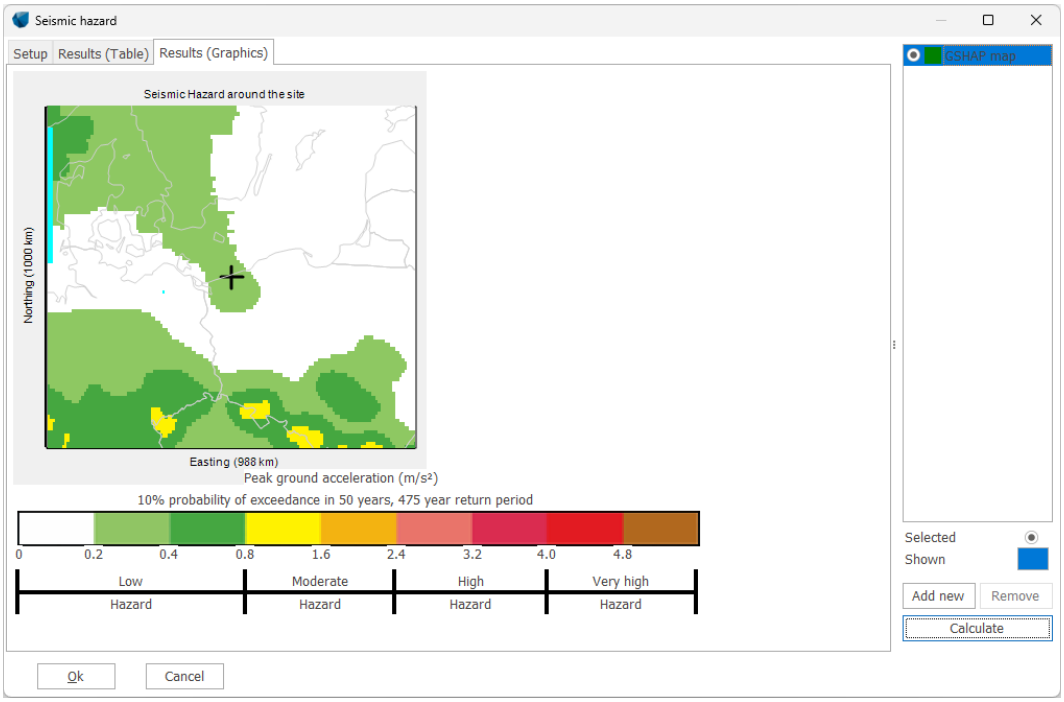


Figure 77. Results (Graphics) tab of the Seismic hazard check.

5.2.3.2 Temperature range

Description and limit

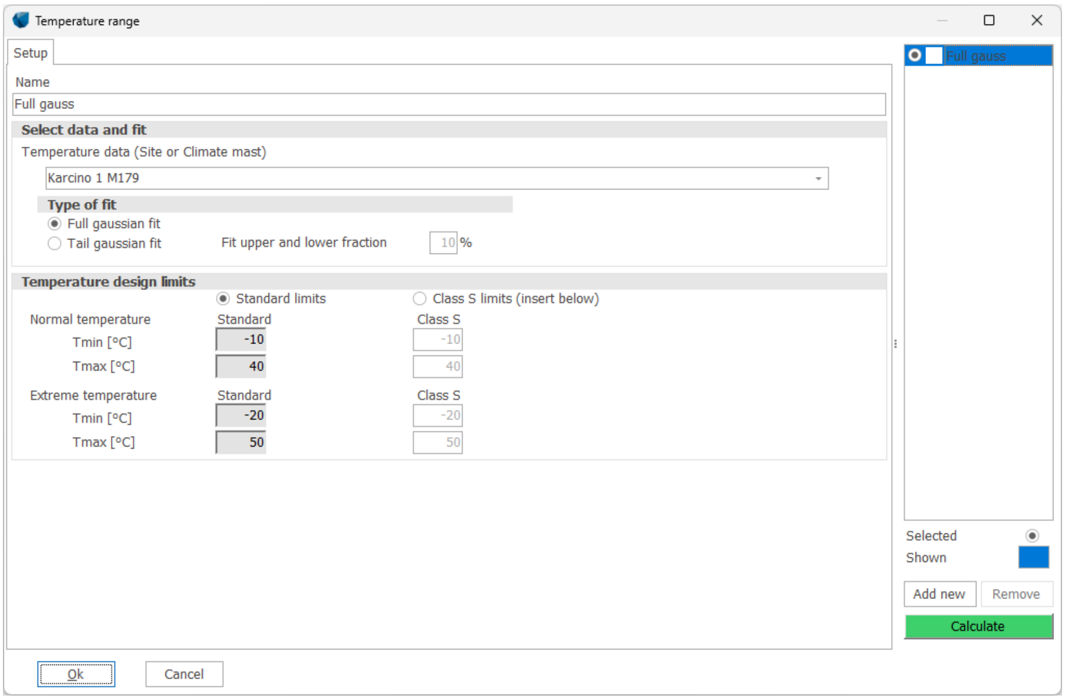
Wind turbines are designed for operation within a certain range of temperatures: the operational or *Normal range*. A wind turbine may survive temperatures beyond the operational range, but will cease operation in order to survive. If temperatures exceed the so-called *Extreme range* or survival range, components within the wind turbine may suffer permanent damage.

The *Normal range* for the IEC standard class WTGs is: -10°C to +40°C.
The *Extreme range* for the IEC standard class WTGs is: -20°C to +50°C.

Most manufacturers produce high or low temperature versions of their WTG models with extended normal and extreme ranges for specific markets. Such models are categorized as Class S WTGs. The temperature range is typically extended by around 10°C at the high or low end of the ranges noted above in Class S versions. Calculations for customized Class S temperature ranges are supported by SITE COMPLIANCE and described below.

Setup, Calculation and Results

On the *Setup* tab of the Temperature range check, there are two setup groups; *Select data and fit* and *Temperature design limits*. In the former group, a mast with temperature measurements must be selected. In the latter group, the fit option must be selected as either *Full Gaussian* or *Tail Gaussian*, deciding whether to fit the full the range of measurements or just the high and low tails, respectively. If the *Tail Gaussian* option is selected, the tail fraction may be adjusted. By default, the highest and lowest 10% of the samples are fitted in this option.



Name: Full gauss

Select data and fit

Temperature data (Site or Climate mast): Karcino 1 M179

Type of fit

● Full gaussian fit

○ Tail gaussian fit — Fit upper and lower fraction 10 %

Temperature design limits

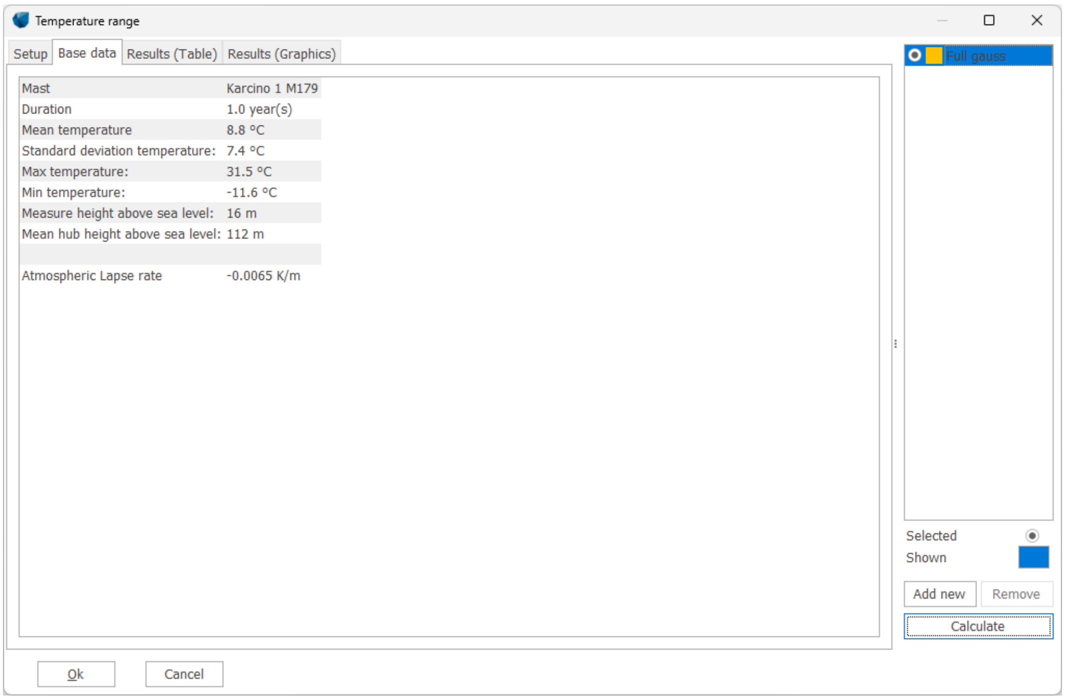
● Standard limits ○ Class S limits (insert below)

Normal temperature	Standard	Class S
Tmin [°C]	-10	-10
Tmax [°C]	40	40

Extreme temperature	Standard	Class S
Tmin [°C]	-20	-20
Tmax [°C]	50	50

Figure 78. Setup tab of the Temperature range check.

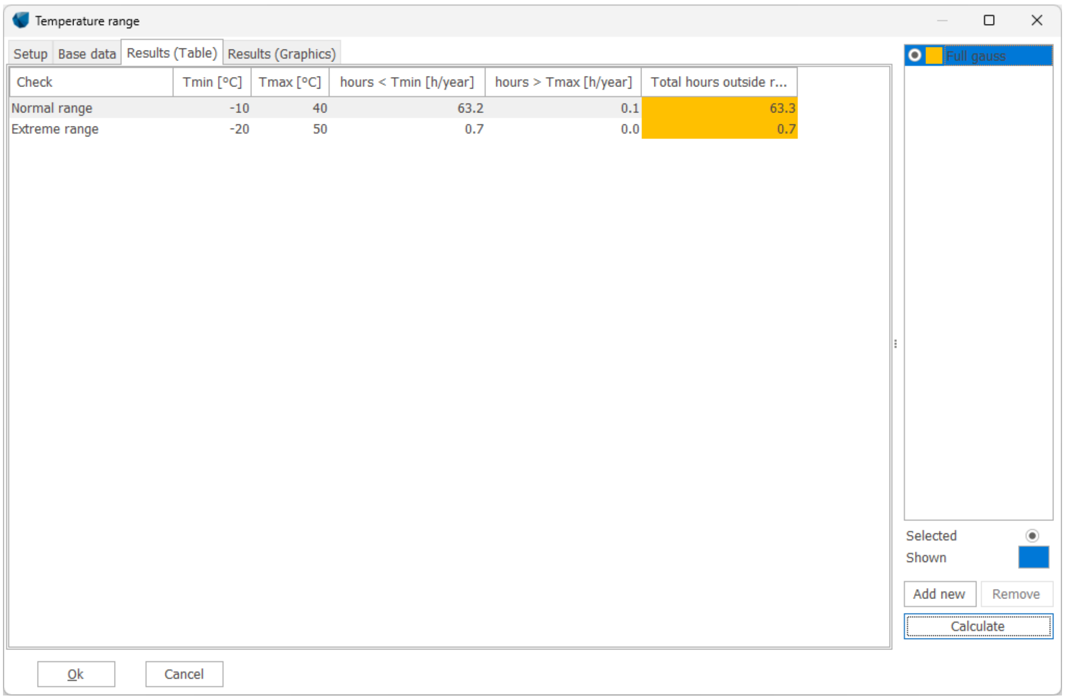
Once the calculation has been performed by clicking the green “Calculate” button, the results tabs appear. The *Base data* tab summarizes the chosen temperature measurements and the mast details as well as the mean WTG HH above sea level, which is used to estimate a single result for the entire site.



Mast	Karcino 1 M179
Duration	1.0 year(s)
Mean temperature	8.8 °C
Standard deviation temperature:	7.4 °C
Max temperature:	31.5 °C
Min temperature:	-11.6 °C
Measure height above sea level:	16 m
Mean hub height above sea level:	112 m
Atmospheric Lapse rate	-0.0065 K/m

Figure 79. Base data tab of the Temperature range check.

The *Results (Table)* lists the chosen limits for the normal and extreme temperature ranges. In the table, the column labelled “hours < Tmin [h/year]” shows the estimated hours below the normal and extreme low temperature limits, respectively. The column labelled “hours > Tmax [h/year]” shows the hours above the normal and extreme high temperature limits, respectively. The total result is the estimated sum of hours outside the two ranges, shown in the rightmost column.

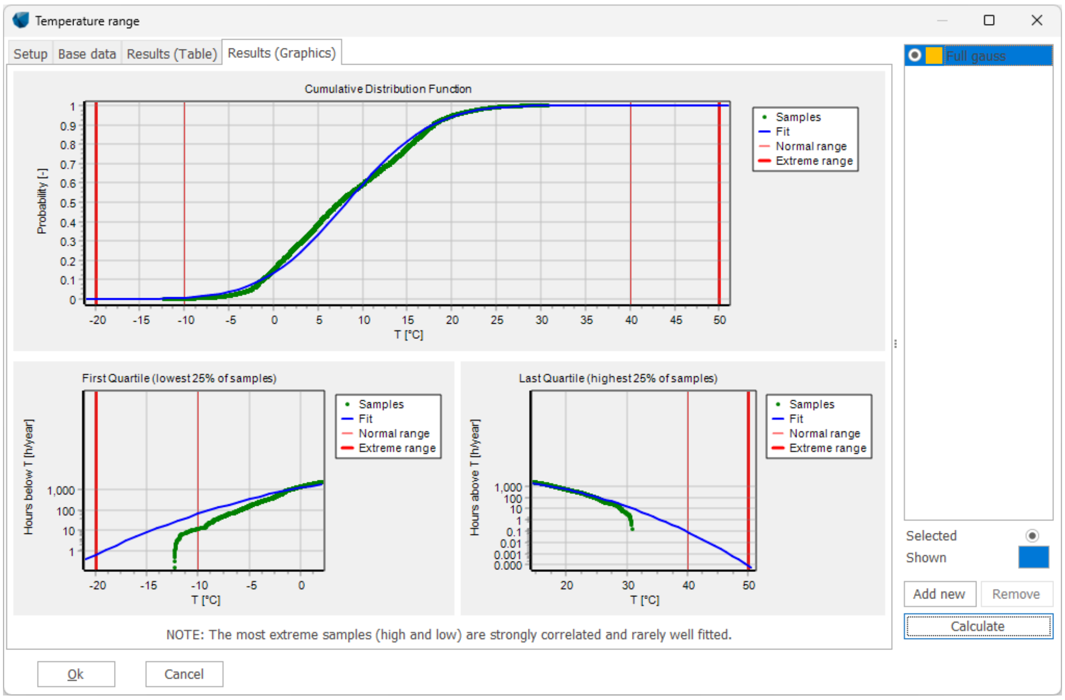


Check	Tmin [°C]	Tmax [°C]	hours < Tmin [h/year]	hours > Tmax [h/year]	Total hours outside r...
Normal range	-10	40	63.2	0.1	63.3
Extreme range	-20	50	0.7	0.0	0.7

Figure 80. Results (Table) tab of the Temperature range check.

On the *Results (Graphics)* tab, the measurements and the fits are presented. In the upper (larger) plot, the cumulative sample distribution is shown with the normal and extreme ranges indicated using the vertical red lines. If the Full Gaussian fit was chosen in the setup, this fit is also illustrated in the plot as the blue curve.

The two lower plots illustrate the upper and lower quantiles (25%) of the samples, respectively. The frequency of occurrence axis (y-axis) has been transformed to illustrate, directly, the hours below (left graph) or above (right graph) the temperatures on the x-axis. The fit(s) are also illustrated in both these plots. The hours below or above the normal and extreme limits may be read directly at the y-axis besides the crossing points where the fit(s) cross the vertical red lines.



NOTE: The most extreme samples (high and low) are strongly correlated and rarely well fitted.

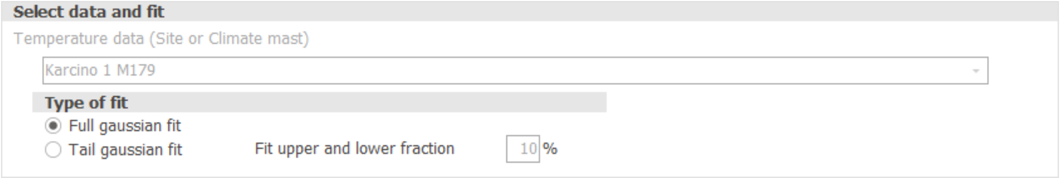
Figure 81. Results (Graphics) tab of the Temperature check.

Calculation options

The calculation options of the Temperature range check are described in the following.

Select data and fit

A Site or Climate mast with temperature data may be chosen in the setup as illustrated below. The SYNOP stations are often a good alternative if no on-site data is available. Users should make sure that the mast elevation above sea level is properly defined in the properties of the Meteo object as this may strongly influence the results. Usually, the mast evelation may be read from the header lines of the data files in the Meteo object.



Select data and fit

Temperature data (Site or Climate mast)

Karcino 1 M179

Type of fit

● Full gaussian fit

○ Tail gaussian fit

Fit upper and lower fraction 10 %

Figure 82. Setup details of data source and fit for Temperature range check.

Full Gaussian fit

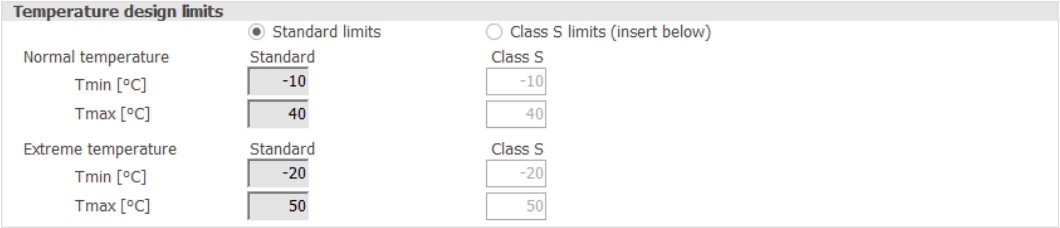
Selecting this option fits the full sample distribution using a Gaussian relationship, which has the same mean and standard deviation as the samples (method of moments). This method is very robust but for many sites. The fit is not always satisfactory which is clearly visible from the graphs.

Tail Gaussian fit

This option fits separate Gaussian distributions to the low tail and to the high tail ranges with the default “tail range” set to fit the lowest 10% and the highest 10% of the samples. The fits are performed using the so-called Normal probability plots of the ordered samples against the theoretical Gaussian quantiles, but only fitting the relevant tail range.

Temperature design limits

The figure below illustrates the setup of the *Temperature design limits*.



Temperature design limits

● Standard limits

○ Class S limits (insert below)

Normal temperature	Standard	Class S
Tmin [°C]	-10	-10
Tmax [°C]	40	40
Extreme temperature	Standard	Class S
Tmin [°C]	-20	-20
Tmax [°C]	50	50

Figure 83. Setup of Temperature design limits in the Temperature range check.

Standard limits

The default option *Standard limits* is used for standard class WTGs or in initial screenings of the Temperature range check. Note that some manufacturers, such as Vestas, have extended the temperature range on all their standard WTG models to, e.g., -20°C for the *Normal range* minimum temperature. Such models should be calculated using *Class S limits* for temperature range although the WTG model is not a special high- or low-temperature version.

Class S limits

The *Class S limits* option should be selected and *Normal* and *Extreme* temperature ranges adjusted appropriately if the WTG model in question is known to be a low- or high-temperature version. This option is also appropriate if, perhaps, a Temperature range calculation was initially performed for the standard limits, but resulted in a Critical exceedance. In such cases, it is necessary to explore which temperature limits would then be needed/acceptable. Usually, the special high- or low-temperature versions have *Normal* and *Extreme* limits which are extended by 10°C or 20°C, to, e.g., -30°C and -40°C for a low-temperature version.

5.2.3.3 Lightning rate

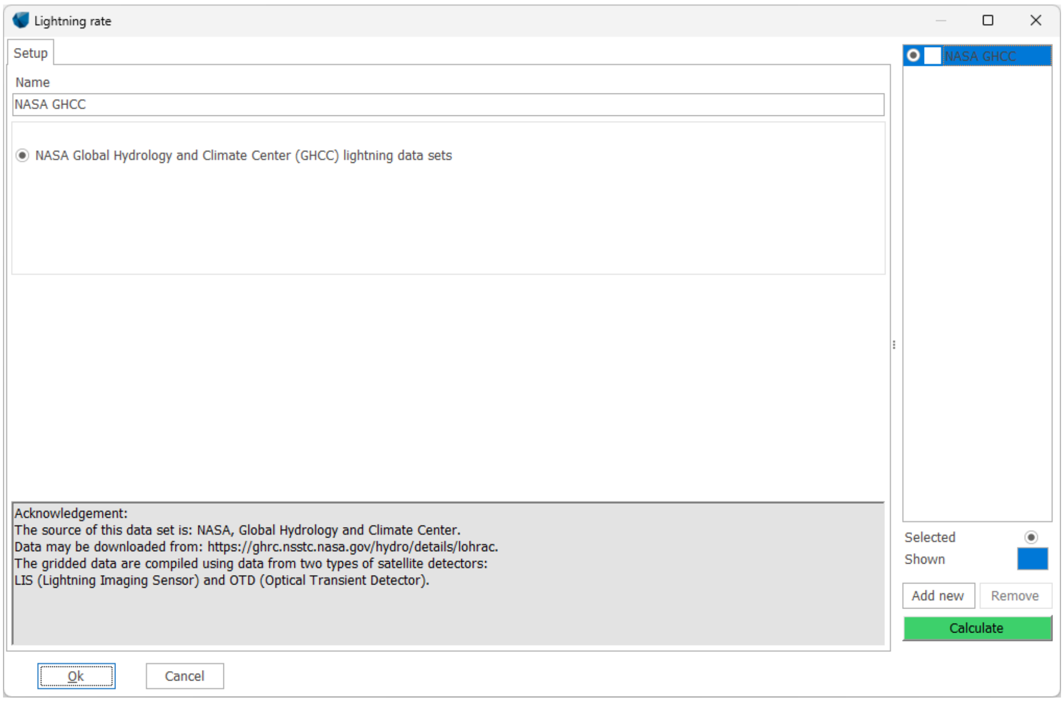
Description and limit

The estimation of Lightning rate in SITE COMPLIANCE is based on a database established by the NASA Global Hydrology and Climate Center (GHCC) [17]. Data were collected using two kinds of satellite detectors LIS (Lightning Imaging Sensor) and OTD (Optical Transient Detector).

The IEC standard does not specify a specific limit for the lightning rate.

Setup, Calculation and Results

No alternatives are available in the setup of the Lightning rate check.



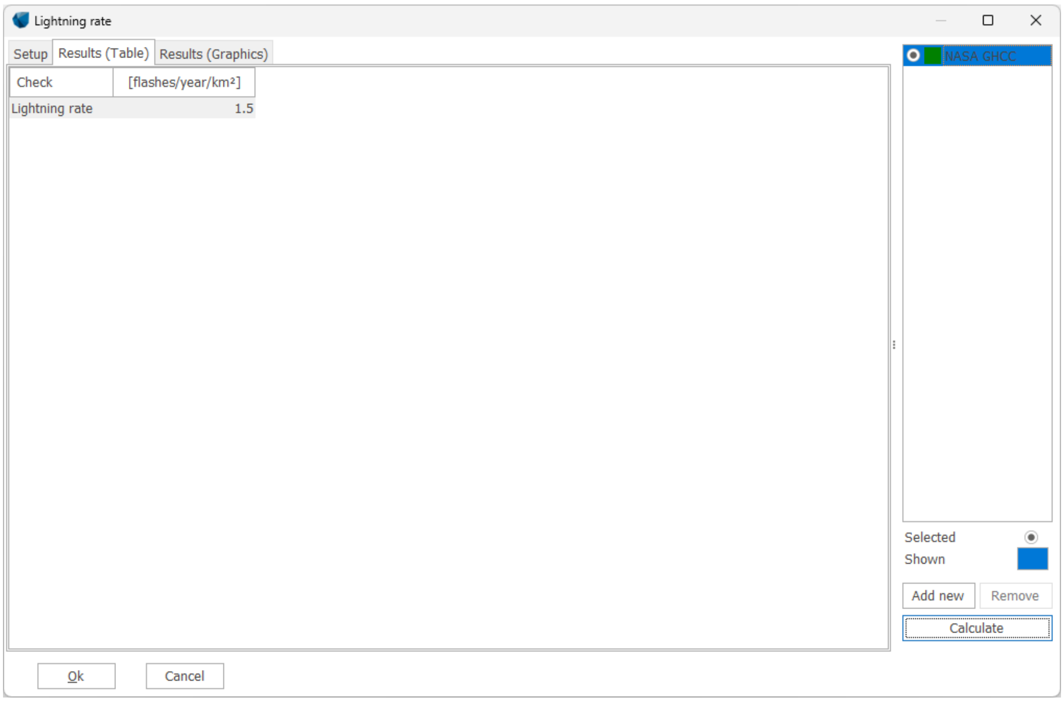
Name: NASA GHCC

● NASA Global Hydrology and Climate Center (GHCC) lightning data sets

Acknowledgement:
The source of this data set is: NASA, Global Hydrology and Climate Center.
Data may be downloaded from: https://ghrc.nsstc.nasa.gov/hydro/details/lohrac.
The gridded data are compiled using data from two types of satellite detectors:
LIS (Lightning Imaging Sensor) and OTD (Optical Transient Detector).

Figure 84. Setup tab of the Lightning rate check.

The *Results (Table)* provides the expected lightning rate for the site.



Check	[flashes/year/km²]
Lightning rate	1.5

Figure 85. Results (Table) tab of the Lightning rate check.

The last tab *Results (Graphics)* illustrates the lightning rate in a ca. 1000km by 1000km square, centred on the site.

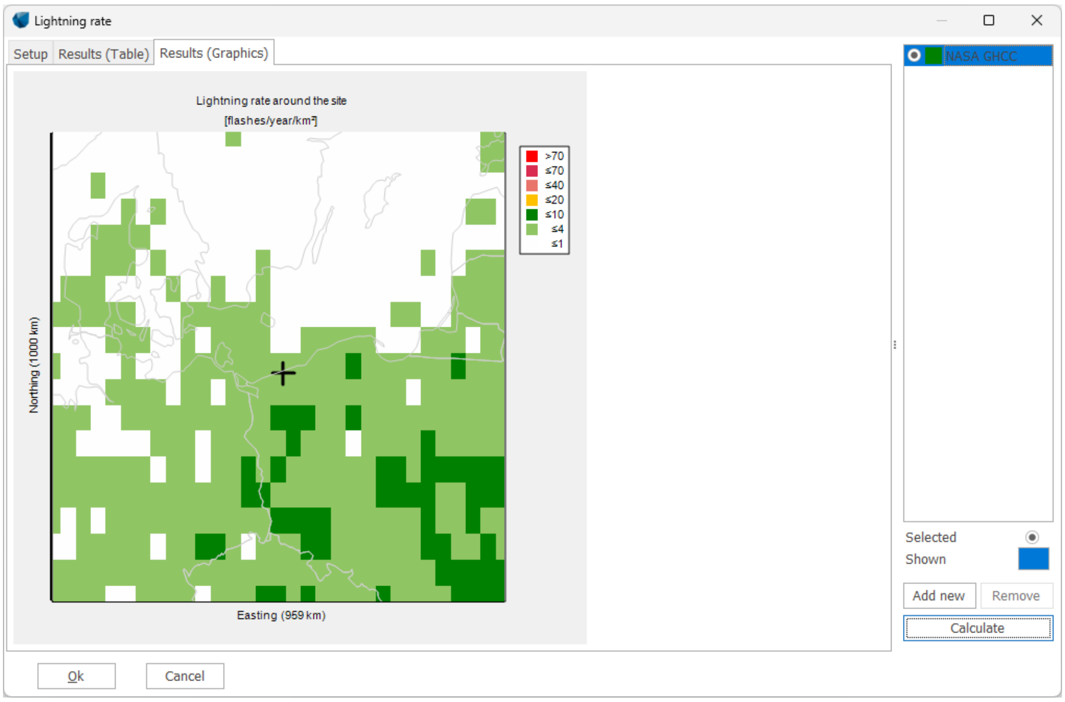
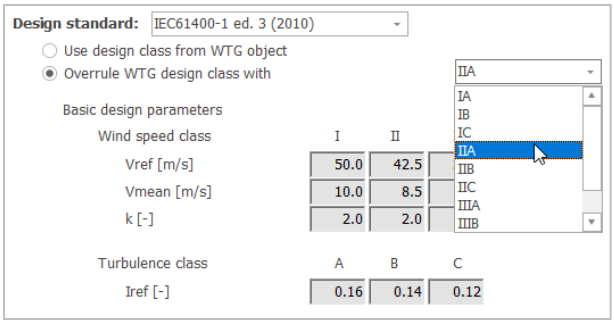


Figure 86. Results (Graphics) tab of the Lightning rate check.

5.2.4 (Re)calculate all

Once a complete SITE COMPLIANCE calculation has been setup and each included calculation is performed, it is time to assess the overall results. In the case shown below, design class IIIB is checked for a site. Most checks came out as *OK*, three checks got the result *Caution,* and two checks (Extreme wind and Wind distribution) ended in the category *Critical*.

To check another design class for the site is very easy and fast in SITE COMPLIANCE. Just go back to the *Main* tab and change the design class to, e.g., a higher wind speed class, e.g., class IB or IIB instead of IIIB.



Design standard: IEC61400-1 ed. 3 (2010)

○ Use design class from WTG object

● Overrule WTG design class with IIA

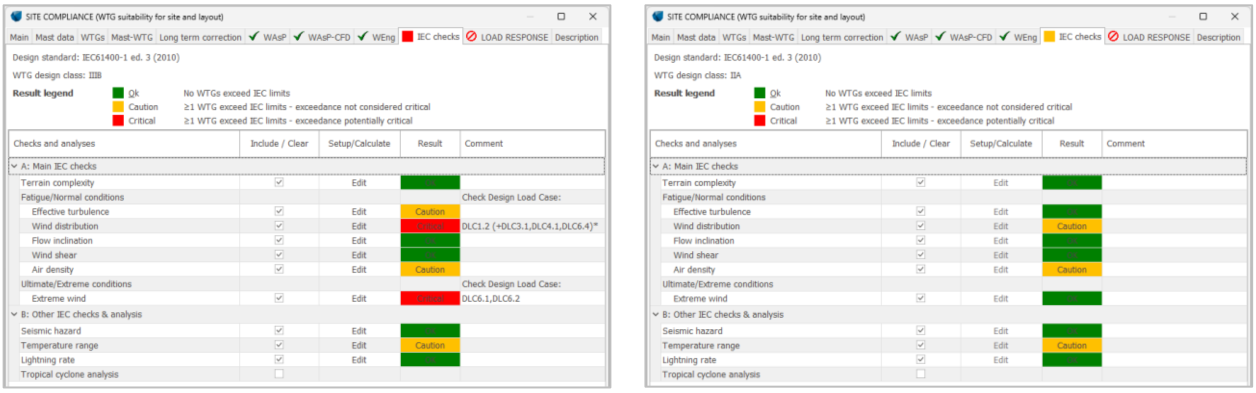
Basic design parameters

Wind speed class	I	II
Vref [m/s]	50.0	42.5
Vmean [m/s]	10.0	8.5
k [-]	2.0	2.0

Turbulence class	A	B	C
Iref [-]	0.16	0.14	0.12

Figure 87. Part of the Main tab where design class is set.

Back on the *Calculations* tab, all results will be cleared as one of the basic settings has been changed. To recalculate all included checks simply click the *(Re)calculate all* button. This will recalculate all calculations included for each check and update the visual results accordingly.



Class IIIB

Design standard: IEC61400-1 ed. 3 (2010)

WTG design class: IIIB

Result legend

🟩	Ok	No WTGs exceed IEC limits
🟨	Caution	≥1 WTG exceed IEC limits - exceedance not considered critical
🟥	Critical	≥1 WTG exceed IEC limits - exceedance potentially critical

Checks and analyses	Include / Clear	Setup/Calculate	Result	Comment
A: Main IEC checks				
Terrain complexity	☑	Edit	Ok	
Fatigue/Normal conditions				Check Design Load Case:
Effective turbulence	☑	Edit	Caution	
Wind distribution	☑	Edit	Critical	DLC1.2 (+DLC3.1,DLC4.1,DLC6.4)*
Flow inclination	☑	Edit	Ok	
Wind shear	☑	Edit	Ok	
Air density	☑	Edit	Caution	
Ultimate/Extreme conditions				Check Design Load Case:
Extreme wind	☑	Edit	Critical	DLC6.1,DLC6.2
B: Other IEC checks & analysis				
Seismic hazard	☑	Edit	Ok	
Temperature range	☑	Edit	Caution	
Lightning rate	☑	Edit	Ok	
Tropical cyclone analysis	☐			

Class IIA

Design standard: IEC61400-1 ed. 3 (2010)

WTG design class: IIA

Result legend

🟩	Ok	No WTGs exceed IEC limits
🟨	Caution	≥1 WTG exceed IEC limits - exceedance not considered critical
🟥	Critical	≥1 WTG exceed IEC limits - exceedance potentially critical

Checks and analyses	Include / Clear	Setup/Calculate	Result	Comment
A: Main IEC checks				
Terrain complexity	☑	Edit	Ok	
Fatigue/Normal conditions				
Effective turbulence	☑	Edit	Ok	
Wind distribution	☑	Edit	Caution	
Flow inclination	☑	Edit	Ok	
Wind shear	☑	Edit	Ok	
Air density	☑	Edit	Caution	
Ultimate/Extreme conditions				
Extreme wind	☑	Edit	Ok	
B: Other IEC checks & analysis				
Seismic hazard	☑	Edit	Ok	
Temperature range	☑	Edit	Caution	
Lightning rate	☑	Edit	Ok	
Tropical cyclone analysis	☐			

Figure 88. Left: Calculation and overall result for the initial design class IIIB. Right: Re-calculation for the design class IIA.

A suitable design class maybe found by iteratively increasing the selected design class for wind speed (e.g., III to II) and turbulence (e.g., B to A) until all main checks are green or, perhaps, yellow.

However, there is a more accurate and less conservative alternative to just iteratively increasing the selected design class. This alternative is the module LOAD RESPONSE, which allows the user to perform a fatigue load assessment for each WTG position in the layout. LOAD RESPONSE is an independent module but is fully integrated in SITE COMPLIANCE and may be activated on the Main tab of SITE COMPLIANCE, if a valid license is available.

The next section of this manual describes LOAD RESPONSE.

Note:

- Red checks do not always exclude a WTG model/class as suitable.
- Final suitability depends on fatigue trade-off between checks and manufacturers load margins.
- SITE COMPLIANCE does not fully model the trade-off and does not know the load margins.
- Consult the manufacturer for final justification of suitability including trade-offs and margins.

5.3 LOAD RESPONSE

From windPRO version 3.0, the module LOAD RESPONSE has been integrated in SITE COMPLIANCE for estimation of fatigue loads for each WTG in a layout.

LOAD RESPONSE is developed as part of the publicly funded research project: “Optimized Integration of Load Calculations in Development and Design of Wind Farms” led by Post Doc. Henrik Stensgaard Toft. The project is a collaboration between EMD, Aalborg University (Department of Civil Engineering)[11] and Innovation Fund Denmark[12]. This setup has ensured a very strong scientific basis for LOAD REPONSE. In addition, the generic wind turbines provided with LOAD RESPONSE have been thoroughly validated in collaboration with a leading wind turbine manufacturer to ensure their representability and accuracy. Finally, the response surface methodology employed in LOAD RESPONSE to establish fatigue loads has been previously certified by TÜV-SÜD for consistency with the ÌEC61400-1 ed. 3 standard.

LOAD RESPONSE, in its current implementation (windPRO 4.0), is focussed on fatigue loads during power production, which in IEC 61400-1 e. 3 (2010) is denoted “design load case 1.2”. This is typically the most significant fatigue design load case, because it covers most of the wind turbines design lifetime and depends strongly on the site specific wind climate. However, extreme loads which are not covered in LOAD RESPONSE can also be design driving for wind turbines, but these are typically handled directly via, e.g., evaluation of the Extreme wind speed check in SITE COMPLIANCE.

Justification

Many SITE COMPLIANCE calculations are not fully conclusive in the sense that one or more of the main IEC checks relating to fatigue loads are partly (yellow) or fully (red) exceeded, whereas other main checks are well within IEC limits. The yellow and red main checks are often due to exceedances of the wind climate parameters for specific wind speeds as shown in the figure below. It is, therefore, possible that the exceedance of some wind climate parameters at specific wind speeds can be compensated by lower values at other wind speeds or in other wind climate parameters. This evaluation is performed in LOAD RESPONSE based on a response surface methodology.

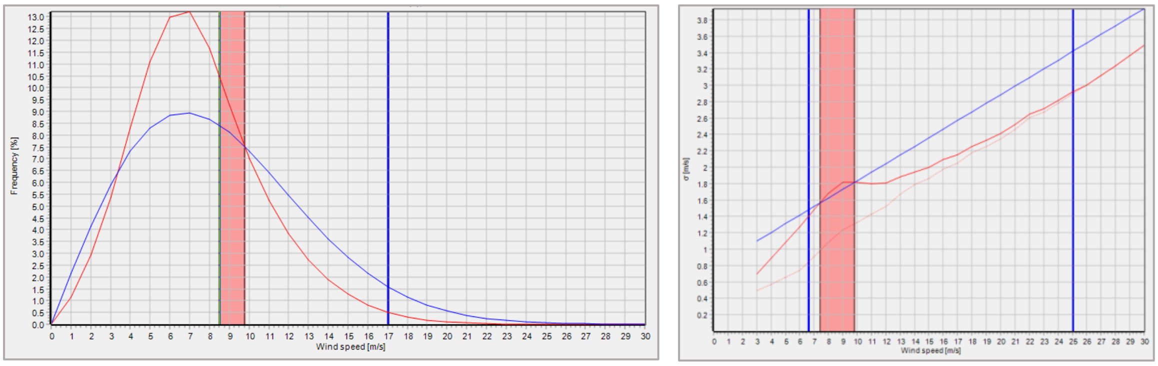


Figure 89. Exceedance of wind speed distribution (left) and turbulence (right) at specific wind speeds.

In the SITE COMPLIANCE calculation shown below, a case is illustrated where the main checks *Effective turbulence*, *Wind distribution*, *Wind shear* and *Air density* are all partly exceeded, whereas *Flow inclination* is well within the limits.

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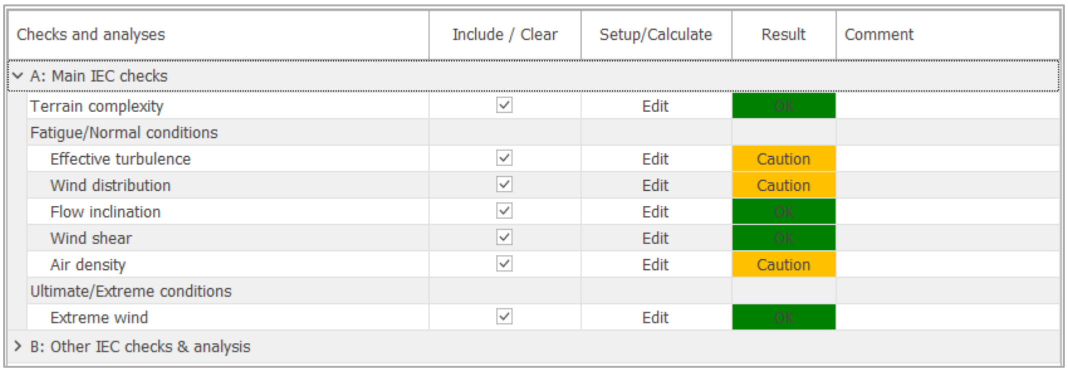
[11] http://www.civil.aau.dk/

[12] http://innovationsfonden.dk/en



Checks and analyses	Include / Clear	Setup/Calculate	Result	Comment
˅ A: Main IEC checks				
Terrain complexity	☑	Edit	OK	
Fatigue/Normal conditions				
Effective turbulence	☑	Edit	Caution	
Wind distribution	☑	Edit	Caution	
Flow inclination	☑	Edit	OK	
Wind shear	☑	Edit	OK	
Air density	☑	Edit	Caution	
Ultimate/Extreme conditions				
Extreme wind	☑	Edit	OK	
› B: Other IEC checks & analysis				

Figure 90. A SITE COMPLIANCE calculation illustrating the need for LOAD RESPONSE.

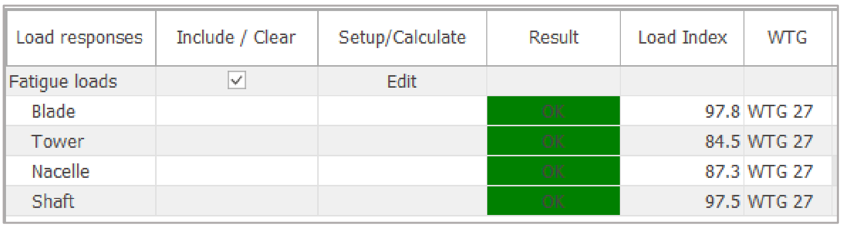
Based on the above SITE COMPLIANCE result, it is not possible to directly make an accurate decision if the turbine model/design class is suitable for the site and layout or not. A fatigue load assessment is required to make an appropriate conclusion. In fact, the IEC standard requires a fatigue load calculation in these cases by the statement in Section 11.1 ([1], p 52):

> *"…It shall be shown that the site-specific conditions do not compromise the structural integrity. The demonstration requires an assessment of the site complexity, see 11.2, and an assessment of the wind conditions at the site, see 11.3. For assessment of structural integrity two approaches may be used:*
>
> *a) a demonstration that all these conditions are no more severe than those assumed for the design of the wind turbine, see 11.9;*
>
> *b) a demonstration of the structural integrity for conditions, each equal to or more severe than those at the site, see 11.10.*
>
> *If any conditions are more severe than those assumed in the design, the structural and electrical compatibility shall be demonstrated using the second approach."*

In other words, approach b) is required if one or more of the IEC checks are exceeded. LOAD RESPONSE is an implementation of the requirement in approach b), as it allows the user to compare the site specific fatigue loads with the design loads assumed in the IEC standard for all the important turbine components.

Only the manufacturers have access to the complete aero-elastic model of a wind turbine model, which is needed for "approach b" (see above). For this reason, LOAD REPONSE comes with two generic wind turbine models, which allows the user to estimate fatigue loads without access to the original aero-elastic model.

Figure 91 below illustrates the overall result of a LOAD RESPONSE calculation for the problematic SITE COMPLIANCE result above in Figure 90. The results show that site specific loads for all WTG positions are OK for all the main components, and that the WTG with the highest loads is "WTG 27". The column *Load Index* shows the WTG loads for the site/layout normalized with the IEC design loads. A load index of <100% means that WTG loads are less than the design loads and, hence, OK.



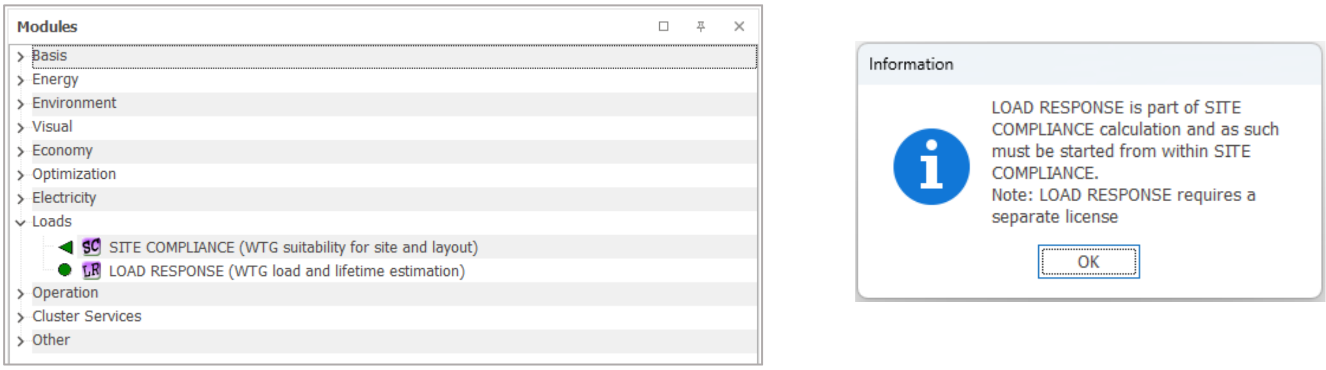
Load responses	Include / Clear	Setup/Calculate	Result	Load Index	WTG
Fatigue loads	☑	Edit			
Blade			OK	97.8	WTG 27
Tower			OK	84.5	WTG 27
Nacelle			OK	87.3	WTG 27
Shaft			OK	97.5	WTG 27

>

Figure 91. The overall LOAD REPONSE result for the SITE COMPLIANCE result in Figure 90.

Practicalities

LOAD RESPONSE is a separate module and requires a separate license, but it is fully integrated in SITE COMPLIANCE. In the module list, this is illustrated by the different shapes of the green markers of the two modules (see below).



Modules

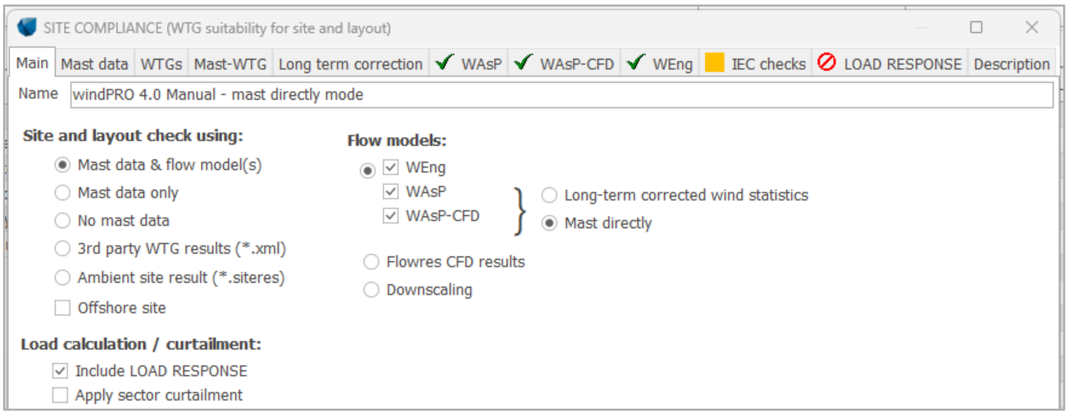
- Basis
- Energy
- Environment
- Visual
- Economy
- Optimization
- Electricity
- Loads
  - SITE COMPLIANCE (WTG suitability for site and layout)
  - LOAD RESPONSE (WTG load and lifetime estimation)
- Operation
- Cluster Services
- Other

Information

LOAD RESPONSE is part of SITE COMPLIANCE calculation and as such must be started from within SITE COMPLIANCE.
Note: LOAD RESPONSE requires a separate license

Figure 92. Left: module list with the Loads group expanded. Note that LOAD REPONSE has a green circle and SITE COMPLIANCE a green triangle. Right: the message if one tries to start LOAD RESPONSE on its own from the module list.

LOAD REPONSE is activated from the main tab of SITE COMPLIANCE under the headline *Load calculation* by checking the box *Include LOAD RESPONSE* (see figure below). When this box is checked, a new tab named *LOAD RESPONSE* appears. Initially, the tab has a red stop mark to indicate that no load results are available yet.



SITE COMPLIANCE (WTG suitability for site and layout)

Name: windPRO 4.0 Manual - mast directly mode

Site and layout check using:

● Mast data & flow model(s)
○ Mast data only
○ No mast data
○ 3rd party WTG results (*.xml)
○ Ambient site result (*.siteres)
☐ Offshore site

Flow models:

● ☑ WEng
☑ WAsP
☑ WAsP-CFD
○ Long-term corrected wind statistics
● Mast directly
○ Flowres CFD results
○ Downscaling

Load calculation / curtailment:

☑ Include LOAD RESPONSE
☐ Apply sector curtailment

Figure 93. Activation of LOAD RESPONSE from the main tab of SITE COMPLIANCE. Note the yellow indication on the tab "IEC checks" and the stop sign on the tab LOAD RESPONSE illustrating the overall result of SITE COMPLIANCE and that the LOAD RESPONSE calculation is not yet run.

Wind turbine manufacturers can easily, and without any data leaving the company, add their own turbine models for in-house use or to share with, e.g., developers. When implemented, manufacturer specific models are protected by a high level of security via both encrypted file format and license control (see section 5.3.4 for further details).

What is a response model?

LOAD RESPONSE uses a response surface methodology to calculate fatigue loads for a particular set of WTG wind climate parameters. The response model is simply a set of pre-run aero-elastic simulation results (fatigue loads) for certain combinations of wind climate parameters combined with a surrogate model trained on these pre-run data.

LOAD RESPONSE support two different types of surrogate models, see Appendix IV - Theory of LOAD RESPONSE and Fatigue for more information.

A response model is required for each component or cross section in the wind turbine model – referred to as "sensors". Typical sensors are, e.g., "Tower bottom for-aft bending moment" or "Blade out-of-plane bending moment". Figure 94 shows an example of the aero-elastic response for a sensor as function of wind speed and wind shear, where the surrogate model is trained on a subset of points located on this surface.

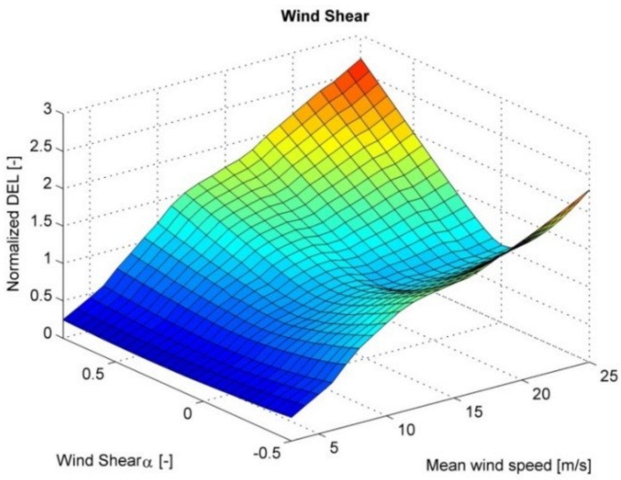
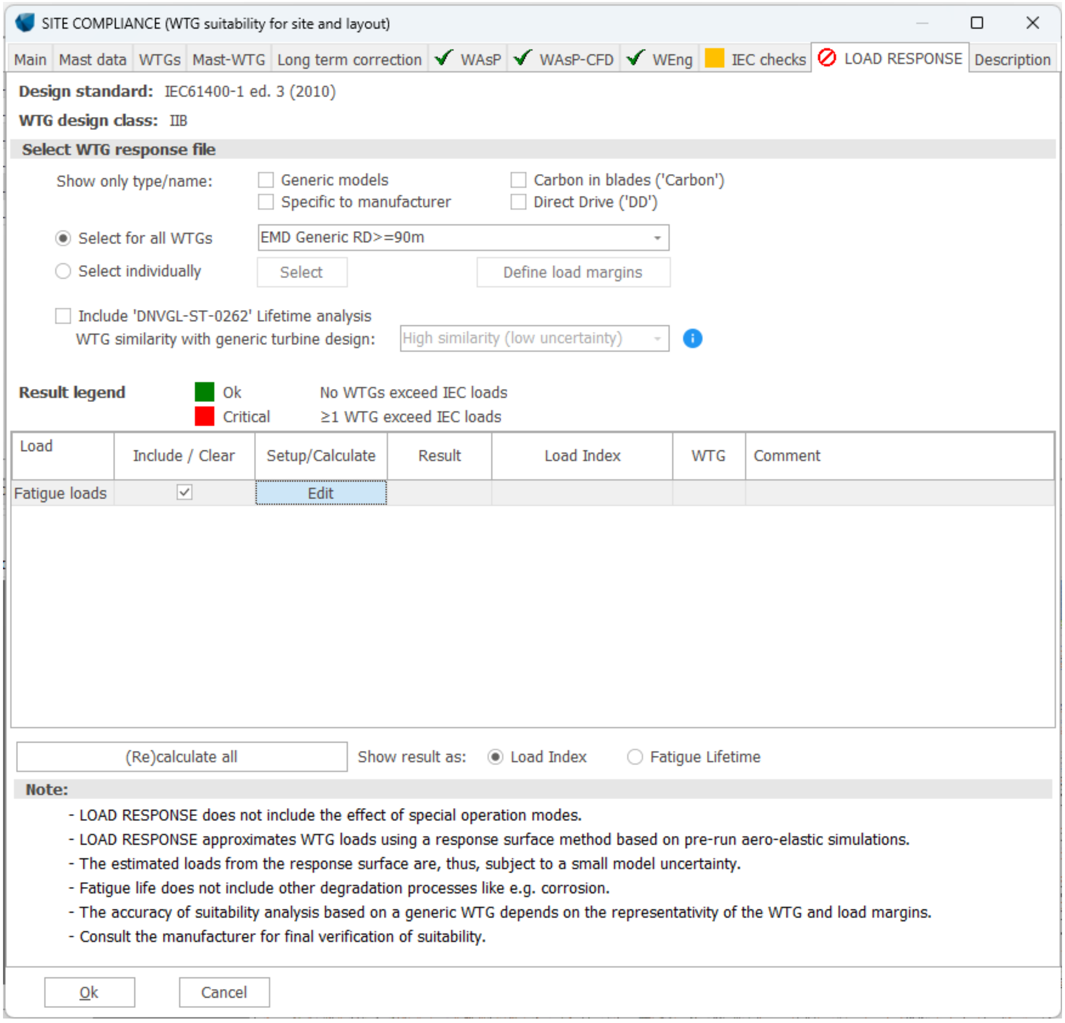


Figure 94. Aero-elastic response for the sensor: “Blade out-of-plane bending moment” as a function of wind speed and wind shear. The vertical axes show normalized Damage Equivalent Loads (DEL).

5.3.1 Setting up and running the fatigue load calculation

First, make sure that LOAD RESPONSE is activated by checking it on the main tab of SITE COMPLIANCE.

The next step is to select the response model for use in the load calculation. This is done on the LOAD RESPONSE tab via the dropdown menu *Select WTG response file for all turbines* at the top of the tab. LOAD RESPONSE comes with several generic response models, as shown below: a response model for rotor diameters of 90m and up and a model for rotors below 90m.



Design standard: IEC61400-1 ed. 3 (2010)

WTG design class: IIB

Select WTG response file

Show only type/name: ☐ Generic models ☐ Specific to manufacturer ☐ Carbon in blades ('Carbon') ☐ Direct Drive ('DD')

● Select for all WTGs: EMD Generic RD>=90m

○ Select individually

☐ Include 'DNVGL-ST-0262' Lifetime analysis

WTG similarity with generic turbine design: High similarity (low uncertainty)

Result legend 🟩 Ok — No WTGs exceed IEC loads; 🟥 Critical — ≥1 WTG exceed IEC loads

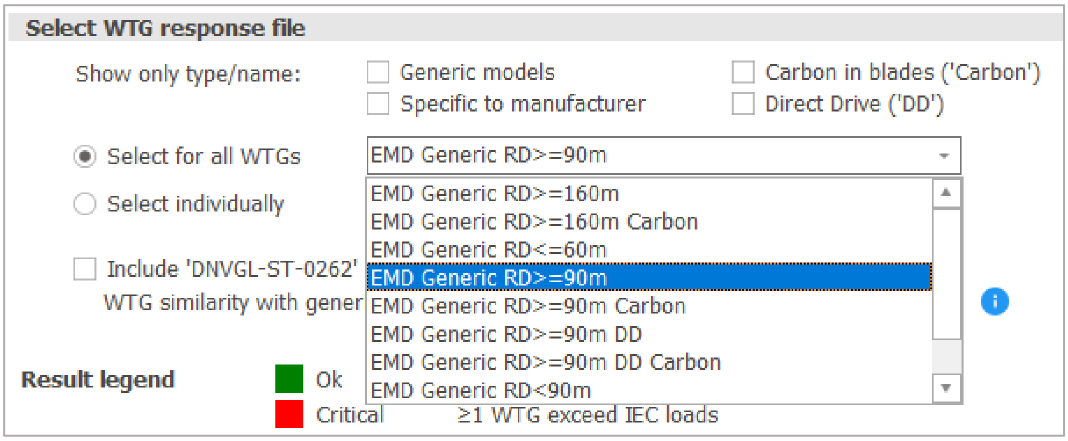
Load	Include / Clear	Setup/Calculate	Result	Load Index	WTG	Comment
Fatigue loads	☑	Edit				

Show result as: ● Load Index ○ Fatigue Lifetime

Note:

- LOAD RESPONSE does not include the effect of special operation modes.
- LOAD RESPONSE approximates WTG loads using a response surface method based on pre-run aero-elastic simulations.
- The estimated loads from the response surface are, thus, subject to a small model uncertainty.
- Fatigue life does not include other degradation processes like e.g. corrosion.
- The accuracy of suitability analysis based on a generic WTG depends on the representativity of the WTG and load margins.
- Consult the manufacturer for final verification of suitability.

Figure 95. The LOAD RESPONSE tab in SITE COMPLIANCE.



Select WTG response file

Show only type/name: ☐ Generic models ☐ Carbon in blades ('Carbon')
☐ Specific to manufacturer ☐ Direct Drive ('DD')

● Select for all WTGs: EMD Generic RD>=90m

○ Select individually

☐ Include 'DNVGL-ST-0262'
WTG similarity with gener

EMD Generic RD>=160m
EMD Generic RD>=160m Carbon
EMD Generic RD<=60m
EMD Generic RD>=90m
EMD Generic RD>=90m Carbon
EMD Generic RD>=90m DD
EMD Generic RD>=90m DD Carbon
EMD Generic RD<90m

Result legend 🟩 Ok
🟥 Critical ≥1 WTG exceed IEC loads

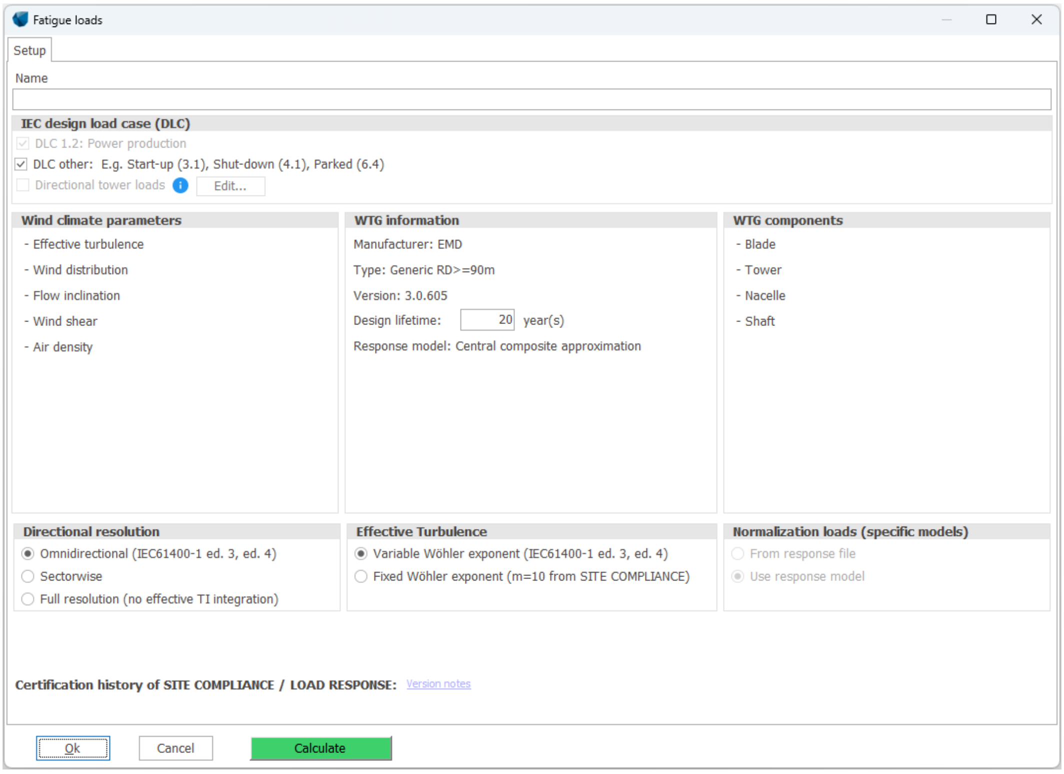
Figure 96. Selection of generic response model.

This choice of response model will apply to all WTGs in the layout, which is the typical situation when using the generic turbine models unless the layout consists of turbines with very different rotor diameters. If the layout consists of turbines with different IEC design classes which have been setup in each individual WTG object, this is handled automatically when the generic turbine models are used.

The alternative option, named *Select WTG response file (individual turbines)*, just below the default option, activates the *Select* button to access selection of individual response models for each WTG in the layout. This option is only relevant if the generic model is used for layouts with different rotor diameters or when manufacturer specific responses are used for layouts which include different turbine models or different IEC design classes.

Once the response model has been selected, the next step is to select *Fatigue loads* by checking the *Include* box beside it. Once included, an *Edit* button appears, which gives access to the fatigue load setup and calculation.

The *Fatigue loads* window is shown below. To start the calculation, press the green *Calculate* button at the bottom of the window. Before doing that it is recommended to review the main assumptions and calculation setup summarized in the window. The following text describes these assumptions and options.



Name

IEC design load case (DLC)

☑ DLC 1.2: Power production

☑ DLC other: E.g. Start-up (3.1), Shut-down (4.1), Parked (6.4)

☐ Directional tower loads Edit...

Wind climate parameters

- Effective turbulence
- Wind distribution
- Flow inclination
- Wind shear
- Air density

WTG information

Manufacturer: EMD

Type: Generic RD>=90m

Version: 3.0.605

Design lifetime: 20 year(s)

Response model: Central composite approximation

WTG components

- Blade
- Tower
- Nacelle
- Shaft

Directional resolution

● Omnidirectional (IEC61400-1 ed. 3, ed. 4)

○ Sectorwise

○ Full resolution (no effective TI integration)

Effective Turbulence

● Variable Wöhler exponent (IEC61400-1 ed. 3, ed. 4)

○ Fixed Wöhler exponent (m=10 from SITE COMPLIANCE)

Normalization loads (specific models)

○ From response file

● Use response model

Certification history of SITE COMPLIANCE / LOAD RESPONSE:

Figure 97. The Fatigue Loads setup and calculation window in LOAD RESPONSE.

IEC design load case (DLC)

The fatigue load estimation in LOAD RESPONSE includes the IEC design load case DLC 1.2 “Power production” which covers fatigue during normal operation and there is an option to include ‘DLC other’. The latter represents the combined contribution of the additonal fatigue related load cases 3.1, 4.1 and 6.4 covering ‘start-up’, ‘normal shut-down’ and ‘parked’ situations. For further details, see the appendix on the theory behind LOAD RESPONSE.

The option “Directional tower loads” may be activated to include the effect of wind direction on fatigue accumulation in the tower. It works by dividing the tower circumference into 36 equidistant points, and then the fatigue load is calculated at each point. Subsequently, the critical point with the highest fatigue load is chosen to be representative of the strength requirement of the tower. Note that this option combines the tower “fore-aft” and “side-side” loads into a single combined load which is simply named “TwbMax” for tower bottom max across all evaluated points. For more information on the applied method please refer to [33].

Wind climate parameters

Only some of the IEC main checks contribute to the estimation of fatigue loads, these checks are listed in this field and include: *Effective turbulence* (including the turbulence structure correction parameter for complex terrain), *Wind distribution*, *Flow inclination*, *Wind shear* and *Air density*.

WTG Information

This field descripes the selected wind turbine model which forms the basis of the response model - in the case shown, the model chosen is the generic turbine model for typical/intermediate rotors (≥90m) which comes with LOAD RESPONSE. The design lifetime is part of the turbine specification and is typically defined as 20 years. The bottom entry in the field specifies the mathematical response model named *Central composite approximation* – this is the response surface method previously certified by TÜV-SÜD (see Appendix IV for further details).

WTG Components

This field lists the WTG components included in the selected response model. The generic response models include the components: *Blade*, *Tower*, *Nacelle* and *Shaft*. In the actual fatigue load calculations, each component is represented by a number of cross sections and material parameters referred to as *Sensors* and *Wöhler exponents*, respectively. Manufacturer specific turbine models may include other components and sensors than those included for the generic models.

Directional resolution

LOAD RESPONSE provides three options for the directional resolution of the fatigue load assessment. All options are in accordance with the requirements in the IEC standard, however, the omnidirectional case is the default case in the IEC standard and also in LOAD REPONSE.

Omnidirectional (IEC61400-1 ed. 3, 2010)

With this option, omnidirectional values are used for all the wind climate parameter in the main IEC checks.

Sectorwise

In this option, the fatigue load estimation is performed sectorwise using the sectorial values of the wind climate parameters except for air density. Using a sectorwise wind climate partly relieves the dependence on the coarse assumptions, e.g., in the Frandsen model of effective turbulence and using the sector-weighted average of the wind shear. Thus, overall sectorwise load assessments are expected to provide more accurate results than omnidirectional assessments.

Full resolution (no effective TI integration)

This option uses the wind climate parameters wind shear, flow inclination, and total turbulence (wake+ambient) for each single degree (centred on half degrees, e.g., 0.5°, 1.5°, 2.5° etc.) with the response model. In most cases, the climate parameters do not vary within each 30 degree sector, except for turbulence, where the wake added turbulence does not align with sectors and may inflict significant variation of turbulence within sectors. The use of the “Full resolution” options avoids the need to make a Frandsen integration over all directions or over each sector to approximate the effect of varying turbulence on fatigue accumulation. In this option, the fatigue accumulation is done explicitly and directly using the response models of LOAD RESPONSE.
Note: This option has been added after the original certification by TÜV SÜD. However, it is very similar to the sectorwise option, and will, in most cases, provide close to identical results. From a theoretical perspective, this option is the most stringent one, as it relives the need for the much simplifying and disputed approximation in the Frandsen integration, which mixes the climatic parameter turbulence with the material parameter (Wöhler exponent).

Effective turbulence

For application of the Effective turbulence, LOAD RESPONSE provides two options, *variable* or *fixed*. Both options are in accordance with the IEC standard, but can result in quite different load levels mainly for the tower or other steel parts represented by low Wöhler exponents. Hence, for manufacturer specific models, it is important to use the same approach as used in the type certification of the turbine model.

Variable Wöhler exponent (IEC61400-1 ed. 3, 2010)

In this option, the Effective turbulence is calculated for all the relevant Wöhler exponents covered by the different components/sensors. For each sensor/component, the appropriate Wöhler-dependent Effective turbulence is used.

Fixed Wöhler exponent (m=XX from Site Compliance)

In this approach, the Effective turbulence is calculated only for the particular Wöhler exponent chosen by the user in the SITE COMPLIANCE calculation (the value XX, default is m=10). This Wöhler-independent Effective turbulence is used for all components/sensors regardless if their material is represented by a different Wöhler exponent.

Normalization loads

Normalization load is synonymous with ‘design load’ or ‘reference load’ which represent the denominator when calculating load indices. For generic turbine models no loads margins/reserves are known and, hence, the normalization loads are always calculated using the response model (*Use response model*) for the design wind climate for the design class in question. For manufacturer specific models the design loads are defined directly in the load response file (*From response file*), and these will be used in calculation using the turbines correct design class. However, in the special case where the user wishes to calculate for another design class than the turbine is certified for, the included design loads are no longer valid and the normalization loads must be calculated using with the *Use response model* option.

5.3.2 Results – the fatigue load estimates

Once the calculation has been run (takes a few seconds), a number of new result tabs will appear. The following text describes the content of these result tabs and serves as guidance on how to interpret the results.

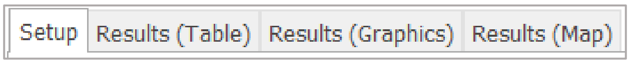


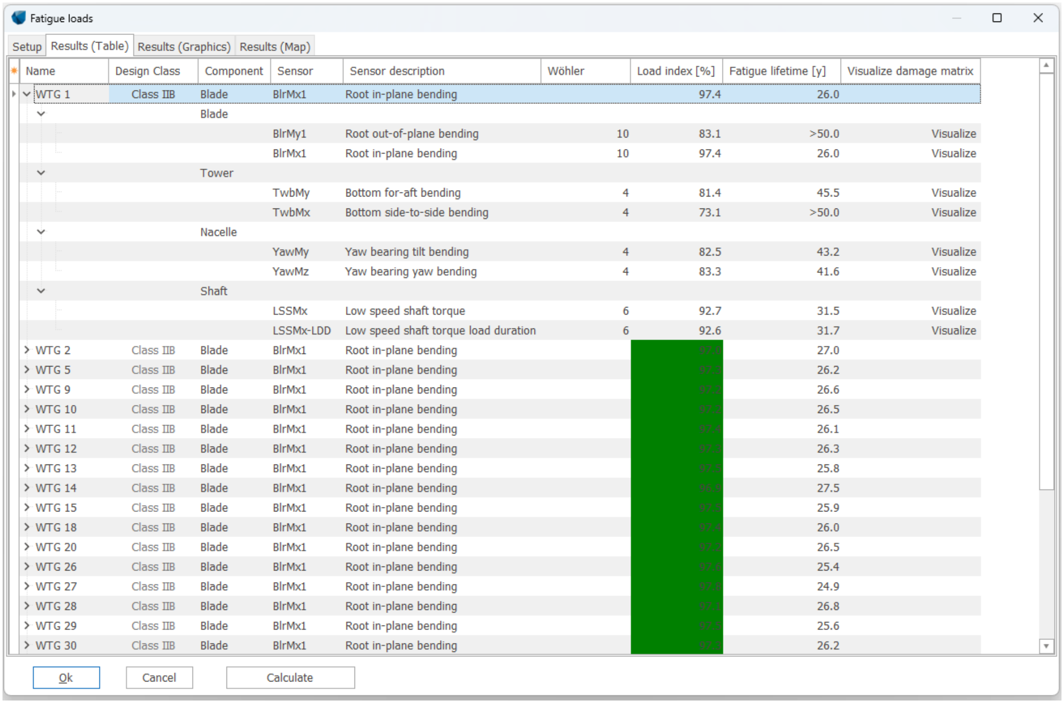
Figure 98. The result tabs, which emerge when the calculation is completed.

Results (Table)

The Result table provides the most comprehensive and complete presentation of the fatigue load results. For each WTG position, the table presents the *Load Index* for each sensor grouped according to the component it represents. For each sensor the data columns describe the following: the *Sensor description* in human language, the *Wöhler* exponent, the *Load index* and finally, a column called *Fatigue life*. For manufacturer specific turbine models, it is also possible to see the estimated fatigue loads.

Load index is simply defined as: “WTG loads” / “IEC design loads”, where IEC design loads means the loads obtained by using the wind climate parameters (limits) of the IEC design class in question, e.g., IIIA.

Fatigue life is calculated from the load index and Wöhler exponent as described in the appendix. Note that a *Load index* of 100% will result in a *Fatigue life* equal to the design lifetime - 20 years for the generic WTGs.



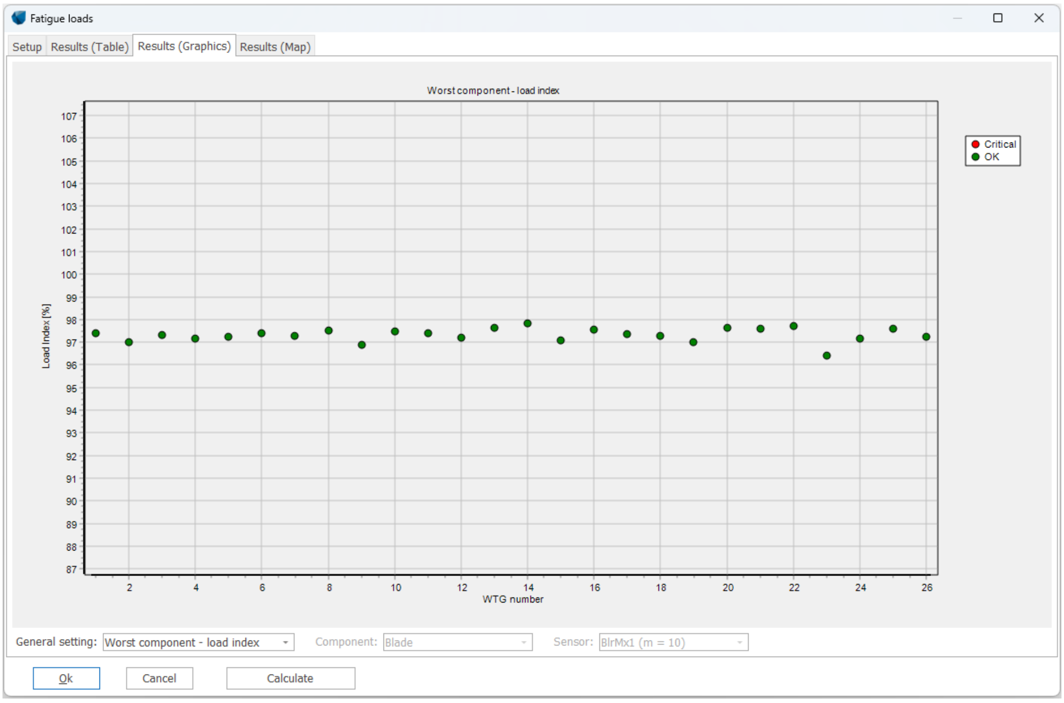
Name	Design Class	Component	Sensor	Sensor description	Wöhler	Load index [%]	Fatigue lifetime [y]	Visualize damage matrix
WTG 1	Class IIB	Blade	BlrMx1	Root in-plane bending		97.4	26.0	
		Blade						
			BlrMy1	Root out-of-plane bending	10	83.1	>50.0	Visualize
			BlrMx1	Root in-plane bending	10	97.4	26.0	Visualize
		Tower						
			TwbMy	Bottom for-aft bending	4	81.4	45.5	Visualize
			TwbMx	Bottom side-to-side bending	4	73.1	>50.0	Visualize
		Nacelle						
			YawMy	Yaw bearing tilt bending	4	82.5	43.2	Visualize
			YawMz	Yaw bearing yaw bending	4	83.3	41.6	Visualize
		Shaft						
			LSSMx	Low speed shaft torque	6	92.7	31.5	Visualize
			LSSMx-LDD	Low speed shaft torque load duration	6	92.6	31.7	Visualize
WTG 2	Class IIB	Blade	BlrMx1	Root in-plane bending		97.0	27.0	
WTG 5	Class IIB	Blade	BlrMx1	Root in-plane bending		97.3	26.2	
WTG 9	Class IIB	Blade	BlrMx1	Root in-plane bending		97.2	26.6	
WTG 10	Class IIB	Blade	BlrMx1	Root in-plane bending		97.2	26.5	
WTG 11	Class IIB	Blade	BlrMx1	Root in-plane bending		97.4	26.1	
WTG 12	Class IIB	Blade	BlrMx1	Root in-plane bending		97.3	26.3	
WTG 13	Class IIB	Blade	BlrMx1	Root in-plane bending		97.5	25.8	
WTG 14	Class IIB	Blade	BlrMx1	Root in-plane bending		96.9	27.5	
WTG 15	Class IIB	Blade	BlrMx1	Root in-plane bending		97.5	25.9	
WTG 18	Class IIB	Blade	BlrMx1	Root in-plane bending		97.4	26.0	
WTG 20	Class IIB	Blade	BlrMx1	Root in-plane bending		97.2	26.5	
WTG 26	Class IIB	Blade	BlrMx1	Root in-plane bending		97.6	25.4	
WTG 27	Class IIB	Blade	BlrMx1	Root in-plane bending		97.8	24.9	
WTG 28	Class IIB	Blade	BlrMx1	Root in-plane bending		97.1	26.8	
WTG 29	Class IIB	Blade	BlrMx1	Root in-plane bending		97.5	25.6	
WTG 30	Class IIB	Blade	BlrMx1	Root in-plane bending		97.3	26.2	

Figure 99. The Result (Table) tab.

It is important keep in mind that the fatigue life does not account for other material degradation phenomena, such as abrasion or corrosion. Fatigue life only accounts for fatigue, hence the name. Nevertheless, fatigue life estimates can be very useful to quantify the effect of extending a wind farm in terms of the accelerated material fatigue on the turbine components, e.g., blades, due to the increase in wake turbulence from installing additional turbines. Such an assessment can be done rather simply by performing two LOAD RESPONSE calculations: one without the additional turbines and one with the additional turbines. The difference in fatigue life for the original layout obtained in the two calculations is a meaningful quantification of the reduction in component (fatigue) lifetime. In the case that the existing wind farm has already been in operation for several years, this should be taken into account in the assessment.

Results (Graphics)

The graph in the *Results (Graphics)* tab shows, per default, the Load Index for the worst component/sensor for each WTG. This load index can represent different components for the different WTGs, to see which component/sensor represents the worst load index, move the cursor/mouse to the data point of interest. Use the dropdown menus below the graph to show load indices for a particular component/sensor.

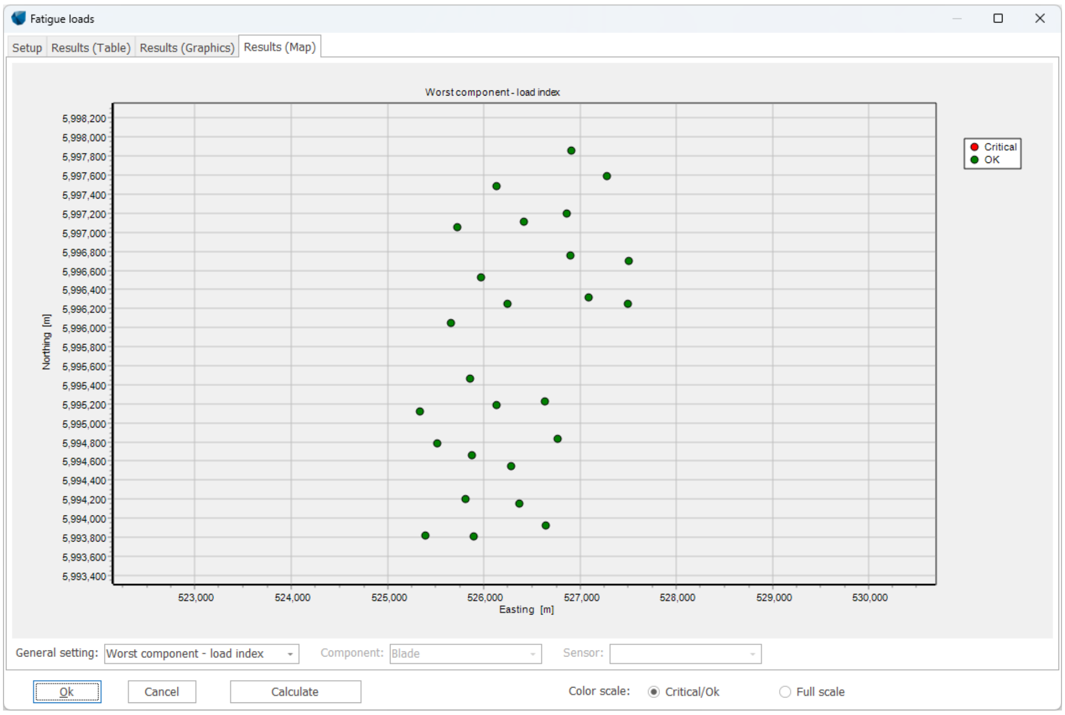


General setting: Worst component - load index
Component: Blade
Sensor: BlrMx1 (m = 10)

Figure 100. The Results (Graphics) tab.

Results (Map)

The final tab shows an overview map of the results with the relative turbine positions and a colour coding to indicate if the Load index is OK or not (i.e., below or above 100%). Again, the default view shows the results for the worst component and can be changed to any component/sensor using the dropdown menus just below the graph. The *Color scale* can be changed from binary OK / Critical (green / red) to a full color scale indicating the variation in the load across the WTG layout. This view gives the user a fast overview of the most critical wind turbines in the layout.



General setting: Worst component - load index

Component: Blade

Sensor:

Color scale: ● Critical/Ok ○ Full scale

Figure 101. The Results (Map) tab.

Visualize Damage Matrix via 'Results (Table)'

On the *Results (Table)* tab for each WTG and sensor result there is a button named *Visualize* in the left most column named *Visualize damage matrix.* By clicking this button the fatigue damage in each bin of wind speed and direction is visualized.

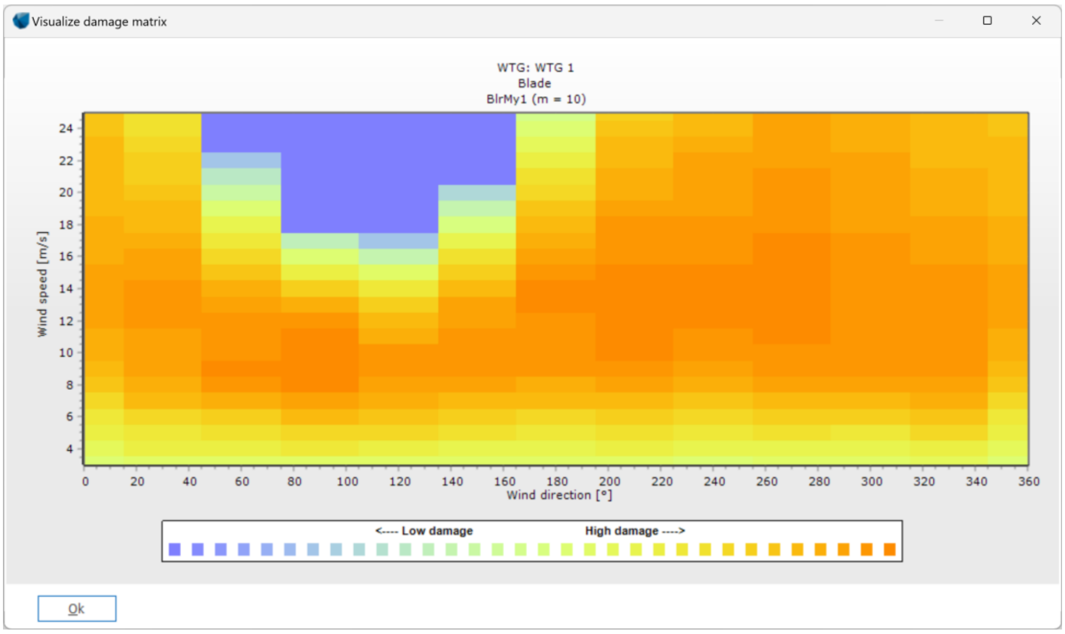


Figure 102. Visualization of a damage matrix for a sectorwise calculation. This plot shows that most damage is accumulated for operation between 70-100° & 7-12m/s and 190-290° & 10-16m/s (deep orange areas).

5.3.3 Description of the generic wind turbine models

LOAD RESPONSE comes with several generic response models:

- a model for turbines with small rotors (<90m),
- a model for turbines with typical/intermediate rotors (≥90m)
- a model for turbines with very large rotors (≥160m).
- a direct drive (DD) version of the model for typical/intermediate rotors (≥90m)

Each of these models are available with and without carbon in the blades. All these response models are based on a modern standard wind turbine design with the main characteristics being the following:
Generic turbine configuration:

- 3 blades
- Pitch control (collective)
- Standard PID controller
- Gearbox (except for the DD version)
- Steel tower
- Onshore

The underlying aero-elastic simulations for the generic response models have been run for a selection of sensors to represent the main components of the wind turbine as listed below.

Components and sensors included for the generic response models:

- Blade:
    - Root out-of-plane (DEL)
    - In-plane moment (DEL)
- Tower:
    - Bottom for-aft (DEL)
    - Side-to-side moment (DEL)
- Nacelle:
    - Yaw bearing tilt (DEL)
    - Yaw moment (DEL)
- Shaft:
    - Low-speed-shaft torque (DEL)
    - Low-speed-shaft torque (LDD)

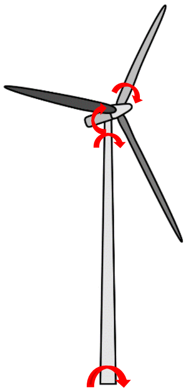


Figure 103. Left: list of sensors for the generic response models. Right: turbine sketch with the sensor hot spots indicated.

The abbreviation *DEL* indicates *Damage Equivalent Load* and *LDD* indicate *Load Duration Distribution*. The concept “damage equivalent load” refers to a common way of expressing cumulative fatigue loads. Mathematically, the DEL results from accumulating the fatigue contributions at different cycles (extracted by rainflow-counting) using Miner’s rule to get the cumulative fatigue damage. This damage is combined with a linear S-N curve to get an equivalent stress range (load) for a chosen number of cycles or cycle frequency. The resulting equivalent stress range is referred to as the *Damage Equivalent Load*. The linear S-N curve (defined by the Wöhler exponent m) relates stress range to number of cycles to failure. Load duration distribution is a very similar concept for load durations which better represents damage accumulation in mechanical components, e.g., gearboxes (See Appendix IV for further details).

Wind turbine manufactures who wish to implement their own turbines in LOAD RESPONSE can freely choose their preferred combination of sensors and component groups independent of the setup EMD has chosen for the generic turbine models. The main principles of adding manufacturer specific response models are described in the following section.

5.3.4 How-to add a new turbine load response model (manufacturers only)

Wind turbine manufacturers are recommended to implement their own turbine models for in-house use in LOAD RESPONSE. This will enable them to perform very fast and accurate fatigue load assessments to speed-up the internal project turnaround time by optimizing the interaction between the wind & site department and the load department.

The pre-requisite to implement a wind turbine is to run a number of aero-elastic simulations using the particular turbine model. A document specifying these required runs and the format in which to save them is available from EMD upon request[13]. It is important to note that all aero-elastic simulations and post-processing are done in-house by the manufacturer and using the manufacturers own in-house tools. See the figure below:

---

[13] Please contact: Troels Juul Pedersen, tjp@emd.dk

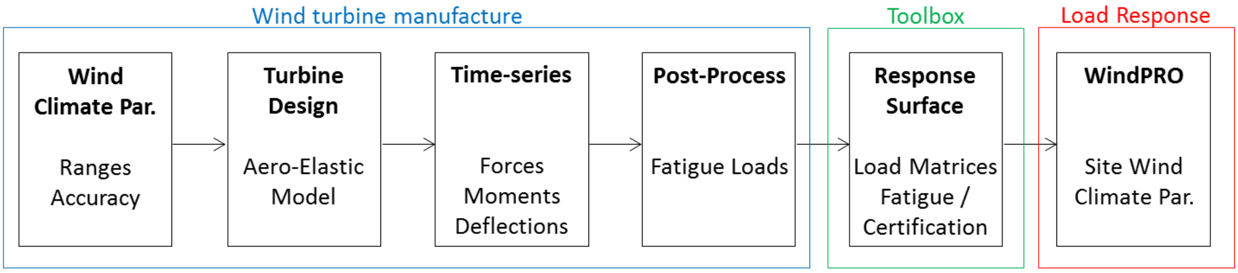


Figure 104. Schematic representation of the steps in order to implement wind turbines LOAD RESPONSE.

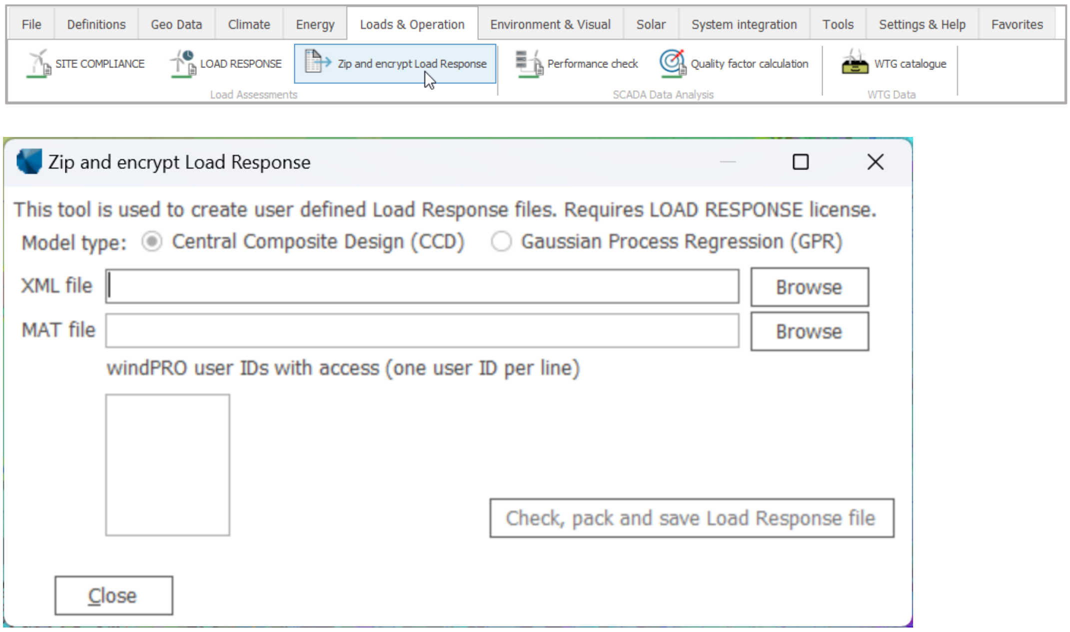
Once the required aero-elastic simulations and post-processing is completed, the results need to be saved in a standard binary file format, “mat”-format also used in MATLAB. The formatting is described in the EMD reference document for turbine implementation [13]. In addition, an “xml”-file is required, which describes the general name and configuration of the wind turbine model. Once the mat-file and xml-file have been prepared, the next step is to wrap and encrypt the files into windPRO’s internal “.loadresponse” file format. In this process, it is also possible to define which windPRO license number will be allowed to use the file from LOAD RESPONSE in windPRO (given the.loadresponse file is available). In summary, the LOAD RESPONSE files implemented by turbine manufacturers for in-house use have the following three layers of security:

- **Encrypted file format** - the aero-elastics data a stored in a binary format with encryption
- **License control** - the manufacturer decides exactly which windPRO licenses can access the file
- **File sharing** - only users which have received the specific load response file from the manufacturer and copied it to the PC can use it (if their license allows it, see above)

As an additional fourth layer of security, the manufacturer can choose to normalize all the aero-elastic load input data for the response model with an arbitrary constant only known to the manufacturer. This will not influence the main result - the load indices - as they are the ratio of WTG loads to IEC design loads which will both contain the constant.

Zip and Encrypt tool

The “*Zip and encrypt Load Response*” tool is accessed via the *Loads & Operation* menu in windPRO 4.0 as shown in the figure below. Note that this tool can only be used with a valid license for LOAD RESPONSE.



This tool is used to create user defined Load Response files. Requires LOAD RESPONSE license.

Model type: ● Central Composite Design (CCD) ○ Gaussian Process Regression (GPR)

XML file

MAT file

windPRO user IDs with access (one user ID per line)

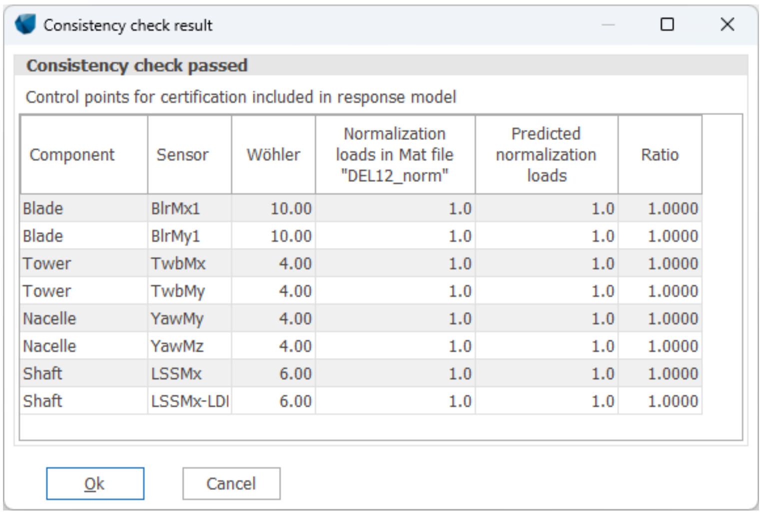
Figure 105. Top: How to open the “Zip and Encrypt Load Response” tool via Tools menu. Bottom: The “Zip and Encrypt Load Response” tool.

Once opened the Zip and Encrypt tool provides an interface to:

- Select with type of model type.
- Select the required .XML file describing the turbine and the aero-elastic runs
- Select the required .MAT file with the fatigue loads from the aero-elastic simulations
- Define which user license IDs are allowed to access the response file from windPRO

Note: If the field with user IDs is left blank, there will be no restriction in terms of which license IDs can access the file in windPRO – of course, given that the file has been copied to the user's PC.

Once all the required inputs have been defined, press the button *Check, Pack and save loadsponse file*. The file should be saved in the LoadResponse folder in windPRO Data: "…./windPRO Data/LoadResponse". Once completed, a window will pop-up (see Figure 106) with a summary of the consistency checks of the xml and mat files.



Consistency check passed

Control points for certification included in response model

Component	Sensor	Wöhler	Normalization loads in Mat file "DEL12_norm"	Predicted normalization loads	Ratio
Blade	BlrMx1	10.00	1.0	1.0	1.0000
Blade	BlrMy1	10.00	1.0	1.0	1.0000
Tower	TwbMx	4.00	1.0	1.0	1.0000
Tower	TwbMy	4.00	1.0	1.0	1.0000
Nacelle	YawMy	4.00	1.0	1.0	1.0000
Nacelle	YawMz	4.00	1.0	1.0	1.0000
Shaft	LSSMx	6.00	1.0	1.0	1.0000
Shaft	LSSMx-LDI	6.00	1.0	1.0	1.0000

Figure 106. Summary of the consistency checks for the selected xml and mat file.

If allowed by the license check, the saved specific wind turbine model will now appear as a selectable response file in LOAD RESPONSE.

Accuracy tab and Certification requirements

For manufacturer specific wind turbine models implemented in LOAD RESPONSE, certain restrictions have been agreed between EMD and TÜV-SÜD as part of the original certification of LOAD RESPONSE. These restrictions ensure that the accuracy of the response model is acceptable for the combination of the manufacturer specific model and WTG climate parameters for the site in question.

Note that since these requirements were based on a surrogate model developed using the Central Composite Design (CCD), these tabs are not available when using a model based on Gaussian Process Regression (GPR).

These certification restrictions apply if the results are used in official contexts as, e.g., in a building permit. For this reason, an additional result tab named *Accuracy* will appear in LOAD RESPONSE when used with manufacturer specific in-house turbines. The top of the tab summarizes the check against the requirements. The following text describes the details of the two check criteria on the *Accuracy* tab.

Evaluation of accuracy for specific response model:

Response model: EMD Specific II-B

Deviation of WTG wind climate parameters: OK

Accuracy of response model: OK

Figure 107. Accuracy tab (top part only) with the summary of the accuracy checks.

Deviation of WTG climate parameters (Accuracy tab)

First sub-tab on the *Accuracy* tab is an analysis of the of the WTG wind climate parameters relative to the reference conditions in the response model and the limit agreed in the original certification. The reason for this check is that the response model is based on a number of aero-elastic simulations covering the typical region of variation of the four WTG wind climate parameters: Effective turbulence (I_{ref}), Wind shear (α), Inflow angle (φ) and Air density (ρ). However, if the WTG wind climate parameters are significantly outside the region covered by the response model, the error on the response model will increase and it's accuracy decrease. To estimate how far outside the area covered by the response model a WTG wind climate is, a normalized "radius" is caculated for each WTG. This radius is simply the euclidian distance from the reference point ($I_{ref,0}$, α_0, φ_0, ρ_0) of the response model (typically the IEC design climate of the relevant class) to the WTG wind climate in the four dimensional (I_{ref}, α, φ, ρ) space. However, each of the four dimensions (axes) are normalized to a characteristic step length used in the response model (ΔI_{ref} , Δα, Δφ, Δρ) as is evident from the equation:

$$R_{norm} = \sqrt{\left(\frac{I_{ref} - I_{ref,0}}{\Delta I_{ref}}\right)^2 + \left(\frac{\alpha - \alpha_0}{\Delta\alpha}\right)^2 + \left(\frac{\varphi - \varphi_0}{\Delta\varphi}\right)^2 + \left(\frac{\rho - \rho_0}{\Delta\rho}\right)^2} \leq 2.5$$

As an example, let us take a case where a WTG has all wind climate parameters equal to the IEC class except for the Air density, which is one step length (Δρ) higher than the reference. In this case, the normalized radius becomes equal to R_{norm}=1.

Evaluation of accuracy for specific response model:

Response model: EMD Specific II-B

Deviation of WTG wind climate parameters: OK

Accuracy of response model: OK

Check of WTG wind climate parameters

To ensure the accuracy required in the certification of the reponse model, wind climate parameters are only allowed to vary with in a certain "normalized radius" from the IEC wind climate.

The normalized radius for each WTG climate is calculated from the air density, wind shear, effective turbulence and inflow angle. See the manual for further details.

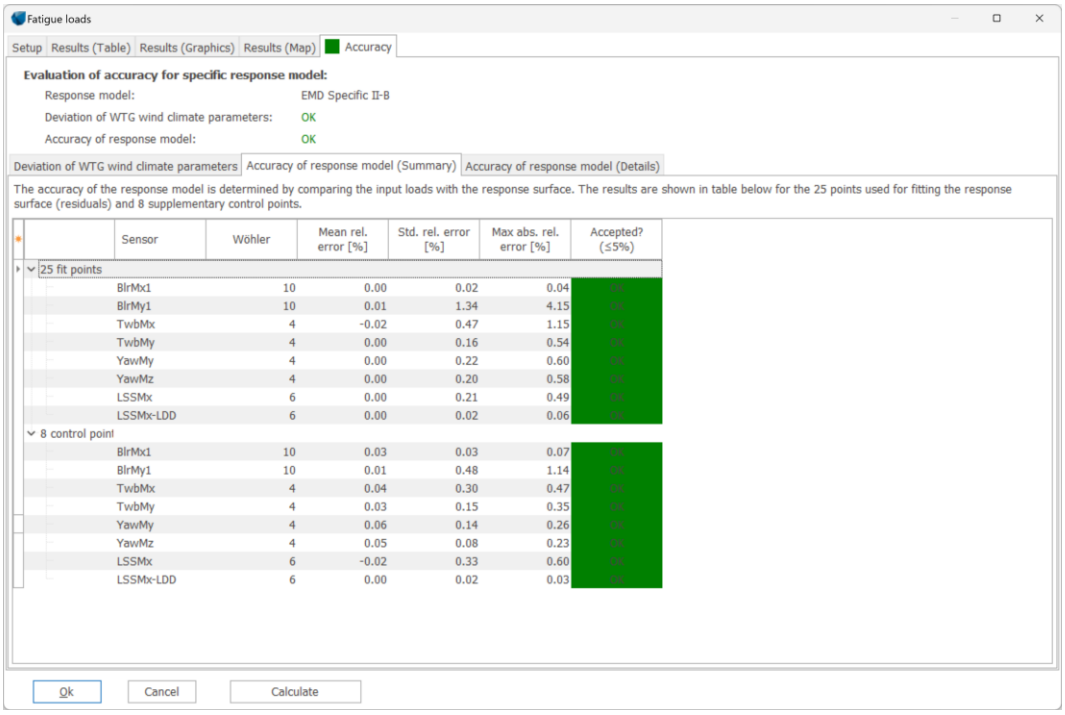
The maximum deviation required by the certification is a normalized radius of 2.5.

Figure 108. Accuracy tab showing the deviation of site climate parameters from the reference climate (manufacturer specific response files only).

Accuracy of response model (Accuracy tab)

The response model in LOAD RESPONSE is based on a fit to 25 combinations of wind climate parameters at each wind speed bin. Each sensor has its own response model. For each sensor and each of the 25 "fit points", it is possible to calculate the error or residual of the fit. The sub-tab *Accuracy of response model* summarizes the errors for these 25 "fit points" in terms of the maximum absolute relative error.

In addition to the 25 fit points, 8 additional "control points" are required to fullfill the requirements of the original certification. These 8 control points are not used in the fit, and thus, allow for an extra independent check of the accuracy of the model. The errors for the control points are also summarized in the sub-tab *Accuracy of response model*.



Evaluation of accuracy for specific response model:

Response model: EMD Specific II-B

Deviation of WTG wind climate parameters: OK

Accuracy of response model: OK

The accuracy of the response model is determined by comparing the input loads with the response surface. The results are shown in table below for the 25 points used for fitting the response surface (residuals) and 8 supplementary control points.

	Sensor	Wöhler	Mean rel. error [%]	Std. rel. error [%]	Max abs. rel. error [%]	Accepted? (≤5%)
25 fit points						
	BlrMx1	10	0.00	0.02	0.04	OK
	BlrMy1	10	0.01	1.34	4.15	OK
	TwbMx	4	-0.02	0.47	1.15	OK
	TwbMy	4	0.00	0.16	0.54	OK
	YawMy	4	0.00	0.22	0.60	OK
	YawMz	4	0.00	0.20	0.58	OK
	LSSMx	6	0.00	0.21	0.49	OK
	LSSMx-LDD	6	0.00	0.02	0.06	OK
8 control point						
	BlrMx1	10	0.03	0.03	0.07	OK
	BlrMy1	10	0.01	0.48	1.14	OK
	TwbMx	4	0.04	0.30	0.47	OK
	TwbMy	4	0.03	0.15	0.35	OK
	YawMy	4	0.06	0.14	0.26	OK
	YawMz	4	0.05	0.08	0.23	OK
	LSSMx	6	-0.02	0.33	0.60	OK
	LSSMx-LDD	6	0.00	0.02	0.03	OK

Figure 109. Accuracy tab showing the check of the response surface accuracy for the fitted 25 points and for the 8 supplementary accuracy control points. In the case shown, the error/deviation for all points are within the acceptable limit.

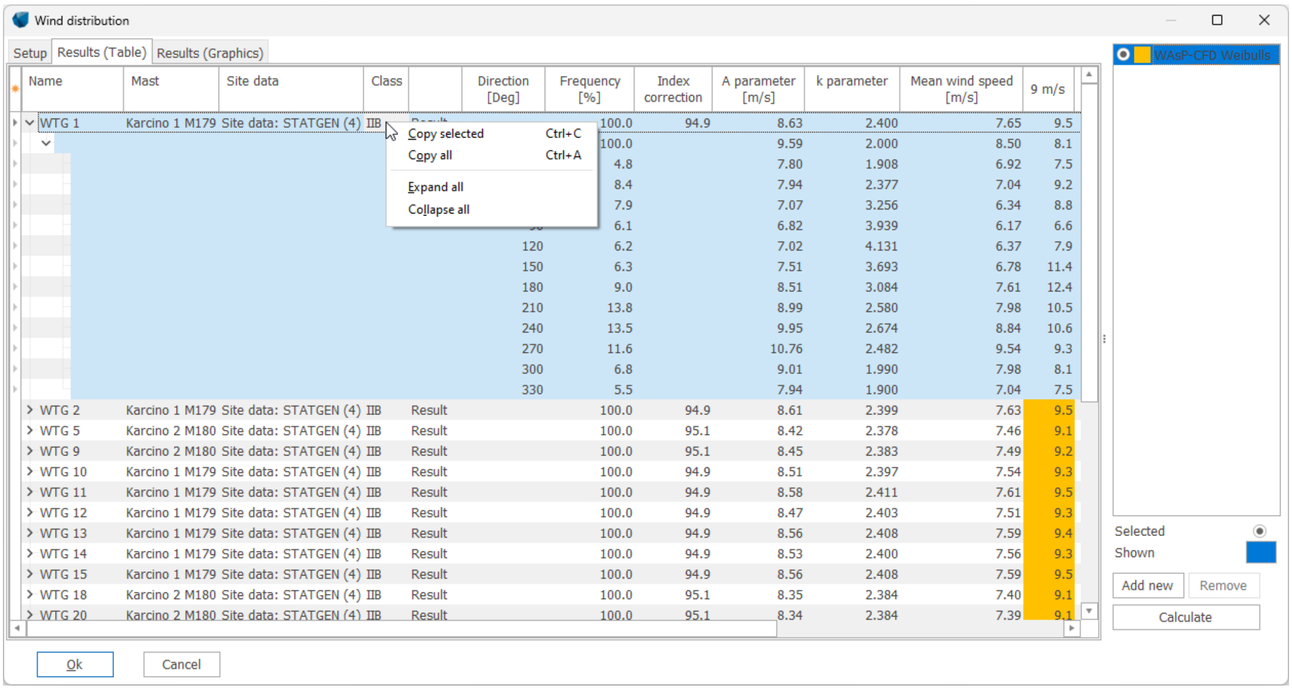
5.3.5 Fatigue Loads in OPTIMIZE

Users with an active LOAD RESPONSE license can also enable fatigue lifetime constraints in the layout optimization within the OPTIMIZE module.

Both specific and generic turbine models can be used in the OPTIMIZE module. However, only specific turbine models based on the Central Composite Design (CCD) are available.

5.4 Exports and Result-to-file

All result tables inside each of the SITE COMPLIANCE check calculations and LOAD RESPONSE results may be copied and pasted to, e.g., Excel (see the figure below).



Name	Mast	Site data	Class		Direction [Deg]	Frequency [%]	Index correction	A parameter [m/s]	k parameter	Mean wind speed [m/s]	9 m/s
WTG 1	Karcino 1 M179	Site data: STATGEN (4)	IIB			100.0	94.9	8.63	2.400	7.65	9.5
						100.0		9.59	2.000	8.50	8.1
						4.8		7.80	1.908	6.92	7.5
						8.4		7.94	2.377	7.04	9.2
						7.9		7.07	3.256	6.34	8.8
						6.1		6.82	3.939	6.17	6.6
					120	6.2		7.02	4.131	6.37	7.9
					150	6.3		7.51	3.693	6.78	11.4
					180	9.0		8.51	3.084	7.61	12.4
					210	13.8		8.99	2.580	7.98	10.5
					240	13.5		9.95	2.674	8.84	10.6
					270	11.6		10.76	2.482	9.54	9.3
					300	6.8		9.01	1.990	7.98	8.1
					330	5.5		7.94	1.900	7.04	7.5
WTG 2	Karcino 1 M179	Site data: STATGEN (4)	IIB	Result		100.0	94.9	8.61	2.399	7.63	9.5
WTG 5	Karcino 2 M180	Site data: STATGEN (4)	IIB	Result		100.0	95.1	8.42	2.378	7.46	9.1
WTG 9	Karcino 2 M180	Site data: STATGEN (4)	IIB	Result		100.0	95.1	8.45	2.383	7.49	9.2
WTG 10	Karcino 1 M179	Site data: STATGEN (4)	IIB	Result		100.0	94.9	8.51	2.397	7.54	9.3
WTG 11	Karcino 1 M179	Site data: STATGEN (4)	IIB	Result		100.0	94.9	8.58	2.411	7.61	9.5
WTG 12	Karcino 1 M179	Site data: STATGEN (4)	IIB	Result		100.0	94.9	8.47	2.403	7.51	9.3
WTG 13	Karcino 1 M179	Site data: STATGEN (4)	IIB	Result		100.0	94.9	8.56	2.408	7.59	9.4
WTG 14	Karcino 1 M179	Site data: STATGEN (4)	IIB	Result		100.0	94.9	8.53	2.400	7.56	9.3
WTG 15	Karcino 1 M179	Site data: STATGEN (4)	IIB	Result		100.0	94.9	8.56	2.408	7.59	9.5
WTG 18	Karcino 2 M180	Site data: STATGEN (4)	IIB	Result		100.0	95.1	8.35	2.384	7.40	9.1
WTG 20	Karcino 2 M180	Site data: STATGEN (4)	IIB	Result		100.0	95.1	8.34	2.384	7.39	9.1

Figure 110. Example of copying data from the results table of a check. Notice the options to copy only the selected part or to copy all of the table including all expandable levels.

Another way of exporting results and data from the module is available once a calculation is completed and closed by clicking OK. The user may right-click on the SITE COMPLIANCE calculation and select the Result-to-file option. This action results in a rather long list of export options available (see below).

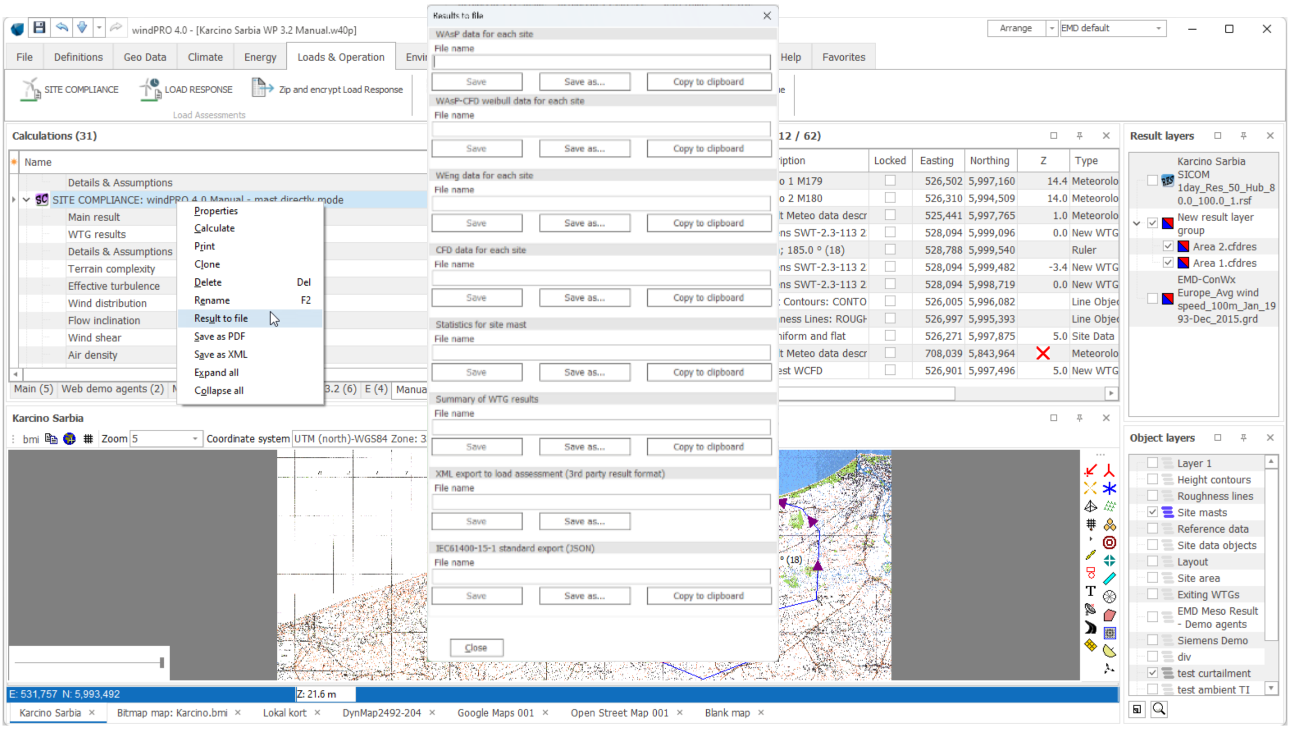


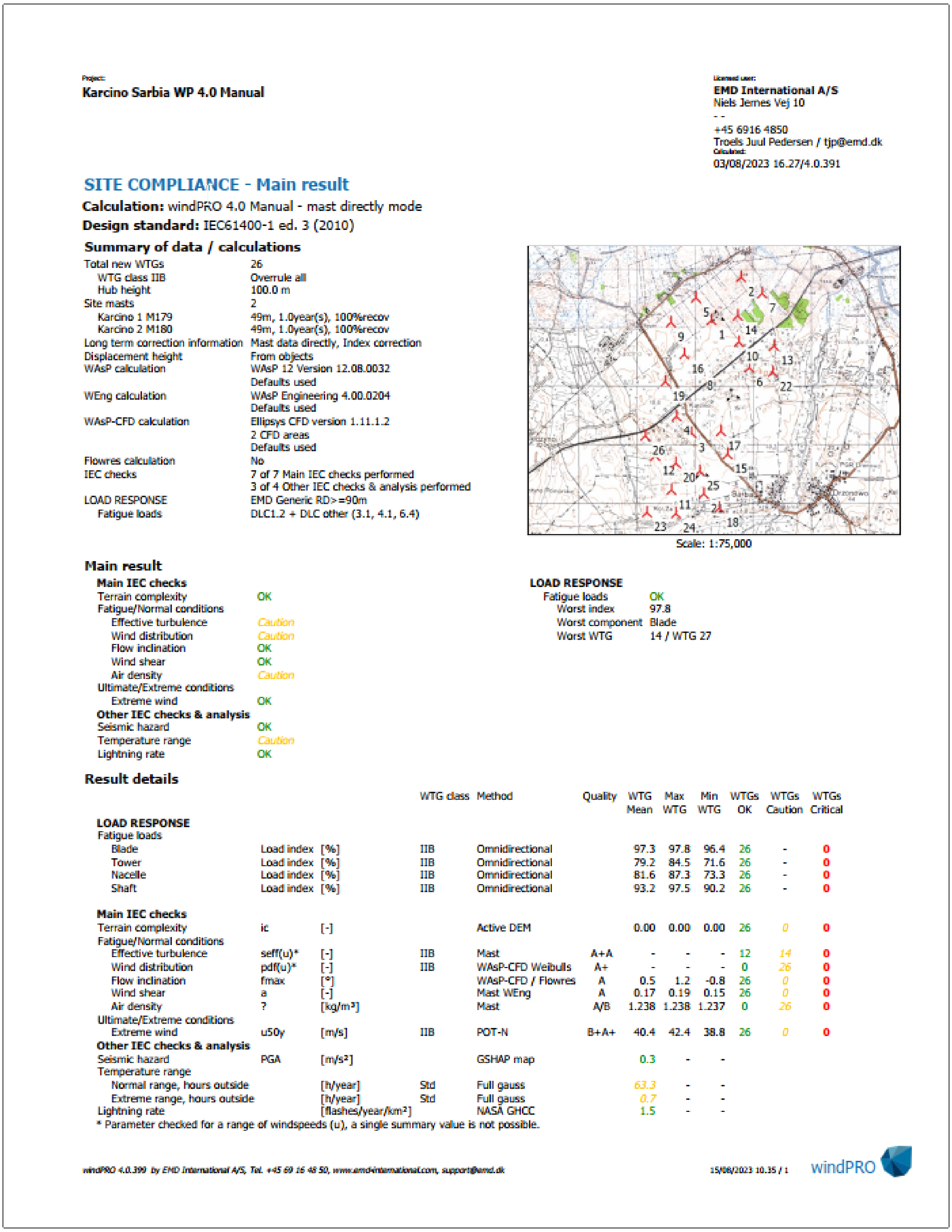
Figure 111. Result-to-file menu accessed via right-clicking on the calculation.

The following outlines each export option in SITE COMPLIANCE along the given requirement before the option is available.

- **WAsP data for each site**
    - **Description:** Includes position, sector-wise Weibull parameters, sector frequencies, and shear exponent with and without displacement height for selected mast(s) and WTG(s). These values are inputs to the SITE COMPLIANCE propagation model and may differ from values in result tables.
    - **Requirements:** WAsP selected in flow model(s) and calculation completed.
- **WAsP-CFD weibull data for each site or Flowres weibull data for each site**
    - **Description:** Contains similar information as the WAsP data for each site export.
    - **Requirements:** WAsP-CFD selected in flow model(s) or using Flowres CFD results and calculation completed.
- **WEng data for each Site**
    - **Description:** Includes position, sector-wise Weibull parameters, sector frequencies, turbulence components, turbulence intensity, turbulence correction factor, and shear exponent with and without displacement height for selected mast(s) and WTG(s). These values are inputs to the SITE COMPLIANCE propagation model and may differ from values in result tables.
    - **Requirements:** WEng selected in flow model(s) and calculation completed.
- **CFD data for each site or Flowres data for each site**
    - **Description:** Includes height, sector-wise wind speed, wind direction, speed up, mesoscale roughness, flow inclination, and turbulence intensity for selected mast(s) and WTG(s).
    - **Requirements:** WAsP-CFD selected in flow model(s) or using Flowres CFD results and calculation completed.
- **Statistics for site mast (all in one file and in separate files)**
    - **Description:** Includes position, measurement duration, recovery rate, wind climate parameters (e.g., Weibull parameters, mean wind speed, turbulence intensity, wind shear, air density, inflow angle), extreme wind conditions (e.g., 50-year wind), and environmental conditions (e.g., temperature, lighting rate, seismic hazard).
    - **Requirements:** Mast(s) data used in SITE COMPLIANCE calculation.
- **Summary of WTG results**
    - **Description:** Provides all relevant information from the SITE COMPLIANCE calculation, including summaries of mast(s), flow model(s), methods used for IEC checks, and siting parameters summary for each selected WTG(s).
    - **Requirements:** IEC checks completed in SITE COMPLIANCE.
- **XML export to load assessment (3rd party result format)**
    - **Description:** Includes position, wind turbine characteristics (e.g., rated power, rotor diameter), extreme and normal wind conditions for selected WTG(s). Can be used in the LOAD RESPONSE module for fatigue load assessment.
    - **Requirements:** IEC checks completed in SITE COMPLIANCE.
- **IEC 61400-15-1 Standard Export (JSON)**
    - **Description:** Contains input parameters for site suitability analyses as per the preliminary IEC standard 61400-15-1. The export is formatted as a JSON file, subject to future modifications as the standard evolves.
    - **Requirements:** IEC checks completed in SITE COMPLIANCE.

5.5 Reports and printing

Main result



Project:
Karcino Sarbia WP 4.0 Manual

Licensed user:
EMD International A/S
Niels Jernes Vej 10
- -
+45 6916 4850
Troels Juul Pedersen / tjp@emd.dk
Calculated:
03/08/2023 16.27/4.0.391

SITE COMPLIANCE - Main result

Calculation: windPRO 4.0 Manual - mast directly mode

Design standard: IEC61400-1 ed. 3 (2010)

Summary of data / calculations

Total new WTGs	26
WTG class IIB	Overrule all
Hub height	100.0 m
Site masts	2
Karcino 1 M179	49m, 1.0year(s), 100%recov
Karcino 2 M180	49m, 1.0year(s), 100%recov
Long term correction information	Mast data directly, Index correction
Displacement height	From objects
WAsP calculation	WAsP 12 Version 12.08.0032 Defaults used
WEng calculation	WAsP Engineering 4.00.0204 Defaults used
WAsP-CFD calculation	Ellipsys CFD version 1.11.1.2 2 CFD areas Defaults used
Flowres calculation	No
IEC checks	7 of 7 Main IEC checks performed 3 of 4 Other IEC checks & analysis performed
LOAD RESPONSE	EMD Generic RD>=90m
Fatigue loads	DLC1.2 + DLC other (3.1, 4.1, 6.4)

Scale: 1:75,000

Main result

Main IEC checks	
Terrain complexity	OK
Fatigue/Normal conditions	
Effective turbulence	*Caution*
Wind distribution	*Caution*
Flow inclination	OK
Wind shear	OK
Air density	*Caution*
Ultimate/Extreme conditions	
Extreme wind	OK
Other IEC checks & analysis	
Seismic hazard	OK
Temperature range	*Caution*
Lightning rate	OK

LOAD RESPONSE	
Fatigue loads	OK
Worst index	97.8
Worst component	Blade
Worst WTG	14 / WTG 27

Result details

			WTG class	Method	Quality	WTG Mean	Max WTG	Min WTG	WTGs OK	WTGs Caution	WTGs Critical
LOAD RESPONSE											
Fatigue loads											
Blade	Load index	[%]	IIB	Omnidirectional		97.3	97.8	96.4	26	-	0
Tower	Load index	[%]	IIB	Omnidirectional		79.2	84.5	71.6	26	-	0
Nacelle	Load index	[%]	IIB	Omnidirectional		81.6	87.3	73.3	26	-	0
Shaft	Load index	[%]	IIB	Omnidirectional		93.2	97.5	90.2	26	-	0
Main IEC checks											
Terrain complexity	ic	[-]		Active DEM		0.00	0.00	0.00	26	*0*	0
Fatigue/Normal conditions											
Effective turbulence	seff(u)*	[-]	IIB	Mast	A+A	-	-	-	12	*14*	0
Wind distribution	pdf(u)*	[-]	IIB	WAsP-CFD Weibulls	A+	-	-	-	0	*26*	0
Flow inclination	fmax	[°]		WAsP-CFD / Flowres	A	0.5	1.2	-0.8	26	*0*	0
Wind shear	a	[-]		Mast WEng	A	0.17	0.19	0.15	26	*0*	0
Air density	?	[kg/m³]		Mast	A/B	1.238	1.238	1.237	0	*26*	0
Ultimate/Extreme conditions											
Extreme wind	u50y	[m/s]	IIB	POT-N	B+A+	40.4	42.4	38.8	26	*0*	0
Other IEC checks & analysis											
Seismic hazard	PGA	[m/s²]		GSHAP map		0.3	-	-			
Temperature range											
Normal range, hours outside		[h/year]	Std	Full gauss		*63.3*	-	-			
Extreme range, hours outside		[h/year]	Std	Full gauss		*0.7*	-	-			
Lightning rate		[flashes/year/km²]		NASA GHCC		1.5	-	-			

* Parameter checked for a range of windspeeds (u), a single summary value is not possible.

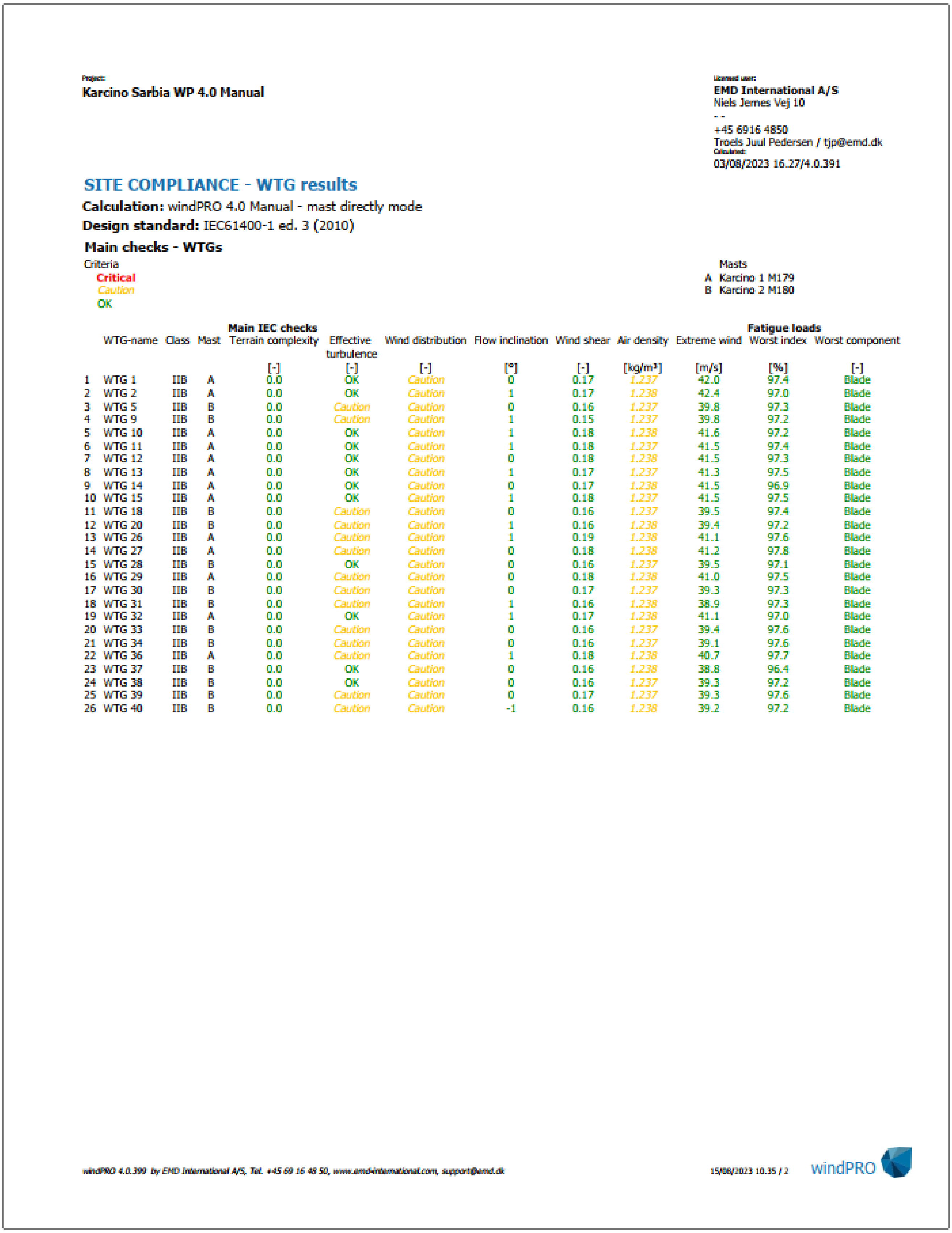
windPRO 4.0.399 by EMD International A/S, Tel. +45 69 16 48 50, www.emd-international.com, support@emd.dk

15/08/2023 10.35 / 1

windPRO

Figure 112. The main page of the report highlights the conclusion of the site assessment and gives an overview of the results on a park level in the table.

WTG results



Project:
Karcino Sarbia WP 4.0 Manual

Licensed user:
EMD International A/S
Niels Jernes Vej 10
- -
+45 6916 4850
Troels Juul Pedersen / tjp@emd.dk
Calculated:
03/08/2023 16.27/4.0.391

SITE COMPLIANCE - WTG results

Calculation: windPRO 4.0 Manual - mast directly mode

Design standard: IEC61400-1 ed. 3 (2010)

Main checks - WTGs

Criteria
- **Critical**
- *Caution*
- OK

Masts
A Karcino 1 M179
B Karcino 2 M180

				Main IEC checks							Fatigue loads	
	WTG-name	Class	Mast	Terrain complexity	Effective turbulence	Wind distribution	Flow inclination	Wind shear	Air density	Extreme wind	Worst index	Worst component
				[-]	[-]	[-]	[°]	[-]	[kg/m³]	[m/s]	[%]	[-]
1	WTG 1	IIB	A	0.0	OK	*Caution*	0	0.17	*1.237*	42.0	97.4	Blade
2	WTG 2	IIB	A	0.0	OK	*Caution*	1	0.17	*1.238*	42.4	97.0	Blade
3	WTG 5	IIB	B	0.0	*Caution*	*Caution*	0	0.16	*1.237*	39.8	97.3	Blade
4	WTG 9	IIB	B	0.0	*Caution*	*Caution*	1	0.15	*1.237*	39.8	97.2	Blade
5	WTG 10	IIB	A	0.0	OK	*Caution*	1	0.18	*1.238*	41.6	97.2	Blade
6	WTG 11	IIB	A	0.0	OK	*Caution*	1	0.18	*1.237*	41.5	97.4	Blade
7	WTG 12	IIB	A	0.0	OK	*Caution*	0	0.18	*1.238*	41.5	97.3	Blade
8	WTG 13	IIB	A	0.0	OK	*Caution*	1	0.17	*1.237*	41.3	97.5	Blade
9	WTG 14	IIB	A	0.0	OK	*Caution*	0	0.17	*1.238*	41.5	96.9	Blade
10	WTG 15	IIB	A	0.0	OK	*Caution*	1	0.18	*1.237*	41.5	97.5	Blade
11	WTG 18	IIB	B	0.0	*Caution*	*Caution*	0	0.16	*1.237*	39.5	97.4	Blade
12	WTG 20	IIB	B	0.0	*Caution*	*Caution*	1	0.16	*1.238*	39.4	97.2	Blade
13	WTG 26	IIB	A	0.0	*Caution*	*Caution*	1	0.19	*1.238*	41.1	97.6	Blade
14	WTG 27	IIB	A	0.0	*Caution*	*Caution*	0	0.18	*1.238*	41.2	97.8	Blade
15	WTG 28	IIB	B	0.0	OK	*Caution*	0	0.16	*1.237*	39.5	97.1	Blade
16	WTG 29	IIB	A	0.0	*Caution*	*Caution*	0	0.18	*1.238*	41.0	97.5	Blade
17	WTG 30	IIB	B	0.0	*Caution*	*Caution*	0	0.17	*1.237*	39.3	97.3	Blade
18	WTG 31	IIB	B	0.0	*Caution*	*Caution*	1	0.16	*1.238*	38.9	97.3	Blade
19	WTG 32	IIB	A	0.0	OK	*Caution*	1	0.17	*1.238*	41.1	97.0	Blade
20	WTG 33	IIB	B	0.0	*Caution*	*Caution*	0	0.16	*1.237*	39.4	97.6	Blade
21	WTG 34	IIB	B	0.0	*Caution*	*Caution*	0	0.16	*1.237*	39.1	97.6	Blade
22	WTG 36	IIB	A	0.0	*Caution*	*Caution*	1	0.18	*1.238*	40.7	97.7	Blade
23	WTG 37	IIB	B	0.0	OK	*Caution*	0	0.16	*1.238*	38.8	96.4	Blade
24	WTG 38	IIB	B	0.0	OK	*Caution*	0	0.16	*1.237*	39.3	97.2	Blade
25	WTG 39	IIB	B	0.0	*Caution*	*Caution*	0	0.17	*1.237*	39.3	97.6	Blade
26	WTG 40	IIB	B	0.0	*Caution*	*Caution*	-1	0.16	*1.238*	39.2	97.2	Blade

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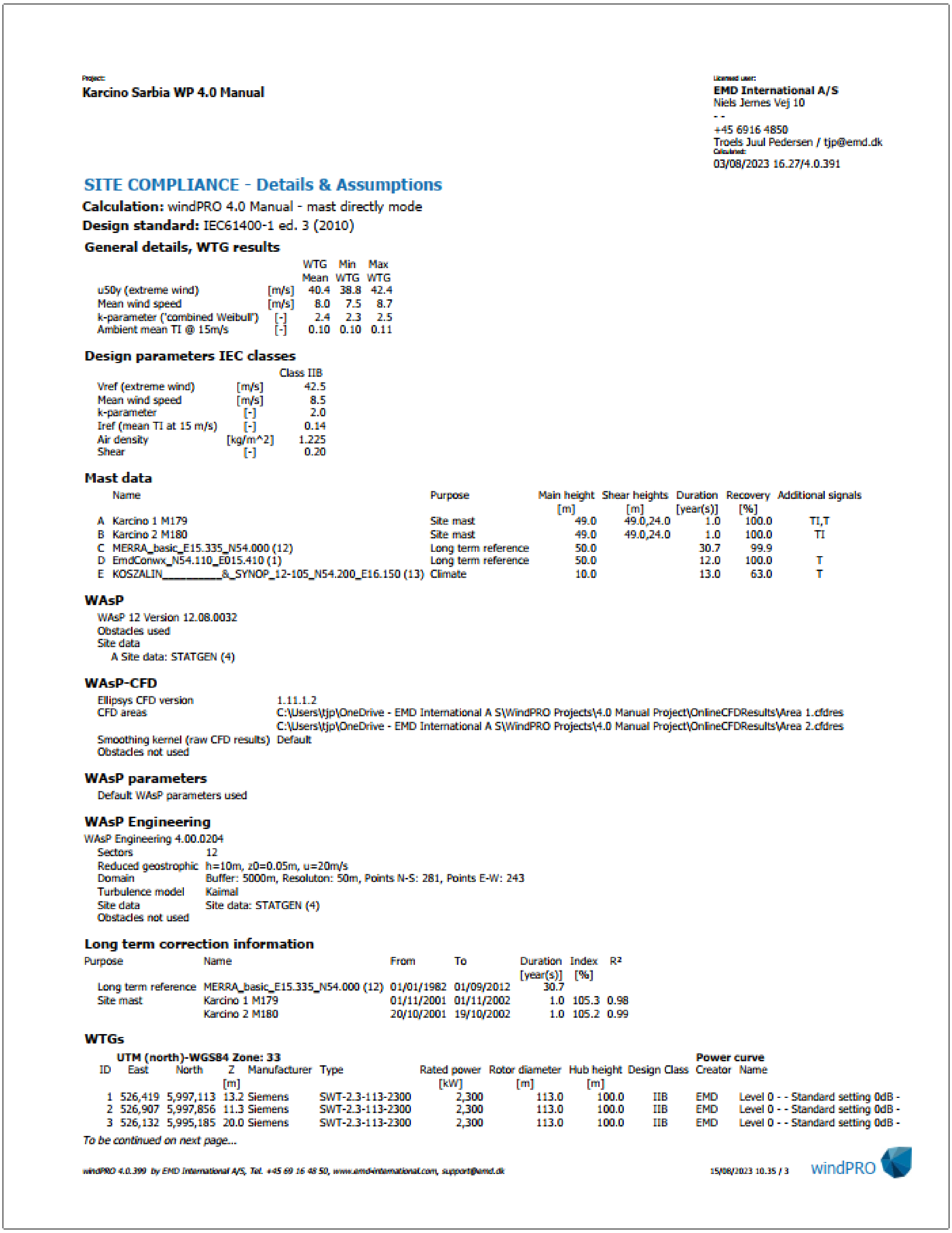
Figure 113. Second report page summarizing the results of all the main checks (columns) for each WTG (rows).

Details and Assumptions



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SITE COMPLIANCE - Details & Assumptions

Calculation: windPRO 4.0 Manual - mast directly mode
Design standard: IEC61400-1 ed. 3 (2010)

General details, WTG results

		WTG Mean	Min WTG	Max WTG
u50y (extreme wind)	[m/s]	40.4	38.8	42.4
Mean wind speed	[m/s]	8.0	7.5	8.7
k-parameter ('combined Weibull')	[-]	2.4	2.3	2.5
Ambient mean TI @ 15m/s	[-]	0.10	0.10	0.11

Design parameters IEC classes

		Class IIB
Vref (extreme wind)	[m/s]	42.5
Mean wind speed	[m/s]	8.5
k-parameter	[-]	2.0
Iref (mean TI at 15 m/s)	[-]	0.14
Air density	[kg/m^2]	1.225
Shear	[-]	0.20

Mast data

	Name	Purpose	Main height [m]	Shear heights [m]	Duration [year(s)]	Recovery [%]	Additional signals
A	Karcino 1 M179	Site mast	49.0	49.0,24.0	1.0	100.0	TI,T
B	Karcino 2 M180	Site mast	49.0	49.0,24.0	1.0	100.0	TI
C	MERRA_basic_E15.335_N54.000 (12)	Long term reference	50.0		30.7	99.9	
D	EmdConwx_N54.110_E015.410 (1)	Long term reference	50.0		12.0	100.0	T
E	KOSZALIN__________&_SYNOP_12-105_N54.200_E16.150 (13)	Climate	10.0		13.0	63.0	T

WAsP

WAsP 12 Version 12.08.0032
Obstacles used
Site data
A Site data: STATGEN (4)

WAsP-CFD

Ellipsys CFD version	1.11.1.2
CFD areas	C:\Users\tjp\OneDrive - EMD International A S\WindPRO Projects\4.0 Manual Project\OnlineCFDResults\Area 1.cfdres C:\Users\tjp\OneDrive - EMD International A S\WindPRO Projects\4.0 Manual Project\OnlineCFDResults\Area 2.cfdres
Smoothing kernel (raw CFD results)	Default
Obstacles not used	

WAsP parameters

Default WAsP parameters used

WAsP Engineering

WAsP Engineering 4.00.0204

Sectors	12
Reduced geostrophic	h=10m, z0=0.05m, u=20m/s
Domain	Buffer: 5000m, Resoluton: 50m, Points N-S: 281, Points E-W: 243
Turbulence model	Kaimal
Site data	Site data: STATGEN (4)
Obstacles not used	

Long term correction information

Purpose	Name	From	To	Duration [year(s)]	Index [%]	R²
Long term reference	MERRA_basic_E15.335_N54.000 (12)	01/01/1982	01/09/2012	30.7		
Site mast	Karcino 1 M179	01/11/2001	01/11/2002	1.0	105.3	0.98
	Karcino 2 M180	20/10/2001	19/10/2002	1.0	105.2	0.99

WTGs

	UTM (north)-WGS84 Zone: 33									Power curve	
ID	East	North	Z [m]	Manufacturer	Type	Rated power [kW]	Rotor diameter [m]	Hub height [m]	Design Class	Creator	Name
1	526,419	5,997,113	13.2	Siemens	SWT-2.3-113-2300	2,300	113.0	100.0	IIB	EMD	Level 0 - - Standard setting 0dB -
2	526,907	5,997,856	11.3	Siemens	SWT-2.3-113-2300	2,300	113.0	100.0	IIB	EMD	Level 0 - - Standard setting 0dB -
3	526,132	5,995,185	20.0	Siemens	SWT-2.3-113-2300	2,300	113.0	100.0	IIB	EMD	Level 0 - - Standard setting 0dB -

To be continued on next page...

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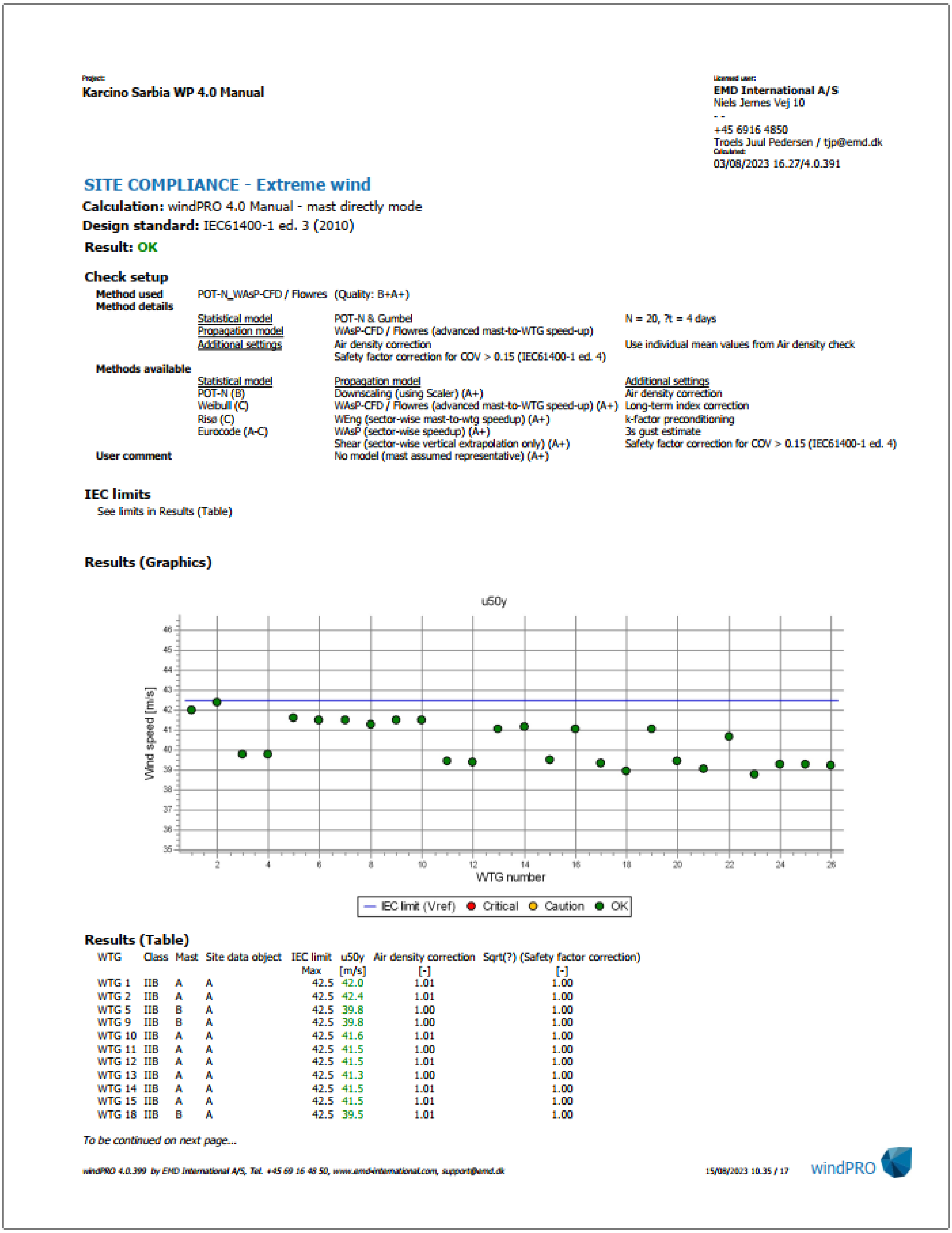
Figure 114. The Details and assumptions page which summarizes the most important of the general assumptions in the setup of SITE COMPLIANCE.

Detailed results and setup (available for each check)

For each of the checks included and calculated, a separate detailed report is available. The detailed report for each check summarizes the selected method, the available methods for that check, and the results in a graphical and tabular format. Below is shown the detailed report (two pages) for the Extreme wind check.



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SITE COMPLIANCE - Extreme wind

Calculation: windPRO 4.0 Manual - mast directly mode
Design standard: IEC61400-1 ed. 3 (2010)
Result: OK

Check setup

Method used	POT-N_WAsP-CFD / Flowres	(Quality: B+A+)	
Method details			
	Statistical model	POT-N & Gumbel	N = 20, ?t = 4 days
	Propagation model	WAsP-CFD / Flowres (advanced mast-to-WTG speed-up)	
	Additional settings	Air density correction	Use individual mean values from Air density check
		Safety factor correction for COV > 0.15 (IEC61400-1 ed. 4)	
Methods available			
	Statistical model	Propagation model	Additional settings
	POT-N (B)	Downscaling (using Scaler) (A+)	Air density correction
	Weibull (C)	WAsP-CFD / Flowres (advanced mast-to-WTG speed-up) (A+)	Long-term index correction
	Risø (C)	WEng (sector-wise mast-to-wtg speedup) (A+)	k-factor preconditioning
	Eurocode (A-C)	WAsP (sector-wise speedup) (A+)	3s gust estimate
		Shear (sector-wise vertical extrapolation only) (A+)	Safety factor correction for COV > 0.15 (IEC61400-1 ed. 4)
User comment		No model (mast assumed representative) (A+)	

IEC limits

See limits in Results (Table)

Results (Graphics)

Results (Table)

WTG	Class	Mast	Site data object	IEC limit Max	u50y [m/s]	Air density correction [-]	Sqrt(?) (Safety factor correction) [-]
WTG 1	IIB	A	A	42.5	42.0	1.01	1.00
WTG 2	IIB	A	A	42.5	42.4	1.01	1.00
WTG 5	IIB	B	A	42.5	39.8	1.00	1.00
WTG 9	IIB	B	A	42.5	39.8	1.00	1.00
WTG 10	IIB	A	A	42.5	41.6	1.01	1.00
WTG 11	IIB	A	A	42.5	41.5	1.00	1.00
WTG 12	IIB	A	A	42.5	41.5	1.01	1.00
WTG 13	IIB	A	A	42.5	41.3	1.00	1.00
WTG 14	IIB	A	A	42.5	41.5	1.01	1.00
WTG 15	IIB	A	A	42.5	41.5	1.01	1.00
WTG 18	IIB	B	A	42.5	39.5	1.01	1.00

To be continued on next page...

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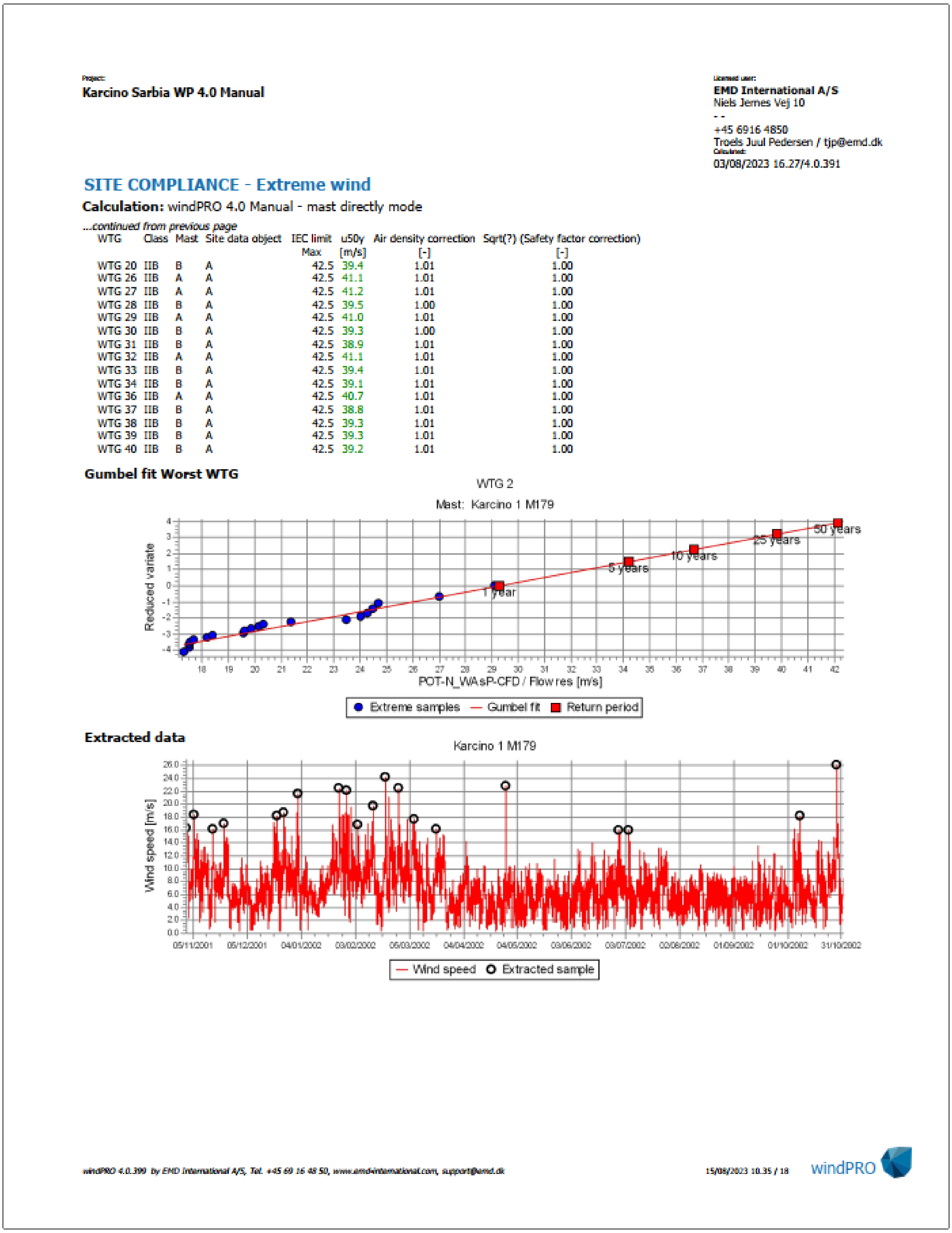
Figure 115. First page of the Extreme wind check, detailed report.



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SITE COMPLIANCE - Extreme wind

Calculation: windPRO 4.0 Manual - mast directly mode

...continued from previous page

WTG	Class	Mast	Site data object	IEC limit Max	u50y [m/s]	Air density correction [-]	Sqrt(?) (Safety factor correction) [-]
WTG 20	IIB	B	A	42.5	39.4	1.01	1.00
WTG 26	IIB	A	A	42.5	41.1	1.01	1.00
WTG 27	IIB	A	A	42.5	41.2	1.01	1.00
WTG 28	IIB	B	A	42.5	39.5	1.00	1.00
WTG 29	IIB	A	A	42.5	41.0	1.01	1.00
WTG 30	IIB	B	A	42.5	39.3	1.00	1.00
WTG 31	IIB	B	A	42.5	38.9	1.01	1.00
WTG 32	IIB	A	A	42.5	41.1	1.01	1.00
WTG 33	IIB	B	A	42.5	39.4	1.01	1.00
WTG 34	IIB	B	A	42.5	39.1	1.01	1.00
WTG 36	IIB	A	A	42.5	40.7	1.01	1.00
WTG 37	IIB	B	A	42.5	38.8	1.01	1.00
WTG 38	IIB	B	A	42.5	39.3	1.01	1.00
WTG 39	IIB	B	A	42.5	39.3	1.01	1.00
WTG 40	IIB	B	A	42.5	39.2	1.01	1.00

Gumbel fit Worst WTG

Extracted data

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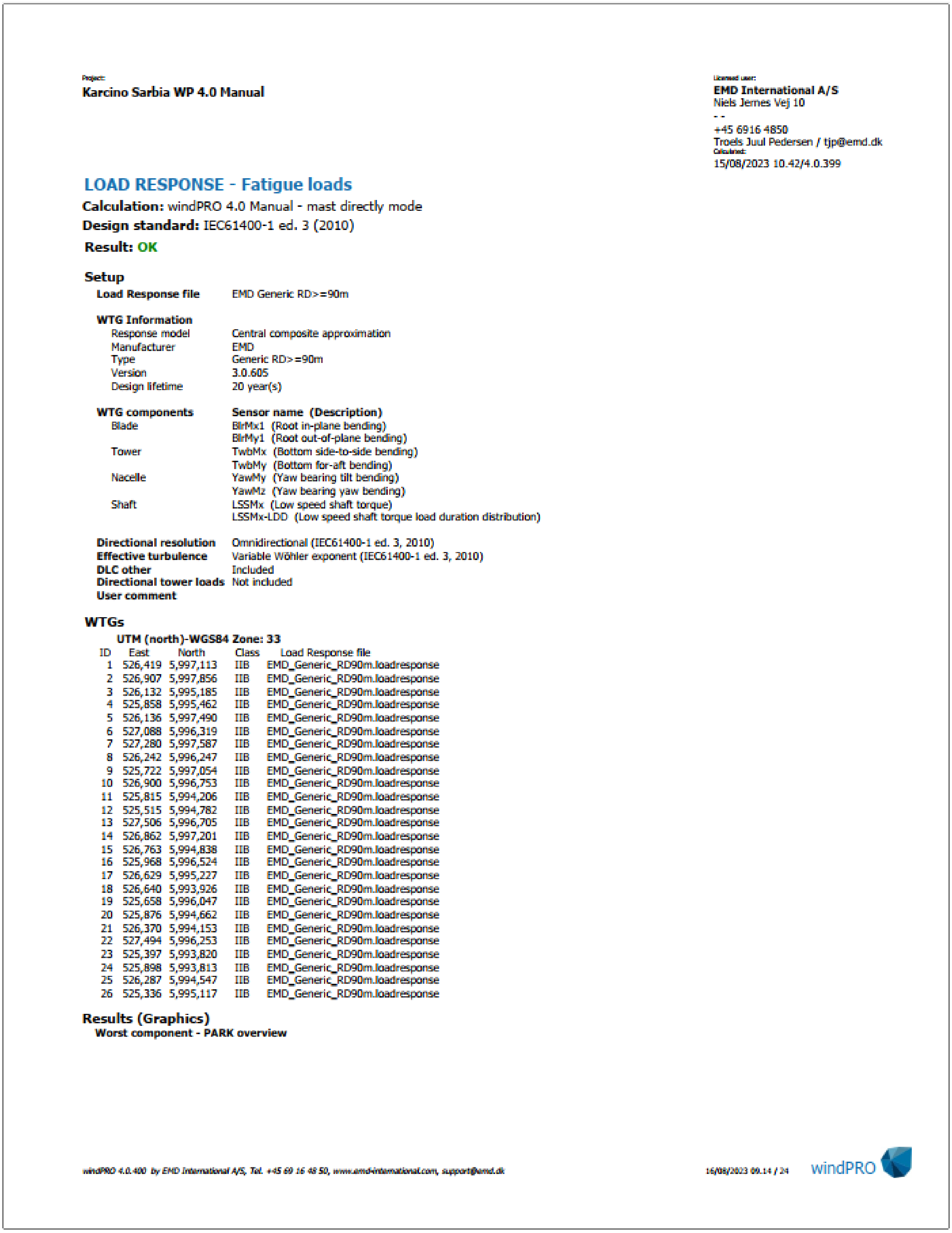
Figure 116. Second page of the Extreme wind check, detailed report.

The remaining IEC checks have similar “detailed reports” which are not shown in this manual.

LOAD RESPONSE



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LOAD RESPONSE - Fatigue loads

Calculation: windPRO 4.0 Manual - mast directly mode
Design standard: IEC61400-1 ed. 3 (2010)

Result: OK

Setup

Load Response file	EMD Generic RD>=90m
WTG Information	
Response model	Central composite approximation
Manufacturer	EMD
Type	Generic RD>=90m
Version	3.0.605
Design lifetime	20 year(s)

WTG components	**Sensor name (Description)**
Blade	BlrMx1 (Root in-plane bending) BlrMy1 (Root out-of-plane bending)
Tower	TwbMx (Bottom side-to-side bending) TwbMy (Bottom for-aft bending)
Nacelle	YawMy (Yaw bearing tilt bending) YawMz (Yaw bearing yaw bending)
Shaft	LSSMx (Low speed shaft torque) LSSMx-LDD (Low speed shaft torque load duration distribution)

Directional resolution	Omnidirectional (IEC61400-1 ed. 3, 2010)
Effective turbulence	Variable Wöhler exponent (IEC61400-1 ed. 3, 2010)
DLC other	Included
Directional tower loads	Not included
User comment	

WTGs

UTM (north)-WGS84 Zone: 33

ID	East	North	Class	Load Response file
1	526,419	5,997,113	IIB	EMD_Generic_RD90m.loadresponse
2	526,907	5,997,856	IIB	EMD_Generic_RD90m.loadresponse
3	526,132	5,995,185	IIB	EMD_Generic_RD90m.loadresponse
4	525,858	5,995,462	IIB	EMD_Generic_RD90m.loadresponse
5	526,136	5,997,490	IIB	EMD_Generic_RD90m.loadresponse
6	527,088	5,996,319	IIB	EMD_Generic_RD90m.loadresponse
7	527,280	5,997,587	IIB	EMD_Generic_RD90m.loadresponse
8	526,242	5,996,247	IIB	EMD_Generic_RD90m.loadresponse
9	525,722	5,997,054	IIB	EMD_Generic_RD90m.loadresponse
10	526,900	5,996,753	IIB	EMD_Generic_RD90m.loadresponse
11	525,815	5,994,206	IIB	EMD_Generic_RD90m.loadresponse
12	525,515	5,994,782	IIB	EMD_Generic_RD90m.loadresponse
13	527,506	5,996,705	IIB	EMD_Generic_RD90m.loadresponse
14	526,862	5,997,201	IIB	EMD_Generic_RD90m.loadresponse
15	526,763	5,994,838	IIB	EMD_Generic_RD90m.loadresponse
16	525,968	5,996,524	IIB	EMD_Generic_RD90m.loadresponse
17	526,629	5,995,227	IIB	EMD_Generic_RD90m.loadresponse
18	526,640	5,993,926	IIB	EMD_Generic_RD90m.loadresponse
19	525,658	5,996,047	IIB	EMD_Generic_RD90m.loadresponse
20	525,876	5,994,662	IIB	EMD_Generic_RD90m.loadresponse
21	526,370	5,994,153	IIB	EMD_Generic_RD90m.loadresponse
22	527,494	5,996,253	IIB	EMD_Generic_RD90m.loadresponse
23	525,397	5,993,820	IIB	EMD_Generic_RD90m.loadresponse
24	525,898	5,993,813	IIB	EMD_Generic_RD90m.loadresponse
25	526,287	5,994,547	IIB	EMD_Generic_RD90m.loadresponse
26	525,336	5,995,117	IIB	EMD_Generic_RD90m.loadresponse

Results (Graphics)
Worst component - PARK overview

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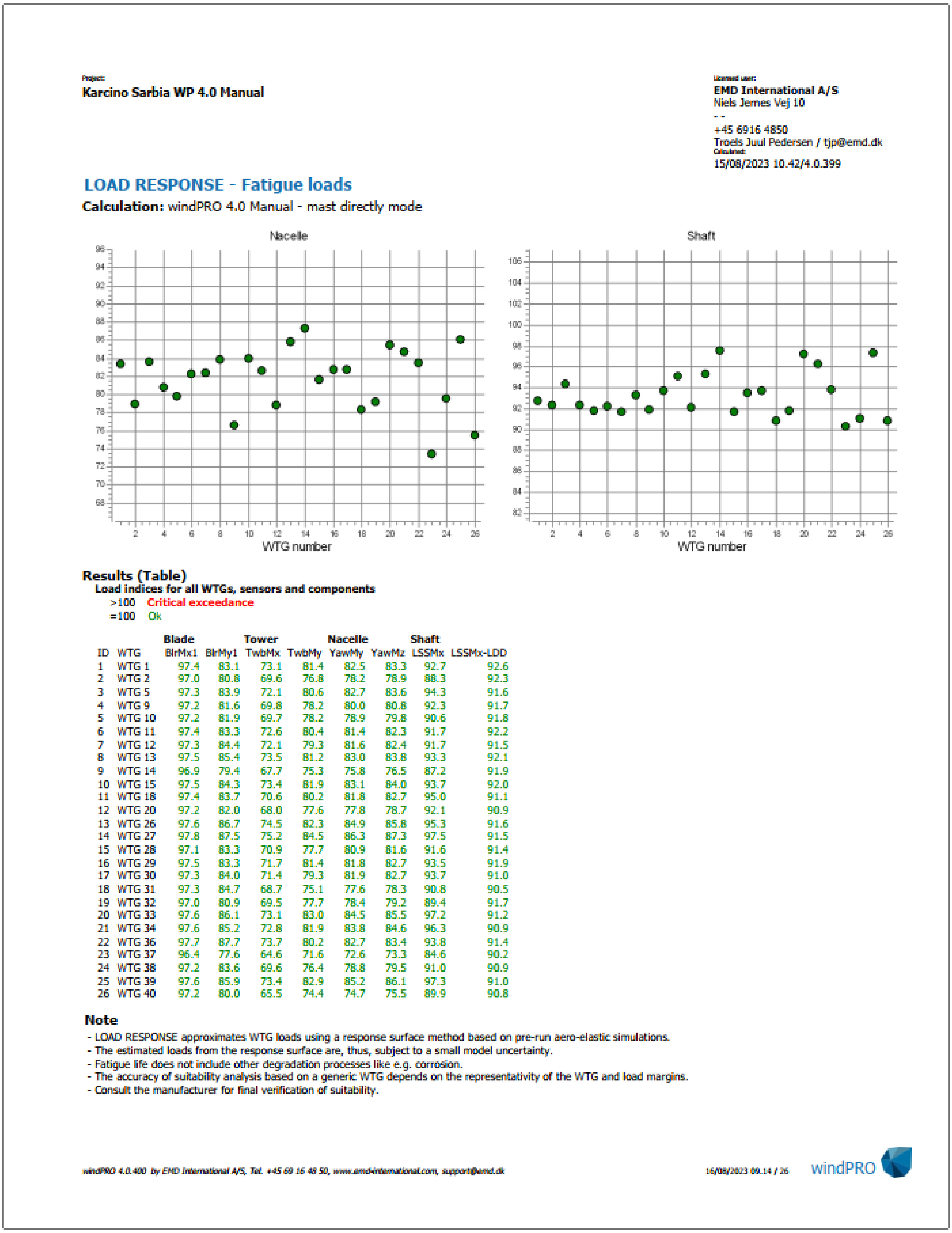
Figure 117. Main overview report page of the LOAD RESPONSE report.



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LOAD RESPONSE - Fatigue loads

Calculation: windPRO 4.0 Manual - mast directly mode

Results (Table)

Load indices for all WTGs, sensors and components

>100 Critical exceedance
=100 Ok

		Blade		Tower		Nacelle		Shaft	
ID	WTG	BlrMx1	BlrMy1	TwbMx	TwbMy	YawMy	YawMz	LSSMx	LSSMx-LDD
1	WTG 1	97.4	83.1	73.1	81.4	82.5	83.3	92.7	92.6
2	WTG 2	97.0	80.8	69.6	76.8	78.2	78.9	88.3	92.3
3	WTG 5	97.3	83.9	72.1	80.6	82.7	83.6	94.3	91.6
4	WTG 9	97.2	81.6	69.8	78.2	80.0	80.8	92.3	91.7
5	WTG 10	97.2	81.9	69.7	78.2	78.9	79.8	90.6	91.8
6	WTG 11	97.4	83.3	72.6	80.4	81.4	82.3	91.7	92.2
7	WTG 12	97.3	84.4	72.1	79.3	81.6	82.4	91.7	91.5
8	WTG 13	97.5	85.4	73.5	81.2	83.0	83.8	93.3	92.1
9	WTG 14	96.9	79.4	67.7	75.3	75.8	76.5	87.2	91.9
10	WTG 15	97.5	84.3	73.4	81.9	83.1	84.0	93.7	92.0
11	WTG 18	97.4	83.7	70.6	80.2	81.8	82.7	95.0	91.1
12	WTG 20	97.2	82.0	68.0	77.6	77.8	78.7	92.1	90.9
13	WTG 26	97.6	86.7	74.5	82.3	84.9	85.8	95.3	91.6
14	WTG 27	97.8	87.5	75.2	84.5	86.3	87.3	97.5	91.5
15	WTG 28	97.1	83.3	70.9	77.7	80.9	81.6	91.6	91.4
16	WTG 29	97.5	83.3	71.7	81.4	81.8	82.7	93.5	91.9
17	WTG 30	97.3	84.0	71.4	79.3	81.9	82.7	93.7	91.0
18	WTG 31	97.3	84.7	68.7	75.1	77.6	78.3	90.8	90.5
19	WTG 32	97.0	80.9	69.5	77.7	78.4	79.2	89.4	91.7
20	WTG 33	97.6	86.1	73.1	83.0	84.5	85.5	97.2	91.2
21	WTG 34	97.6	85.2	72.8	81.9	83.8	84.6	96.3	90.9
22	WTG 36	97.7	87.7	73.7	80.2	82.7	83.4	93.8	91.4
23	WTG 37	96.4	77.6	64.6	71.6	72.6	73.3	84.6	90.2
24	WTG 38	97.2	83.6	69.6	76.4	78.8	79.5	91.0	90.9
25	WTG 39	97.6	85.9	73.4	82.9	85.2	86.1	97.3	91.0
26	WTG 40	97.2	80.0	65.5	74.4	74.7	75.5	89.9	90.8

Note

- LOAD RESPONSE approximates WTG loads using a response surface method based on pre-run aero-elastic simulations.
- The estimated loads from the response surface are, thus, subject to a small model uncertainty.
- Fatigue life does not include other degradation processes like e.g. corrosion.
- The accuracy of suitability analysis based on a generic WTG depends on the representativity of the WTG and load margins.
- Consult the manufacturer for final verification of suitability.

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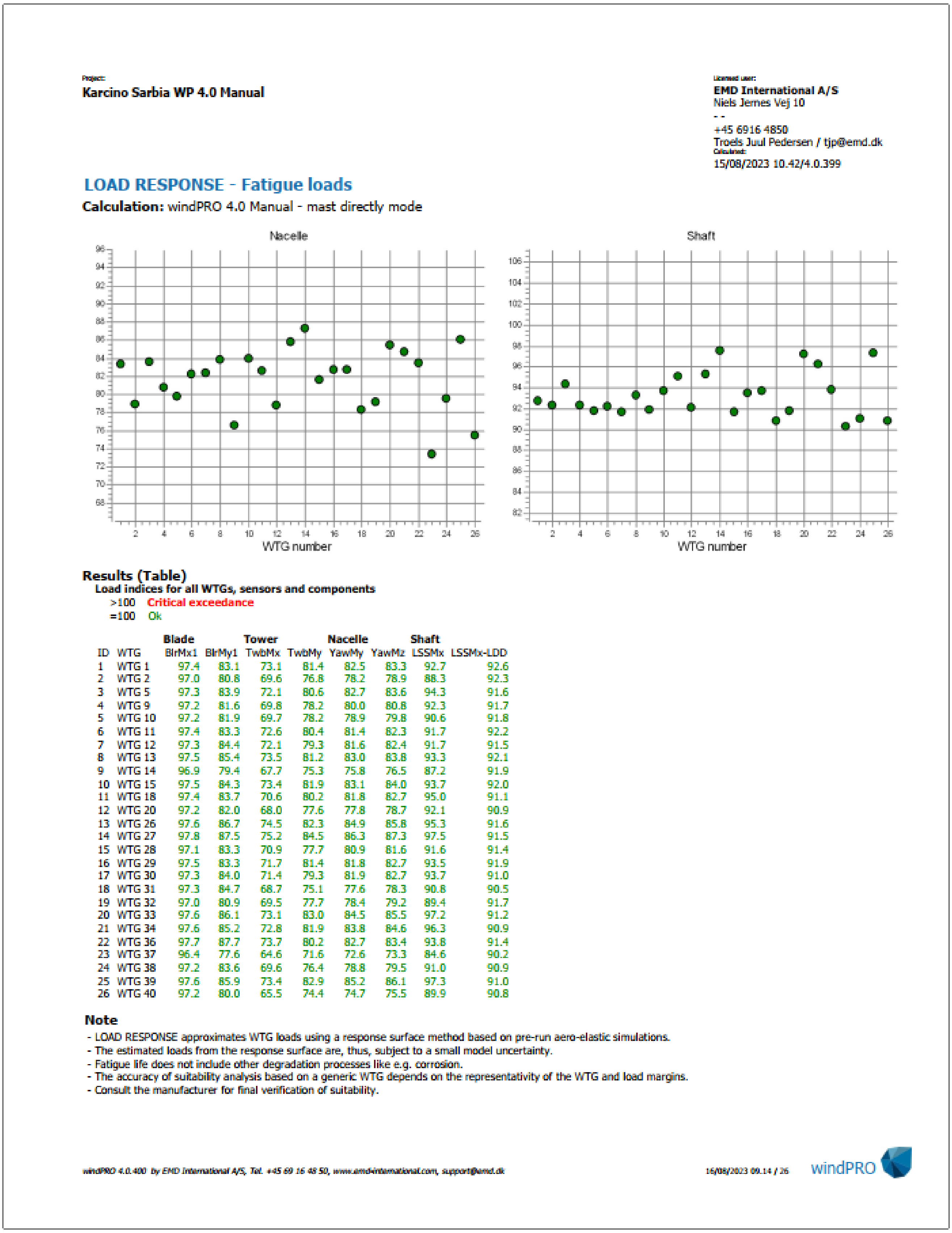
Figure 118. Second page of the LOAD RESPONSE report.



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LOAD RESPONSE - Fatigue loads

Calculation: windPRO 4.0 Manual - mast directly mode

Results (Table)

Load indices for all WTGs, sensors and components

>100 **Critical exceedance**
=100 Ok

		Blade		Tower		Nacelle		Shaft	
ID	WTG	BlrMx1	BlrMy1	TwbMx	TwbMy	YawMy	YawMz	LSSMx	LSSMx-LDD
1	WTG 1	97.4	83.1	73.1	81.4	82.5	83.3	92.7	92.6
2	WTG 2	97.0	80.8	69.6	76.8	78.2	78.9	88.3	92.3
3	WTG 5	97.3	83.9	72.1	80.6	82.7	83.6	94.3	91.6
4	WTG 9	97.2	81.6	69.8	78.2	80.0	80.8	92.3	91.7
5	WTG 10	97.2	81.9	69.7	78.2	78.9	79.8	90.6	91.8
6	WTG 11	97.4	83.3	72.6	80.4	81.4	82.3	91.7	92.2
7	WTG 12	97.3	84.4	72.1	79.3	81.6	82.4	91.7	91.5
8	WTG 13	97.5	85.4	73.5	81.2	83.0	83.8	93.3	92.1
9	WTG 14	96.9	79.4	67.7	75.3	75.8	76.5	87.2	91.9
10	WTG 15	97.5	84.3	73.4	81.9	83.1	84.0	93.7	92.0
11	WTG 18	97.4	83.7	70.6	80.2	81.8	82.7	95.0	91.1
12	WTG 20	97.2	82.0	68.0	77.6	77.8	78.7	92.1	90.9
13	WTG 26	97.6	86.7	74.5	82.3	84.9	85.8	95.3	91.6
14	WTG 27	97.8	87.5	75.2	84.5	86.3	87.3	97.5	91.5
15	WTG 28	97.1	83.3	70.9	77.7	80.9	81.6	91.6	91.4
16	WTG 29	97.5	83.3	71.7	81.4	81.8	82.7	93.5	91.9
17	WTG 30	97.3	84.0	71.4	79.3	81.9	82.7	93.7	91.0
18	WTG 31	97.3	84.7	68.7	75.1	77.6	78.3	90.8	90.5
19	WTG 32	97.0	80.9	69.5	77.7	78.4	79.2	89.4	91.7
20	WTG 33	97.6	86.1	73.1	83.0	84.5	85.5	97.2	91.2
21	WTG 34	97.6	85.2	72.8	81.9	83.8	84.6	96.3	90.9
22	WTG 36	97.7	87.7	73.7	80.2	82.7	83.4	93.8	91.4
23	WTG 37	96.4	77.6	64.6	71.6	72.6	73.3	84.6	90.2
24	WTG 38	97.2	83.6	69.6	76.4	78.8	79.5	91.0	90.9
25	WTG 39	97.6	85.9	73.4	82.9	85.2	86.1	97.3	91.0
26	WTG 40	97.2	80.0	65.5	74.4	74.7	75.5	89.9	90.8

Note

- LOAD RESPONSE approximates WTG loads using a response surface method based on pre-run aero-elastic simulations.
- The estimated loads from the response surface are, thus, subject to a small model uncertainty.
- Fatigue life does not include other degradation processes like e.g. corrosion.
- The accuracy of suitability analysis based on a generic WTG depends on the representativity of the WTG and load margins.
- Consult the manufacturer for final verification of suitability.

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Figure 119. Third page of the LOAD RESPONSE report.

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Appendix I - Gumbel's Theory of Extremes and more

Emil J. Gumbel's model of extremes published in "Statistics of Extremes" [3] in 1958 is the classical standard model for describing the statistics of extreme events. The model is also called Fisher-Tippett Type 1 asymptote or Generalized Extreme Value model (GEV) type 1. The Gumbel model describes the distribution function of annual extremes, i.e., the cumulative probability, G(u), that a yearly maximum wind speed u is not exceeded and takes the form:

$$G(u) = e^{-e^{-(u-\beta)/\alpha}}$$

Where the parameters β and α, are called mode and dispersion or, sometimes, location and scale.

There is a simple relation between the Gumbel distribution of annual extremes and the cumulative mean distribution of all wind speeds samples, F(u). The mean distribution, also called the parent distribution, is typically assumed to be Weibull. The simple relation states that the probability that a given extreme wind speed is the largest among N samples is given as the cumulative parent distribution multiplied by itself N times. For large N, the exact distribution of annual extremes converges asymptotically to the Gumbel distribution:

$$G(u) = e^{-e^{-(u-\beta)/\alpha}} \approx F(u)^N$$

The error of using the Gumbel asymptote is related to the number of independent samples in a year as well as the k-parameter of the Weibull parent distribution (i.e., the tail behaviour). For lower k-parameters the rate of convergence (i.e., more accurate already for small N) is much faster than for higher k-factors. It is also important to note that all N samples are assumed to be independent, i.e., not correlated. In real life, this is not the case for all 10-minute or hourly wind speed samples in a year. The demand for independence leads to considerable complexity. Thus, usually the Gumbel distribution is not estimated from the parent distribution, but rather, directly from extracted extreme samples of the time series and then combining these with theoretical estimates of the cumulative probability of non-exceedance ($P_i \approx G(u_i)$) called "plotting positions". A Gumbel distribution is then fitted to (u_i, P_i) to obtain the Gumbel distribution parameters, α and β.

In the original Gumbel approach, the annual maximum samples (u_i) are extracted for each year of an N year time series. These extreme samples are then ranked (i) smallest to largest (i equals 1 to N) and attributed the plotting positions, P_i, the theoretical estimates of the cumulative distribution function, approximating the probability that the annual maximum wind speed u_i is not exceeded. Several formulas for plotting positions have been suggested. The original Gumbel formula is:

$$P_{i,Classic} = \frac{i}{N+1} \approx G(u_i)$$

Which, in fact, was introduced by Weibull (Makkonen, 2004) [6].

An alternative plotting position is due to Hazen (Makkonen, 2004) [6], which is used in the extreme wind plots in, for example, most Risø/DTU software (e.g., WAsP Engineering):

$$P_{i,Hazen} = \frac{i-0.5}{N}$$

The extreme wind speed samples, u_i, are then plotted on the x-axis versus a transform of the chosen P-values, called the reduced variate, y:

$$y_i = -\ln\left(-\ln(P_i)\right)$$

With this transform the Gumbel asymptote takes a very convenient linear form:

$$y = -\ln\left(-\ln\left(G(u)\right)\right) = au+b = \frac{1}{\alpha}u - \frac{\beta}{\alpha}$$

Thus, a linear fit to a plot of (u_i, y_i) provides the parameters of the Gumbel distribution.

The IEC design criterion for extreme wind speed is a 50-year event, where "50" is referred to as the return period. In other words the design criterion is the wind speed that is expected to occur only once in 50 years. The return period is related to the annual risk of exceedance (R) via:

$$R(u_T) = 1 - G(u_T) = \frac{1}{T}$$

Thus, for T=50 years the annual risk of exceedance is R=2%.

Once the Gumbel parameters, α and β, have been obtained from a linear fit to (u_i, y_i) the extreme wind estimate for T=50 years (i.e. R=2%) may be obtained from:

$$u(T) = \alpha y(T) + \beta = \alpha(-\ln\left(-\ln\left(1-\tfrac{1}{T}\right)\right)) + \beta$$

Where y(T=50) equals 3.9. Thus, to obtain the estimate of the 50-year wind speed, the linear Gumbel fit of (u_i, y_i) must be extrapolated to y=3.9.

Implicit assumptions in the choice of "plotting positions"
The plotting position associated to each of the extracted extremes is a theoretical estimate of the annual probability that this wind speed is not exceeded. As such, this probability also implies an assumption of the return period of the highest of the extracted wind speeds.

For the classical Gumbel plotting position, the max wind speed extracted is assumed to have a return period of:

$$T_{max} = \frac{1}{1-P_{max}} = \frac{1}{1-\frac{N}{N+1}} = N+1$$

Using the Hazen plotting positions, the same max wind speed is assumed to have the return period:

$$T_{max} = \frac{1}{1-P_{max}} = \frac{1}{1-\frac{N-0.5}{N}} = 2N$$

As an example with 10 years of data (i.e., N=10), employing the classical Gumbel plotting positions relies on the assumption that the overall maximum wind speed recording has a return period of 11 years. For the Hazen plotting positions, the assumed return period is 20 years. A more extreme example is a time series of 25 years. Using the Hazen estimates assumes the max recording to have a return period of 50 years. Thus, it is obvious that the Hazen plotting positions are much less conservative than those of the classical Gumbel method.

Extreme wind speed estimate at return period 1 year
The IEC standard also mentions that the extreme wind speed for T=1 year must be estimated although it is not used directly in the extreme wind check. However, the exact expression above for y(T) is not defined for T=1 year. Instead, the most likely extreme to encounter in any given year is usually chosen as the most appropriate estimate; this value equals the ***mode*** of the Gumbel distribution, i.e., the parameter β from the linear fit (which does not exactly equal the mean as the distribution is not symmetric). So, we employ the definition of the extreme wind estimate with return period of 1 year as:

$$u(T=1) \equiv \beta$$

This definition is consistent with the equation derived using a Poisson process (see for example, [4]).

Fitting the Gumbel asymptote

The linear fit to (u_i, y_i) described above represents the basis of Gumbel's asymptotic model of extremes. However, this linear fit may be performed in various ways. Firstly, it is worth noting that the fit is performed on (u_i, y_i), i.e., with the reduced variate as the dependent variable. The reason for this is the implicit assumption in the standard least-squares fitting routine that the dependent variable (here, y) has much higher uncertainty than the independent one (u). The argument is that the wind speeds are measured using high quality equipment, whereas y (reduced variate) is a transform of a theoretical estimate of the annual probability of each wind speed not being exceeded, which is associated with considerable uncertainty.

The standard fit is performed using the least-squares method. Monte Carlo simulations (not published) have shown that typically this fit introduces a slight conservative bias.

An alternative fit is done using the Probability Weighted Moments, PWM (Abild, 1992) [4], which only takes the ranked wind speeds as input, and, hence, does not utilize the reduced variate. In this way, the PWM fit avoids the main source of method-induced bias. The PWM expressions for the fit parameters to the Gumbel asymptote, scale (α) and location (β) are:

$$\alpha = \frac{2b_1-b_0}{\ln(2)} \quad \text{and} \quad \beta = b_0 - 0.5772\alpha$$

With estimates of the sample probability weighted moments given as:

$$b_0 = \frac{1}{N}\sum_{i=1}^{N} u_i \quad \text{and} \quad b_1 = \frac{1}{N}\sum_{i=1}^{N} \frac{i-1}{N-1} u_i$$

Monte Carlo simulations (not published) have shown that the PWM fit to the Gumbel asymptote does not introduce a bias in the Gumbel fit. Unfortunately, the PWM fit does not work equally well with all the ways of extracting the extreme samples. It seems that PWM only is bias-free for the traditional Gumbel approach where only the annual extremes are extracted.

Annual maximum method (AM)

The traditional Gumbel method only extracts the most extreme sample of each year, or from, alternatively, the most extreme sample of each period of fixed length sub-dividing the time series. Hence, the method is referred to as the Annual Maximum method (AM) or Periodical Maximum method.

The drawback of the AM method is the requirement of relatively long time series for the fit to the Gumbel asymptote to be meaningful. Typically, at least 5-10 years is recommended to constrain the fit parameters reasonably well.

In SITE COMPLIANCE, at least 5 years of data are required for the AM method to be available.

Fit

The PWM fit is used with the AM method as it guarantees the least bias in the fitting. Since the PWM fit does not require plotting positions, no Gumbel plot is needed. But is simply used for visual presentation.

Peak-Over-Threshold method (POT)

In some applications, this method is also referred to as *method independent storms*. In most applications, 5-10 years of on-site measurements are rarely available, and, within each year, there may be more than one significant storm event. Hence, a group of extreme wind methods have been developed which utilize more than a single storm from each year. These methods are referred to as Peak-Over-Threshold methods. Storms are typically extracted by defining a high threshold to select only high wind events which exceed this threshold. To ensure that the storm events are statistically independent events, a minimum time difference is required between the extracted events, typically a few days. The extracted extreme samples may then be analysed in a way very similar to that of the standard AM Gumbel approach.

Normally, the recommendation for POT methods is given as the number of events to be extracted as 20-50 extremes. This makes the selection of a proper threshold an iterative procedure. As a more efficient way of extracting the extreme samples in SITE COMPLIANCE, we have introduced a variation of the POT method which we call POT-N. Instead of defining a threshold, the wished number of extremes is defined directly, and the program, then, internally selects the proper threshold to obtain this number of extremes.

As in the AM method, the extracted extreme samples are ranked and the “plotting position” (P_i) is attributed to each of the extracted extremes, i.e., the theoretical estimate of the probability of not being exceeded. For POT-N we have decided to use the classical Gumbel plotting positions in SITE COMPLIANCE.

Instead of a “storm rate” of just one storm/year, as in the AM method, the storm rate is λ storms/year in a POT-estimation. Thus, a direct Gumbel fit to the extracted extremes would not yield the distribution of annual extremes, but simply the distribution of the extracted storms. To compensate for this, the plotting positions, P_i, may be raised to the λth power, provides an estimate of the PDF of the annual extremes (see Cook, 1982 [5]). This transformation is equivalent to a simple shift on the y-axis, i.e., the standard reduced variates are shifted by ln(λ):

$$y_{annual} = y_{storm} - \ln(\lambda)$$

After this transform, the POT Gumbel plot is fully equivalent to the AM plot, with $y_{annual} = 3.9$ for T=50 years.

Fit

Our studies have shown that the PWM fit does not work well for the POT method as for the AM, unfortunately. Instead, a linear least squares fit to the (u,y) is used. The classical Gumbel plotting positions are used as the implicit assumption of return period of the max wind recording seems more sensible than for the Hazen plotting positions.

Weibull parent (EWTS/Bergström) method

The occurrence of high extreme events is closely linked to the tail behaviour of the wind speed distribution. The heavier the tail the more likely are high extreme events to occur. For Weibull distributions commonly adopted in wind energy, the shape of the tail is determined by the Weibull shape or k-parameter. A lower k-parameter means a heavier tail and that extreme events are more likely.

This effect has been quantified in the European Wind Turbine Standard (EWTS), which includes a method for extreme wind estimation based on the "Parent"-distribution - in this case, the Weibull distribution. The method simply assumes a universal number of independent extremes per year (N). The so-called "exact distribution" of the annual maximum is then obtained by raising the Weibull cumulative distribution function to the power of this number, N.

There is an error in the EWTS publication in the number of independent samples which they set to 23,037 per year with reference to Bergström (1992) [8]. However, in Bergström (1992) [8], the correct number for 10-minute data is n=2,302 independent samples per year, or around every 20th 10-minute sample. For hourly-averaged data, the number is 883 or approximately every 10th hourly sample. The error arises due to an exponent of effective frequency which is incorrectly transferred by a factor of 10 in EWTS.

The slope and offset of the Gumbel asymptote (for high n) to the "extracted distribution" of annual extremes are given as (Bergström, 1992 [8], EWTS, 1998 [7]):

$$\alpha = \frac{A}{k}[\ln(n)]^{1/k-1}$$

$$\beta = A[\ln(n)]^{1/k}$$

The difference between the "exact" and Gumbel asymptote is not significant, and working with the Gumbel asymptote allows a fully consistent plotting with the other extreme wind estimation methods.

Omni-directional or sector-wise

The EWTS/Bergström method requires omni-directional Weibull parameters. In the WAsP context, Weibull parameters are sector-wise, which is much more realistic and allows for multimodal omni-directional total distribution (several peaks). However, an omni-directional Weibull distribution called "Combined" may be estimated from the sector-wise Weibulls according to the method in the European Wind Atlas [18].

Fit - is the WAsP Weibull fit appropriate for extreme wind estimation?

The WAsP-type Weibull fit, fits exactly the third moment (energy) and frequency above the mean speed of the table data (no power curve or truncation is applied). Thus, the WAsP fit has a very strong emphasis on the tail behaviour. This is in contrast to ordinary least-squares or maximum-likelihood fits, that fit the wind speeds (and not the energy). These fits tend to fit well around the mean where the highest frequencies of occurrence are, at the cost of reproducing the tail behaviour less well. In conclusion, the WAsP Weibull-fit is in fact better than most other fits at reproducing the right tail behaviour, which is of main importance in extreme wind estimation.

Preconditioning

The Gumbel distribution is an asymptotic distribution. As the number of independent (i.e., not correlated) samples in the pool from which the extremes are extracted, e.g., 1 year, approaches infinity, the Gumbel asymptote becomes exact. The accuracy of the asymptotic assumption depends on the number of independent samples but also on the shape of the parent distribution, i.e., the Weibull distribution. For a k-parameter of 1, the convergence is extremely fast and the asymptote practically exact for just few samples. For higher k-factors the convergence is much slower (see Cook, 1982 [8]).

The deviation of the true annual extreme distribution from the Gumbel asymptote is a slight curvature of the extreme samples when plotting the reduced variate, y, on the y-axis versus wind speed on the x-axis. This curvature will be curved downwards (i.e., concave) and generally results in a conservative fit (over-estimation) which is further exaggerated upon extrapolation to high return periods like 50 years (y=3.9) and higher.

A possible solution is to precondition the data before fitting the slope and offset. The wind speeds are transformed so that the parent distribution becomes a Weibull with a k-parameter of 1 for which the convergence is extremely fast, and, thus, the Gumbel approximation is always very good (Cook, 1982 [8]). To achieve this, the wind speeds of the extreme samples are simply raised to the power of k, where k is the parent Weibull distribution. Often k=2 is used as a common assumption in wind energy. In addition, using k=2 makes the transformed wind speeds proportional to the dynamic pressure, related to the thrust exerted by the wind. However, the real argument for preconditioning is purely statistical and is illustrated in the graphs below.

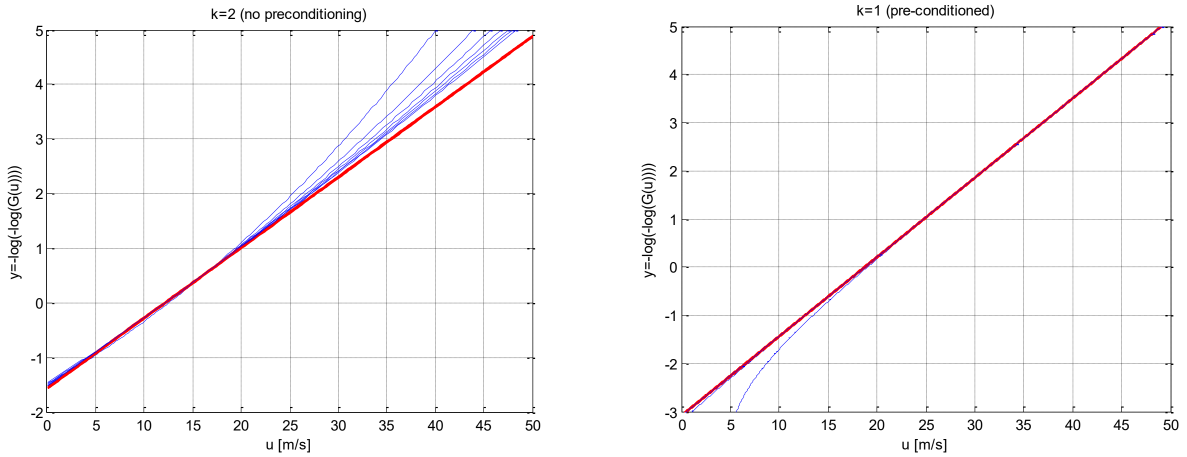

Figure 1. Illustration of the asymptotic nature of the Gumbel model. In both graphs, blue curves show the exact distribution for an annual number of independent samples of N=10^1 to 10^7 in steps of 10. Red curves show the Gumbel asymptote assuming N is infinite (hidden behind the blue curves on the right graph).Note that as N increases the blue curves converges to the red. Left graph illustrates the situation for k=2 and the right graph for k=1, which is equivalent to using preconditioning.

Appendix II - Frandsen Effective turbulence model

The following text describes the main assumptions and steps in the implementation of the Frandsen model or Effective turbulence model. Most assumptions are directly specified in the IEC standard [1, 2] or in Frandsens original publication [13].

The Frandsen model [1, 2, 13] defines the so-called effective turbulence as a combination of ambient and wake generated turbulence integrated overall directions in a way that accounts for accumulation of fatigue using material properties. In the edition specified in the IEC61400-1 ed. 3 2010 amendment [2], the effective turbulence is calculated using the 90th percentile of ambient turbulence.

The illustration below gives a simplified overview of the calculation steps of effective turbulence for a WTG.

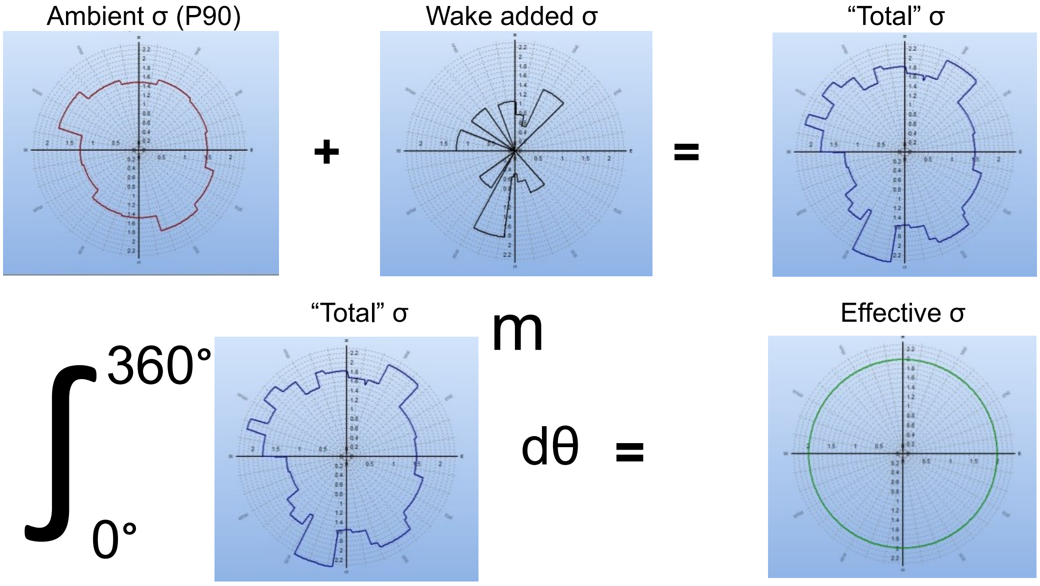

Figure 1. Simplified illustration of the main calculation steps in the Frandsen effective turbulence model. m is the Wöhler exponent.

For each WTG position in the calculation the Frandsen model needs the following input:

1. $\hat{\sigma}(\theta,u)$ and $\hat{\sigma}_{\sigma}(\theta,u)$ - Ambient turbulence (mean & st.dev. functions of direction and speed)
2. $W(A_i,k_i)$ & $f(\theta_i)$ - Sector-wise frequencies and Weibull distributions
3. C_T (turbine thrust curve) and park geometry
4. m - Relevant material fatigue property "Wöhler exponent

Input 1 is used to calculate the ambient characteristic turbulence, i.e., the 90th percentile.

Input 2 is used to calculate the directional wind sped distribution conditioned on wind speed.

Input 3 is used to calculate the wake generated contribution to turbulence.

Input 4 is used in the fatigue weighted combination model of single directions to obtain an omnidirectional effective turbulence as a function of wind speed only.

A main decision in SITE COMPLIANCE regarding the implementation of the Frandsen has been working directly with standard deviations of wind speed (σ) instead of turbulence intensity (TI), which is more common. There are several arguments supporting this decision. Firstly, Frandsen's original publication [13, p. 84] states directly that "The model is expressed in terms of standard deviation of wind speed fluctuations rather than turbulence intensity". Secondly, a fundamental assumption in Frandsen's model is that loads are proportional to σ, the standard deviation of wind speed. Thirdly, the variation of σ with wind speed assumed in the IEC design limit ("Normal turbulence model") is linear for (u,σ), but not for (u,TI).

The implementation of Frandsen's model as specified in [1, 2] includes on a number of assumptions and calculation steps. The main assumptions in the SITE COMPLIANCE implementation are (most are directly given in the standard [1, 2]):

- "No reduction of mean wind speed inside the wind farm shall be assumed" (no wake deficit!) [1, 2]
- Only wake from nearest neighbour WTG considered when multiple wakes overlap [1, 2]
- Turbulence structure correction parameter is applied to both σ and σ_σ
- Wakes have a fixed angular width of 22° independent of distance [13, 15]

The main steps in the calculation of effective turbulence (as illustrated in figure 1) are:

- "Total" turbulence (σ_T) is calculated in each direction combining measured 90th percentile of ambient turbulence (σ_C) and calculated wake added turbulence (σ_{wake}) [1, 2] - "^" indicates measured data:

  $$\hat{\sigma}_T = \sqrt{\sigma_{wake}^2 + \hat{\sigma}_c^2}$$

  where

  $$\hat{\sigma}_c = \hat{\sigma} + 1.28\hat{\sigma}_\sigma \quad \text{(90th percentile of ambient turbulence[14])}$$

  and

  $$\sigma_{wake} = \begin{cases} 0 & \text{If overall nearest neighbour distance is } > 10\text{RD} \\ \square & \square \\ \dfrac{u}{1.5 + \dfrac{0.8\text{d}/RD}{\sqrt{C_T(u)}}} & \begin{matrix}\text{In wake affected directions} \\ \text{d is distance and } \text{C}_\text{T} \text{ is thrust coefficient}\end{matrix} \end{cases}$$

- "Effective turbulence" is calculated from "Total turbulence" raised to the power of m (Wöhler exponent) and integrated (numerically) over all directions weighted by its relative frequency (f):

  $$I_{eff.}(u) = \frac{1}{u}\left[\int_0^{2\pi} \hat{\sigma}_T(\theta \mid u)^m f(\theta \mid u) d\theta\right]^{1/m}$$

The Frandsen model requires a "large wind farm correction" when certain conditions are met, but [1, 2] only considers the special case of a regular rectangular layout. In SITE COMPLIANCE, a more general sector-wise version of this large wind farm correction has been implemented. For each sector, the following evaluation is performed:

- If >5 neighbour WTGs in a sector, the sector is a "large wind farm sector":
  - In direct wake directions σ_T is calculated as above (no correction of ambient level) [1, 2]
  - In non-wake directions (>10RD), ambient σ_c is adjusted using [1, 2]:

    $$\sigma_c = \frac{1}{2} \left(\sqrt{\hat{\sigma}_w^2 + \hat{\sigma}^2} + \hat{\sigma}\right) + 1.28\hat{\sigma}_\sigma$$

    where

    $$\hat{\sigma}_w = \frac{0.36u}{1+0.2\sqrt{\frac{d_r d_f}{C_T}}} \approx \frac{0.36u}{1+0.2\sqrt{\frac{0.5\Delta\theta d_{max}^2}{N_{sec} C_T}}}$$

The latter fraction on the right in the above equation was proposed in [15] as a more generally applicable version of the fraction on the left, which is given explicitly in the standard, covering only regular rectangular layouts. The square root argument represents a "thrust versus area". In the fraction on the right, the rectangular expression is replaced with an angular expression with the area of an "pie slice" $A = 0.5\Delta\theta d_{max}^2$. N_{sec} is the number of WTGs within the "slice" or sector, and d_{max} the radius of the slice and, thus, distance to the furthest neighbour WTG in the sector.

Calculation of Equivalent effective turbulence (not part of the IEC standard)

This calculation is not part of the IEC standard but is based on considerations presented in Frandsen's original paper [13]. The Equivalent effective turbulence is used to decide when the calculated Effective turbulence

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[14] For complex terrain $\hat{\sigma}_c$ is multiplied by the *Turbulence Structure Correction Parameter,* C_{CT}.

exceeds the IEC design limit to evaluate if this exceedance is critical or not. The main assumption is the same as in the Frandsen model, but an extra calculation step is added: integrating the effective turbulence over all relevant wind speeds, whereas Frandsens model only integrates over directions. This second integration over wind speeds assumes that the sensitivity of the WTG to wind speed fluctuations is constant for the relevant wind speed range, which is a significant extension to the approximation of the Frandsen model. The Equivalent effective turbulence is calculated as following:

$$\sigma_{eq} = \left(\int_{u_1}^{u_2} \sigma_{eff.}(u)^m f(u)\, du\right)^{1/m}$$

Where m is the Wöhler exponent, *f(u)* is total frequency of a wind speed bin (omnidirectional) and $\sigma_{eff.}(u)$ is effective turbulence as a function of wind speed bin, i.e., the result from the Frandsen models effective turbulence calculation.

The effective turbulence result for a particular WTG is compared to the IEC design limit for the WTG class by calculating the equivalent effective turbulence for the relevant IEC design class (turbulence and frequency values) and for the actual WTG results. These results for the actual WTG result are normalized by the result for the IEC class. If the normalized result (ratio) exceeds 1, the IEC exceedance is considered critical. The integration limits are set to match the IEC check interval.

Appendix III - Critical, Caution & OK limits in: IEC ed. 2 / ed. 3 / ed. 4.

The following values are used in the windPRO SITE COMPLIANCE module to help the user evaluate if an obtained check value is critical or not. They are based on experience from a large number of projects but further validation and improvements are on-going.

General decisions:

For all checks, the result of a calculation is green/“Ok” if the result is fully within the IEC limits. If the result for a check exceeds the IEC limit, the result will be yellow/“Caution” or red/“Critical”, depending on the degree of exceedance. Caution is used when the exceedance is not considered critical.

At WTG level:
- A WTG is set to Critical if just one check is Critical, Caution if just one check is Caution, and only Ok if all checks are Ok.

At Park level:
- A check is set to Critical for the park if just one WTG is Critical for the check, it is Caution if just one WTG is Caution and only Ok if all WTGs are Ok.

Assessment of Critical, Caution and Ok for each Site Compliance check (ed. 3):

Terrain complexity (I_c):

IEC limit: (none/see details of terrain check)
- Critical: Never
- Caution: If $I_c > 0$
- Ok: if $I_c = 0$

Wind shear (α):

IEC limits: $0 \leq \alpha \leq 0.2$
- Critical: if $\alpha > 0.3$ or $\alpha < 0$
- Caution: if $0.3 \geq \alpha > 0.2$
- Ok: if $0 \leq \alpha \leq 0.2$

Air density (ρ):

IEC limits: 1.225 kg/m^3 is assumed in design
- Critical: Never
- Caution: $\rho > 1.225$ kg/m^3
- Ok: $\rho \leq 1.225$ kg/m^3

Inflow angle (φ_{max}):

IEC limits: $\varphi \leq 8°$ & $\varphi \geq -8°$
- Critical: $\varphi > 12°$ or $\varphi < -12°$
- Caution: $12° \geq \varphi > 8°$ or $-12° \leq \varphi < -8°$
- Ok: $\varphi \leq 8°$ & $\varphi \geq -8°$

Extreme wind (u_{50y}):

IEC limits: $V_{ref} \geq u_{50y}$
- Critical: $u_{50y} > Vref$ or gust $> 1.4 * Vref$
- Caution: Never
- Ok: $V_{ref} \geq U_{50y}$ or $1.4 * Vref \geq$ gust

Effective turbulence ($\sigma_{eff.}(u)$):

IEC limits: $\sigma_1(u) > \sigma_{eff.\ WTG}(u)$ for all u in check interval
- Critical: $\sigma_{eq,\ WTG} > \sigma_{eq,\ IEC}$
- Caution: $\sigma_{eq,\ WTG} < \sigma_{eq,\ IEC}$
- Ok: $\sigma_{eff,\ IEC}(u) > \sigma_{eff.\ WTG}(u)$ for all u

$\sigma_{eq,\ xxx}$ is the Equivalent effective turbulence for WTG for IEC design class. See Appendix II for a description of the calculation of this quantity.

Wind distribution (pdf(u)):

IEC limits: $f_{IEC}(u) > f_{WTG}(u)$ for all u in check interval

- Critical: $F_{hi} < 0$ or $(F_{hi} + F_{lo} < 0)$
- Caution: $F_{hi} \geq 0$ & $(F_{hi} + F_{lo} \geq 0)$
- Ok: $f_{IEC}(u) > f_{WTG}(u)$ for all u

Where:

$$F_{hi} = \int_{0.3V_{ref}}^{0.4V_{ref}} \left(f_{IEC}(u) - f_{WTG}(u)\right) du$$

$$F_{lo} = \int_{0.2V_{ref}}^{0.3V_{ref}} \left(f_{IEC}(u) - f_{WTG}(u)\right) du$$

The main point here is that exceedances at the lower half of the check interval is not as severe as those in the upper half at higher wind speeds where loads are expected to be higher.

Seismic hazard (PGA):

- Critical: PGA > 2.4
- Caution: 2.4 ≥ PGA > 0.8
- Ok: 0.8 ≥ PGA

Lightning rate:

- Critical: rate > 20
- Caution: 20 ≥ rate > 10
- Ok: 10 ≥ rate

Temperature range (T):

Normal range

- Critical: h outside > 240h
- Caution: h outside > 24h
- Ok: 24 h ≥ h outside

Extreme range

- Critical: h outside > 1h
- Caution: 1h ≥ h outside > 0.0 h
- Ok: 0.0 h outside

Assessment of Critical, Caution and Ok – differences for IEC ed. 2:

Only the Effective turbulence check and the Wind distribution check have different OK, Caution and Critical limits in IEC ed. 2 compared to IEC ed. 3.

Effective turbulence ($\sigma_{eff.}(u)$):

IEC limits: $\sigma_1(u) > \sigma_{eff.\ WTG}(u)$ for u=15m/s

- Critical: $\sigma_{eq,\ WTG} > \sigma_{eq,\ IEC}$
- Caution: $\sigma_{eq,\ WTG} < \sigma_{eq,\ IEC}$
- Ok: $\sigma_{eff,\ IEC}(15m/s) > \sigma_{eff.\ WTG}(15m/s)$

$\sigma_{eq,\ xxx}$ is the Equivalent effective turbulence for WTG for IEC design class (See Appendix II for a description of the calculation of this quantity).

Wind distribution (pdf(u), with Weibull A, k and mean V_{ave}):

IEC limit: not explicit, but Compare design and WTG distributions

- Critical: $f_{IEC}(15m/s) < f_{WTG}(15m/s)$
- Caution: $f_{IEC}(15m/s) > f_{WTG}(15m/s)$
- Ok: $V_{ave,\,IEC} > V_{ave,\,WTG}$ & $k_{IEC} < k_{WTG}$

The main point here is that the design climate assumes a Weibull distribution with $k_{IEC}=2$ and average wind speed defined for each design class. Higher average wind speeds will lead to increased loads as will a lower Weibull k parameters. As the wind speed 15m/s plays a special role in the ed. 2, the limit from caution to critical is defined by the frequency of occurrence at 15m/s.

Assessment of Critical, Caution and Ok – differences for IEC ed. 4:

The IEC ed. 4 is mostly consistent with the ed. 3, hence, only the differences for ed.4 check limits are summarized below.

Terrain complexity (I_c):

IEC limit: (none/see details of terrain check)

- Critical: Never
- Caution: If $C_{ct} > 0$ (complexity category: H, M, L)
- Ok: If $C_{ct} = 0$ (complexity category: N)

Wind shear (α):

IEC limits: $0.05 \le \alpha \le 0.25$

- Critical: If $\alpha > 0.3$ or $\alpha < 0$
- Caution: If OK not fulfilled
- Ok: if $0.05 \le \alpha \le 0.25$

Air density (ρ):

IEC limits: $\rho \le 1.225$ kg/m³

- Critical: Never
- Caution: If OK not fulfilled
- Ok: $\rho \le 1.225$ kg/m³ or $\frac{v^2_{ave,site}}{v^2_{ave,IEC}}\,\rho \le 1.225$ kg/m³ when $\rho > 1.225$ kg/m³

Wind distribution (pdf(u)):

IEC limits: $f_{IEC}(u) > f_{WTG}(u)$ for $u \in \{0.2V_{ref}, 0.4V_{ref}\}$

- Critical: $F_{hi} < 0$ or $(F_{hi} + F_{lo} < 0)$
- Caution: If OK not fulfilled.
- Ok: $f_{IEC}(u) > f_{WTG}(u)$ for u interval & $6.5 \cdot \frac{v_{ave,site}}{v_{ave,IEC}} - 4.5 \le k_{omni} \le -6.0 \cdot \frac{v_{ave,site}}{v_{ave,IEC}} + 8.0$

Where:

$$F_{hi} = \int_{0.3V_{ref}}^{0.4V_{ref}} \left(f_{IEC}(u) - f_{WTG}(u)\right)du$$

$$F_{lo} = \int_{0.2V_{ref}}^{0.3V_{ref}} \left(f_{IEC}(u) - f_{WTG}(u)\right)du$$

The main point here is that exceedances at the lower half of the check interval is not as severe as those in the upper half at higher wind speeds where loads are expected to be higher.

Ambient 90% Turbulence [NTM]:

IEC limits: $\sigma_1(u) > \sigma_{omni,90\%}(u)$ for all u in check interval

- Critical: If OK not fulfilled
- Caution: Never (ultimate loads)

- Ok: $\sigma_1(u, I_{ref}) > \sigma_{omni,90\%}(u)$ for $u \in \{0.6 \cdot u_{rated}, 1.6 \cdot u_{rated}\}$

Ambient Extreme Turbulence (AET) [ETM]:

IEC limits: $\sigma_{1,\text{ETM}}(\text{u}) > \sigma_{\text{AET}}(\text{u})$ for all u in operation

- Critical: If OK not fulfilled
- Caution: Never (ultimate loads)
- Ok: $\sigma_{1,ETM}(u, I_{ref}) \geq \sigma_{AET}(u)$ for $u \in \{u_{in}, u_{out}\}$

Max Centre-wake 90% Turbulence (MCWT) [ETM]:

IEC limits: $\sigma_{1,\text{ETM}}(\text{u}) > \sigma_{\text{MCWT}}(\text{u})$ for all u in operation

- Critical: If OK not fulfilled
- Caution: Never (ultimate loads)
- Ok: $\sigma_{1,ETM}(u, I_{ref}) \geq \sigma_{MCWT}(u)$ for $u \in \{u_{in}, u_{out}\}$

Appendix IV - Theory of LOAD RESPONSE and Fatigue

This appendix describes the fatigue design load cases, which should be considered according to the wind turbine standard IEC 61400-1 ed. 3 (2010) and ed. 4 (2019) along with the workflow for determining fatigue loads.

Design load cases

The design load cases in IEC 61400-1 ed. 3 (2010) are developed in order to represent all significant design situations during a wind turbines design lifetime in both ultimate (extreme) and fatigue loading.

1. Power production
2. Power production plus occurrence of faults
3. Start up
4. Normal shut down
5. Emergency shut down
6. Parked (standing still or idling)
7. Parked and fault conditions
8. Transport, assembly, maintenance and repair

The design load cases which should be considered for fatigue loading are listed in the table below (see IEC 61400-1 ed. 3 (2010) for abbreviations). In LOAD RESPONSE, only design load case 1.2 is considered explicitly in the response model, since this is normally is the most dominant design load case and highly dependent on the site specific wind climate parameters. However, the minor contributions from the other DLCs may be included via the 'DLC Other' option from windPRO 3.4. This contribution should represent the expected combined fatigue contribution within the design lifetime of all the fatigue DLCs 'other' than DLC 1.2. other IEC61400-1 ed. 4 provides guidelines for the number of expected start-ups and shut-downs.

Design situation	DLC	Wind model	Wind speeds
1) Power production	1.2	NTM	$V_{in} < V_{hub} < V_{out}$
2) Power production plus occurrence of fault	2.4	NTM	$V_{in} < V_{hub} < V_{out}$
3) Start up	3.1	NWP	$V_{in} < V_{hub} < V_{out}$
4) Normal shut down	4.1	NWP	$V_{in} < V_{hub} < V_{out}$
6) Parked (standing still or idling)	6.4	NTM	$V_{hub} < 0.7V_{ref}$

Table 1. Fatigue design load cases in IEC 61400-1 ed. 3 (2010).

Aero-elastic simulations

Wind turbine loads are normally determined based on aero-elastic simulations of the wind turbine during the different design situations / load cases. The aero-elastic model needs, in general, input concerning:

- Site specific wind climate parameters
  - Mean wind speeds
  - Turbulence
  - Wind shear
  - Air density
  - Inflow angle
- Structural properties
  - Blade properties (length, aero-dynamics, weight, stiffness, etc.)
  - Nacelle properties (gearbox, generator, shaft, etc.)
  - Tower properties (height, weight, stiffness, etc.)
  - Foundation properties (size, stiffness, etc.)
- Control system
  - Power curve
  - Pitch system
  - Actuators
  - Control algorithms

In the aero-elastic model, a turbulence generator is used to generate a random turbulence box containing the 3-dimensional wind speed vector at different locations in the rotor plane at different time steps. The turbulence box is normally generated based on the Kaimal or Mann turbulence model (see [1, 2]). From the turbulence box, the aerodynamic force on the wind turbine at each time step is determined. This is used to determine time-series for the forces, moments and deflections in different parts of the structure, taking the structural dynamics and the control system into account.

Fatigue – Structural components

The fatigue loads for structural components (blades, tower, shaft, etc.) are normally determined by rainflow counting of the simulated time-series (see [19]). The purpose of rainflow counting is to extract the stress ranges from the time-series, which is the cause of the damage of the structure. In rainflow counting, these stress ranges are extracted in a similar way as raindrops falling from a roof, hence the name rainflow counting. Compared to other methods, rainflow counting focuses on extracting the largest stress ranges in the time-series.

The number of cycles to failure is normally determined based on a SN-curve, which, depending on the material, can be more or less complex. However, in order to secure an easy interaction between the aero-elastic model used to determine the overall structural loading on all wind turbine components and the finite-element models used to determine the local stresses for specific structural details, a linear SN-curve is normally used. The linear SN-curve describes the relationship between the stress range $\Delta\sigma$ and the number of cycles to failure N, where, also, the Wöhler exponent m is introduced corresponding to the negative slope of the SN-curve. Note that the term “linear” SN-curve refers to linear in a log-log plot (see the equation and figure below).

$$N = \frac{K}{\Delta\sigma^m} \quad \Leftrightarrow \quad \log N = \log K - m \log \Delta\sigma$$

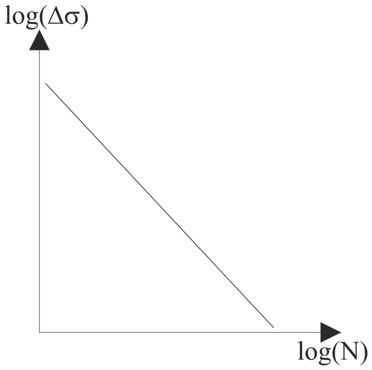


Figure 1. Linear SN-curve in log-log coordinate system.

The total damage D from the individual stress cycles extracted by rainflow-counting is normally determined by Miner’s rule for linear damage accumulation proposed by MA Miner [20]:

$$D = \sum_i \frac{n_i}{N\left(\Delta\sigma_i\right)}$$

where n_i is the number of cycles with stress range $\Delta\sigma_i$ extracted by rainflow counting and N() is the number of cycles to failure for stress range $\Delta\sigma_i$ determined from the SN-curve. If the damage is <1, the applied fatigue loading will not lead to structural failure, whereas a damage >1 will result in structural failure.

In LOAD RESPONSE, the fatigue load for structural components is expressed as Damage Equivalent Load (DEL). The DEL is determined as the fatigue load which for an equivalent number of cycles n_{eq} will lead to the same damage as the actual load time-series for the wind turbines lifetime.

$$DEL = \sqrt[m]{\frac{1}{n_{eq}} \sum_i n_i \Delta\sigma_i{}^m}$$

Fatigue – Mechanical components

For mechanical components, the fatigue stresses normally occur due to the interaction between different gears. This fatigue load is often characterized by the Load Duration Distribution (LDD), which describes how long time the stresses are at a given level (see, e.g., [21]). The LDD is also dependent on the sampling frequency *f* and the number of time steps in the simulations with a given stress level. It is noted that the term Wöhler exponent also is used for the Load Duration Distribution, even though the same relationship to the linear SN-curve not is present.

$$LDD = \sqrt[m]{\frac{1}{f}\sum_i n_i {\sigma_i}^m}$$

Surrogate modelling

Fatigue loads in windPRO are approximated using surrogate models. Surrogate modelling involves creating simplified and computationally efficient models to approximate the complex relationship between input variables, such as wind conditions, and the resulting fatigue loads on the different turbine components. These models enable much quicker predictions and assessments compared to full aero-elastic simulations, facilitating a more efficient design process.

LOAD RESPONSE supports two different types of surrogate models: Central Composite Design (CCD) and Gaussian Process Regression (GPR). All generic turbine models in LOAD RESPONSE are based on the CCD, whereas for specific turbine models these can be created for either type.

Central Composite Design

The Central Composite Design, first proposed by Box & Wilson (1951) [22], was initially developed to assess second order effects in a response where interaction between different variables is present. Therefore, it constitutes a good candidate for a surrogate model, as is often the case for fatigue loads on turbines.

For each sensor in LOAD RESPONSE, a response surface is fitted at each wind speed bin in order to assess the fatigue loads accurately. In design load case 1.2, the following four wind climate parameters (variables) influence the fatigue loads:

- Effective turbulence standard deviation σ_1 (90% quantile – mean wind speed / sector dependent)
- Wind shear α (mean value – sector dependent)
- Inflow angle φ (maximum value – sector dependent)
- Air density ρ (mean value)

The Central Composite Design used in LOAD RESPONSE is, therefore, four dimensional. The figure below shows the principle in establishing the response surface for a two dimensional case using central composite design. The black point refers to the reference point (normally, the wind conditions for the IEC-class), the blue points refer to variations of single wind climate parameters (variables) in order to estimate second order effects, and the red points refer to variations of several wind climate parameters, simultaneously, in order to estimate their interaction.

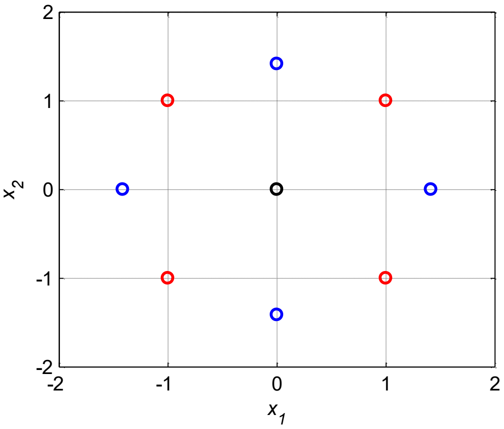


Figure 2. Central Composite Design for two variables.

In order to setup the four dimensional response surface in LOAD RESPONSE, aero-elastic simulations for 25 combinations of the four wind climate parameters are needed at each wind speed bin. The response surface central composite design has been selected for LOAD RESPONSE, because it provides a reasonable balance between accuracy and the required number of simulations.

The regression model $f(\mathbf{x})$ is fitted to the response at the individual wind speed bins using linear least squares regression, where x denotes the wind climate parameters and β_0, β_i and β_{ij} are regression parameters.

$$f(\mathbf{x}) = \beta_0 + \sum_{i=1}^{k} \beta_i x_i + \sum_{i=1}^{k} \sum_{j \geq i}^{k} \beta_{ij} x_i x_j + \varepsilon$$

Gaussian Process Regression

From windPRO 4.1 a more advanced surrogate model using Gaussian Process Regression (GPR) is available for specific turbine models.

Gaussian process regression is a probabilistic surrogate model which assumes the model output $y(\boldsymbol{x})$ to be a realization of a deterministic mean defined by a regression model $f(\boldsymbol{x})$ and a correlated stochastic process $Z(\boldsymbol{x})$.

$$y(\boldsymbol{x}) \approx f(\boldsymbol{x}) + Z(\boldsymbol{x})$$

The first terms $f(\boldsymbol{x})$ to is similar to the Central Composite Design a second order regression model fitted using linear least squares. The second term $Z(\boldsymbol{x})$ is interpolating the known residuals at the experimental design by a stationary zero mean Gaussian process fully described by its covariance.

$$cov(\boldsymbol{x}, \boldsymbol{x}') = \sigma^2 K(\boldsymbol{x}, \boldsymbol{x}'; \boldsymbol{\theta})$$

The overall process variance σ^2 is assumed constant and K models the correlation between $Z(\boldsymbol{x})$ and $Z(\boldsymbol{x}')$ by their inter-distance and the hyperparameters $\boldsymbol{\theta} \in \mathbb{R}^M$. Regression coefficients $\boldsymbol{\beta}$, process variance σ and hyperparameters $\boldsymbol{\theta}$ is estimated by optimization, maximizing the likelihood of observing the response at the experimental design.

The GPR model in windPRO includes mean wind speed at hub height as an additional input variable compared to the Central Composite Design. Furthermore, the model can utilize random sampling of design points. This enables much greater flexibility in terms of model accuracy, as a one can increase the sampling rate at different wind conditions to increase accuracy.

For more information on GPR as a surrogate model for wind turbine fatigue assessment, see [37]. Additionally, for a more fundamental introduction to the topic of Gaussian Process Regression, see [38].

Results

The damage equivalent load (DEL_0) or load duration distribution (LDD_0) is determined at each mean wind speed bin using the given surrogate model. The damage equivalent loads or load duration distribution for the full wind speed distribution (DEL / LDD) can then be determined by weighting the fatigue loads from the individual wind speed bins with the wind speed distribution:

$$DEL = \sqrt[m]{\sum_{V_{hub}=V_{in}}^{V_{out}} w(V_{hub}) DEL_0\left(V_{hub}, \sigma_1(V_{hub}), \alpha, \rho, \varphi\right)^m}$$

$$LDD = \sqrt[m]{\sum_{V_{hub}=V_{in}}^{V_{out}} w(V_{hub}) LDD_0\left(V_{hub}, \sigma_1(V_{hub}), \alpha, \rho, \varphi\right)^m}$$

where $w(V_{hub})$ is weight factor determined from the wind speed distribution.

The estimated fatigue loads are presented in the following three ways in load response:

- Load (specific wind turbines)
- Load index (generic / specific wind turbines)
- Fatigue lifetime (generic / specific wind turbines)

The value of the damage equivalent load or load duration distribution is shown directly in LOAD RESPONSE for each sensor when calculations are performed for specific wind turbines implemented by manufactures.

The load index is the main result, both for specific and generic wind turbines. The load index for each sensor is defined as the ratio between the fatigue load (DEL / LDD), estimated based on the site specific wind conditions, and the fatigue load (DEL_{ref} / LDD_{ref}), estimated based on the wind conditions for the considered IEC class.

$$\delta_{DEL} = \frac{DEL}{DEL_{ref}} \cdot 100\%$$

$$\delta_{LDD} = \frac{LDD}{LDD_{ref}} \cdot 100\%$$

A load index <100% shows that the site specific fatigue loads are less severe than the fatigue loads for the IEC wind climate conditions. If 'DLC Other' is included in the calculation it will be added as a constant contribution to both numerator and denominator for the DEL or LDD (shown only for DEL below).

$$\delta_{DEL} = \frac{\sqrt[m]{DEL_{1.2}^m + DEL_{Other}^m}}{\sqrt[m]{DEL_{ref}^m + DEL_{Other}^m}} \cdot 100\%$$

The fatigue lifetime is also determined for each wind turbine component relative to the assumed design lifetime, which, for the generic wind turbines, is assumed to $T_{turbine}$ = 20 years. The fatigue lifetime will, therefore, be larger than 20 years for sensors with a load index below 100% (below shown without DEL Other contribution).

$$T_{lifetime,DEL} = \left(\frac{DEL^{ref}}{DEL}\right)^m \cdot T_{turbine}$$

$$T_{lifetime,LDD} = \left(\frac{LDD^{ref}}{LDD}\right)^m \cdot T_{turbine}$$

It is noted that the fatigue lifetime does not consider other material degradation phenomena such as abrasion or corrosion.

Appendix V - Curtailment

This appendix describes the curtailment or “wind sector management” calculations in SITE COMPLIANCE and LOAD RESPONSE. The detailed curtailment calculations require curtailment settings to be defined on the WTG objects individually and that the Curtailment option has been checked on the main setup tab of SITE COMPLIANCE.

Curtailment in SITE COMPLIANCE

In SITE COMPLIANCE, the curtailment settings will NOT influence the calculation of the ambient wind climate parameters. The ambient wind shear or turbulence is the same no matter if the turbine is in operation or not. However, the wake induced turbulence behind a wind turbine depends strongly on, whether or not the turbine is operating or shut down (or running in a reduced mode). Hence, in SITE COMPLIANCE, the curtailment will only influence the turbulence checks which combine both the ambient and wake contributions to turbulence, ‘Effective turbulence’ and ‘Max centre-wake 90% turbulence’.

In the Effective turbulence check, the effect of curtailment is quite simple. For each wake situation between two turbines, it is considered whether the wake generating turbine is curtailed or not for each direction wind speed bin. In case the wake generating turbine is curtailed, its wake contribution is omitted for the speed and direction in question. The wake of any further upstream turbines might become important and contribute to the turbulence as the Frandsen wake model only considers the wake turbulence of the nearest upstream turbine (in operation).

The wake signature, sometimes called “view angles”, typically has a fixed width of 22 degrees in the Frandsen model (see Appendix II - Frandsen Effective turbulence model). Hence, a simplifying assumption is needed to handle partial curtailment within the direction interval generating the wake. A basic assumption is adopted saying that each degree where the wake generating turbine is curtailed within the 22 degree directional interval, leads to one degree less wake at the receiving WTG.

Curtailment in LOAD RESPONSE

The effect of curtailment on the load calculation for a wind turbine is more intuitive and directly influences the turbine itself in contrast to the effect of curtailment on the wake effects. For directions and wind speeds where the turbine is shut down, it will experience much reduced fatigue compared to being in operation. On the other hand, there is a minor contribution to fatigue from the additional starts and stops required from the implementation of the curtailment rules.

LOAD RESPONSE implements the main fatigue design load case DLC1.2 “Normal operation” using a response model. Design load cases DLC3.1 “Start up” and DLC4.1 “Normal shut down” are handled via the accumulated “DLC other” contribution. The effect of additional starts and stops enforced by the curtailment strategy would require a detailed time series calculation to estimate the needed number of additional stops and starts. This is not inline with the current ‘statistics’ version of the IEC standard and followingly of SITE COMPLIANCE and LOAD RESPONSE, but it is a clear goal to move towards time series in the future versions.

To compensate for the above simplification of not directly accounting for the fatigue of the additional starts and stops, a simple assumption has been made. Whenever a turbine is shut down, the fatigue load (DEL) contribution of wind speed and direction bin is not decreased to zero (or nearly zero), but reduced by a fixed fraction. If the fatigue of the starts and stops was explicitly accounted for, the fraction would be very close to zero, but since they are not accounted for, the fraction is set to 0.5.

$$DEL_{curtailed} = 0.5\, DEL_{operating}$$

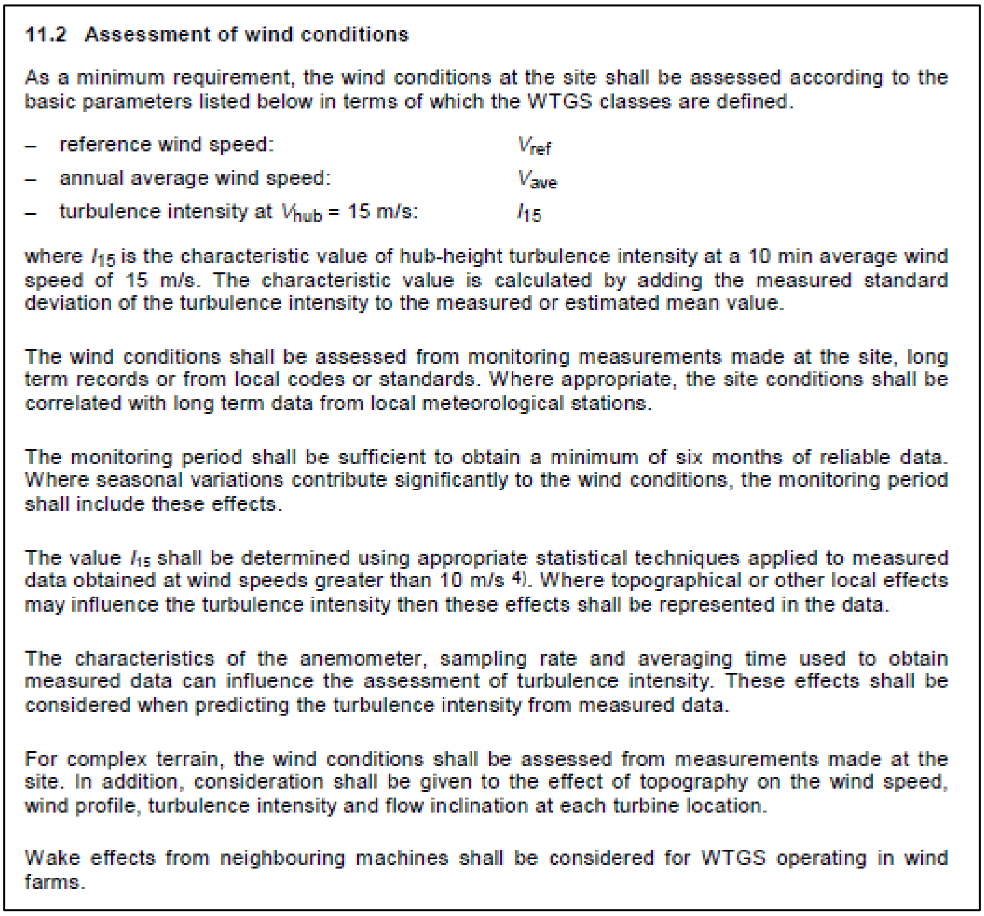
This may seem as a very conservative assumption, but, since the DEL is used in the very non-linear fatigue calculation (see Appendix IV - Theory of LOAD RESPONSE and Fatigue, page 101) using the Wöhler exponent, this is not the case. For a Wöhler exponent of m=10, the fatigue damage contribution of a curtailed wind speed and direction bin is reduced to 0.1% and for m=5 it is reduced to 3%.

The integration of loads in LOAD RESPONSE follows a fixed discretization of 1 degree (centred on half degrees) and 0.5 m/s centred on X.25 m/s and X.75 m/s. Hence, curtailment settings defined with finer resolution than this discretization e.g. X.1 m/s will be rounded off to the actual discretization, however these round-off effects will generally be negligible.

Appendix VI - IEC 61400-1 ed. 2 (1999)

From windPRO version 3.1, SITE COMPLIANCE supports the second edition of IEC 61400-1 (IEC ed. 2), which was released in 1999. The second edition was replaced by the third edition in 2005, which was updated in 2010 (IEC ed. 3). Hence, IEC ed. 2 is, in principle, obsolete, but, nevertheless, it continues to be used by conservative turbine manufacturers or when new park extensions influence existing ed. 2 turbines, and they need to be assessed for, e.g., life reduction due to increased wake turbulence.

The general IEC ed. 2 requirements for assessment of a wind turbine using site-specific conditions is defined in section 11.2 of the standard in the part inserted below.



11.2 Assessment of wind conditions

As a minimum requirement, the wind conditions at the site shall be assessed according to the basic parameters listed below in terms of which the WTGS classes are defined.

– reference wind speed:	V_{ref}
– annual average wind speed:	V_{ave}
– turbulence intensity at V_{hub} = 15 m/s:	I_{15}

where I_{15} is the characteristic value of hub-height turbulence intensity at a 10 min average wind speed of 15 m/s. The characteristic value is calculated by adding the measured standard deviation of the turbulence intensity to the measured or estimated mean value.

The wind conditions shall be assessed from monitoring measurements made at the site, long term records or from local codes or standards. Where appropriate, the site conditions shall be correlated with long term data from local meteorological stations.

The monitoring period shall be sufficient to obtain a minimum of six months of reliable data. Where seasonal variations contribute significantly to the wind conditions, the monitoring period shall include these effects.

The value I_{15} shall be determined using appropriate statistical techniques applied to measured data obtained at wind speeds greater than 10 m/s 4). Where topographical or other local effects may influence the turbulence intensity then these effects shall be represented in the data.

The characteristics of the anemometer, sampling rate and averaging time used to obtain measured data can influence the assessment of turbulence intensity. These effects shall be considered when predicting the turbulence intensity from measured data.

For complex terrain, the wind conditions shall be assessed from measurements made at the site. In addition, consideration shall be given to the effect of topography on the wind speed, wind profile, turbulence intensity and flow inclination at each turbine location.

Wake effects from neighbouring machines shall be considered for WTGS operating in wind farms.

From [23] IEC 61400-1 ed. 2 (1999).

For many of the wind climate requirements in IEC ed. 2, no explicit or direct calculation guideline is given. The below text summarizes the decisions made for calculation and evaluation of the IEC ed. 2 checks – the governing principle has been to re-use as much as possible from the current IEC ed. 3 version.

Terrain complexity
There is no explicit description of how to assess terrain complexity in IEC ed. 2, only that it is required.
We have decided to fully adopt the terrain complexity calculations of IEC ed. 3, to fulfill the IEC ed. 2 requirements.

Extreme wind
The design value and, hence, upper limit of the 50 year extreme wind is *Vref* for the design class in question as in IEC ed. 3.

Wind distribution
There is no specific limits or check ranges defined for wind distribution in IEC ed. 2. Since the design climate is defined by mean wind speed for the wind turbine class and k=2, these values are used as the check limits. (see Appendix III - Critical, Caution & OK limits in:).

(Effective) Turbulence
The IEC ed. 3 Effective turbulence calculation to combine ambient and wake turbulence has been adopted to fulfill the IEC ed. 2 requirements. However, it is with the important difference that the 84th percentile of the ambient turbulence is used for IEC ed. 2 as opposed to the 90th in the IEC ed. 3. The IEC ed. 2 standard only requires the check performed at 15 m/s with a design value and, hence, upper limit of *I15* for the relevant deign class.

Wind shear
The design value and upper limit of wind shear is set to 0.2 in IEC ed. 2. We have chosen to supplement this by the additional lower limit at 0.0 defined in IEC ed.3, as very low wind shears are equally damaging as high wind shears.

Flow inclination
The upper and lower limits of flow inclination are defined as +/-8° from horizontal as in the IEC ed. 3.

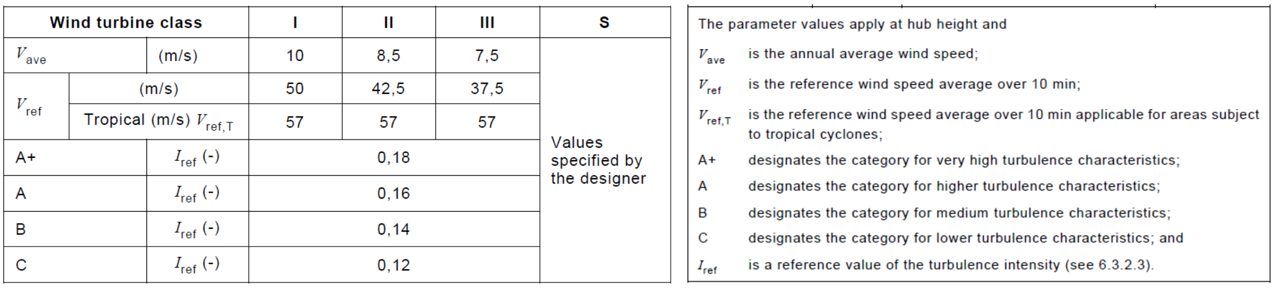
Air density
A design air density and, hence, upper limit of 1.225 kg/m^3 is defined in IEC ed. 2, as in IEC ed. 3.

Appendix VII - IEC 61400-1 ed. 4 (2019)

From windPRO version 3.3, SITE COMPLIANCE supports the fourth edition of IEC 61400-1 [24] (hereafter IEC ed. 4), released in February 2019. Fourth edition is consistent with the third edition in several regards, but at the same time, it introduces new turbine design classes and new checks for the extreme wind climate. The terrain complexity check is replaced by a new methodology, but maintains its purpose of deciding the degree to which ‘turbulence structure correction’ is required for the turbine positions. Another improvement in ed. 4 is a more explicit split of the wind climate checks in the checks that contribute to fatigue and those from extreme events that represent ultimate loads. The following text summarizes these main differences in IEC ed. 4 compared to IEC ed. 3, which are relevant in the context of SITE COMPLIANCE and LOAD RESPONSE.

Design classes

The IEC ed. 4 allows the same standard design classes as IEC ed. 3, the wind speed classes I to III and turbulence classes A to C, with unchanged design parameters Iref, Vref and Vave. In addition, the IEC ed. 4 introduces a new extra high turbulence class “A+”; A new “Tropical” option is also introduced for all design classes, which replaces the design extreme wind speed “Vref” with the increased “Vref,T” of 57m/s, suitable for regions prone to tropical cyclones/typhoons. These classes are summarized in Table 1 of the ed. 4 standard, inserted below.



Wind turbine class		I	II	III	S
V_{ave}	(m/s)	10	8,5	7,5	Values specified by the designer
V_{ref}	(m/s)	50	42,5	37,5	
	Tropical (m/s) $V_{\mathrm{ref,T}}$	57	57	57	
A+	I_{ref} (-)	0,18			
A	I_{ref} (-)	0,16			
B	I_{ref} (-)	0,14			
C	I_{ref} (-)	0,12			

The parameter values apply at hub height and

V_{ave}	is the annual average wind speed;
V_{ref}	is the reference wind speed average over 10 min;
$V_{\mathrm{ref,T}}$	is the reference wind speed average over 10 min applicable for areas subject to tropical cyclones;
A+	designates the category for very high turbulence characteristics;
A	designates the category for higher turbulence characteristics;
B	designates the category for medium turbulence characteristics;
C	designates the category for lower turbulence characteristics; and
I_{ref}	is a reference value of the turbulence intensity (see 6.3.2.3).

From [24] IEC 61400-1 ed. 4 (2019): “Table 1 – Basic parameters for wind turbine classes”.

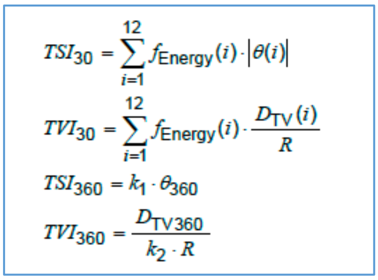
Section 11.2 Terrain Complexity

The updated ed. 4 version of the terrain complexity check changes the way terrain complexity is calculated and categorized. Sectorial fits for the radius measured in hub heights of 5xHH has been included, with an option to extend the sectors by 2xHH downwind of the WTG position. In total 1+3x12 = 37 terrain fits must be performed for the following radii (in HH):

- 5xHH: 12 sectorial fits & 1 omnidirectional fit
- 10xHH: 12 sectorial fits
- 20xHH: 12 sectorial fits

Contrary to the IEC ed. 3, the terrain fits are not constrained to go through the WTG tower base, and the resolution of the utilized terrain grid is required to be ≤50m.

For each of the 37 fits the slope (θ) along the sector center-line (or gradient for the omni-directional fit) is estimated as well as the standard deviation of the difference between the fitted plane and the original terrain heights of the grid points (D_{TV}). The slopes and standard deviations are used to calculate the “Terrain Slope Index” (TSI) and “Terrain Variation Index” (TVI) for the omni-directional fit and across the sectorial fits for each of the radii, as summarized in the equation (34) in the standard (see below).



$$TSI_{30} = \sum_{i=1}^{12} f_{\text{Energy}}(i) \cdot |\theta(i)|$$

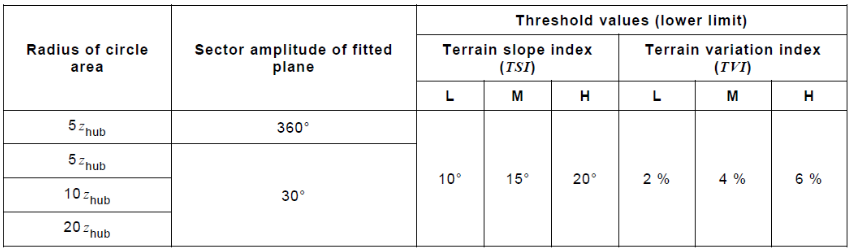
$$TVI_{30} = \sum_{i=1}^{12} f_{\text{Energy}}(i) \cdot \frac{D_{\text{TV}}(i)}{R}$$

$$TSI_{360} = k_1 \cdot \theta_{360}$$

$$TVI_{360} = \frac{D_{\text{TV}360}}{k_2 \cdot R}$$

Equation (34) from [24] IEC 61400-1 ed. 4 (2019), expressions for the TSI and TVI based on sectorial (with subscript 30) and omni-directional (with subscript 360) terrain fits. f_{Energy} *is the energy fraction of each sector at the WTG position based on the sector Weibulls. R is the radius of the fit e.g. 5xHH and* k_1*=5/3 and* k_2*=3 are constants.*

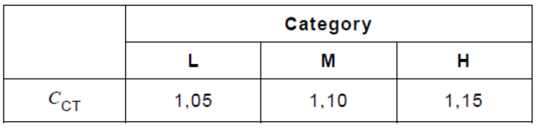
Based the resulting TSI and TVI for each WTG position the complexity category can be found using Table 5 in IEC ed. 4 (see below). The worst TSI or TVI for a WTG position determines the category and each category is defined by its lower TSI and TVI thresholds. The categories “L”, “M” and “H” represent low, medium and high terrain complexity, respectively. We use the label “No” complexity for the category below the “low” category. Contrary to IEC ed. 3 no complexity index is calculated in the IEC ed. 4.



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}							

From [24] IEC 61400-1 ed. 4 (2019): “Table 5 - Threshold values for terrain complexity categories L, M and H”.

Finally, the turbulence structure correction parameter (C_{CT}) can be inferred directly from the complexity category using Table 7 of the IEC ed. 4 standard (see below). In SITE COMPLIANCE this parameter is directly transferred to the relevant turbulence checks, where it may be replaced by more detailed alternative values if WEng modelling results are available.



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

From [24] IEC 61400-1 ed. 4 (2019): “Table 7 – Values of the turbulence structure correction parameter depending on terrain complexity category L, M and H”.

Section 11.9.2 Fatigue load assessment

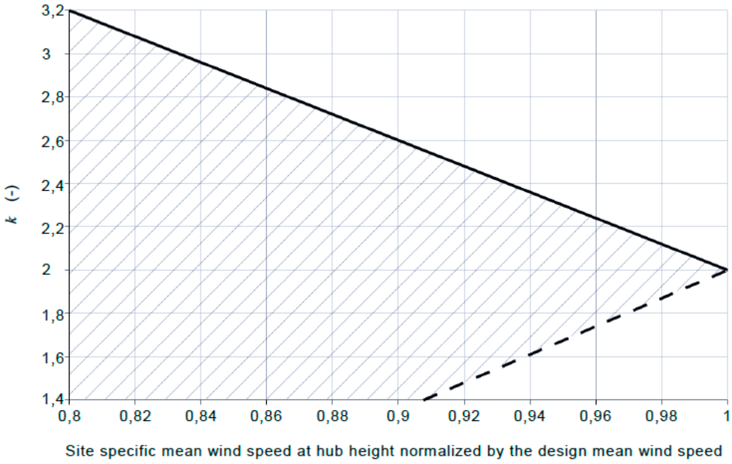
The IEC ed. 4 wind climate checks are split into a list of checks for fatigue loads and a list for ultimate loads. The below list of five checks, a) to e), represent fatigue loads or “normal climate”, were also in IEC ed. 3.

a) Wind Distribution
b) Effective turbulence
c) Flow Inclination
d) Wind Shear
e) Air Density

In these five checks, there are smaller changes to the following checks: Wind Distribution, Flow Inclination, Wind Shear and Air density, which are briefly described below.

Check *(a) Wind Distribution* introduces an additional check criterion on the Weibull k-factor, which is summarized in the standard’s equation (35) and figure 12, shown below. This extra k-factor check penalizes deviations of k outside a range, which depends on the ratio of the mean wind speed of the WTG and the design class. If this ratio is 1 or above the criterion is violated. For ratios below 1 the acceptable k-range centered on the design k=2.0, gradually grows with decreasing mean wind speed ratio. k-factors below 1.4 will also lead to a violation no matter the ratio of mean wind speeds. This additional check makes the Wind Distribution check more restrictive in IEC ed. 4 as compared to IEC ed. 3.

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



Equation (35) and figure 12 from [24] IEC 61400-1 ed. 4 (2019), which describe the additional check introduced on the Weibull k-factor.

Check *(b) Effective turbulence* has to be checked in the wind speed interval V_{ave} to $2V_{ave}$. Previously in IEC ed. 3 the interval was from 60% of the wind speed at turbine rated power to the cut out wind speed.

Check *(c) Flow Inclination* is adjusted to use the energy frequency weighted average inflow angle across sectors as opposed to the max sector inflow angle used in IEC ed. 3. To prevent the non-conservatism from averaging high positive and negative inflow angles to zero, in SITE COMPLIANCE we allow the option of using absolute averages of inflow angles, which also appears more consistent with equation 43 in the terrain complexity check (see above). The sector energy frequencies are calculated from the sector Weibulls. IEC ed. 4 allows the use of slopes of the sectorial 5xHH fits as estimates of the sector flow inclinations in ed. 3 the slope of the omni-directional fit was used for this purpose.

Check *(d) Wind Shear* is adjusted similarly to the Flow Inclination check to use the energy frequency weighted average wind shear across sectors instead of the simple average shear as in IEC ed. 3. In addition, the accepted range of wind shears is adjusted to 0.05 to 0.25 in IEC ed. 4 compared to 0.0 to 0.2 in IEC ed. 3.

Check *(e) Air Density* is adjusted to allow a correction based on the WTG and design mean wind speeds for sites where the design air density of 1.225kg/m^3 is exceeded. This adjustment effectively reduces the WTG air density by the squared ratio on WTG mean wind speed and mean wind speed of the design class. Hence, a margin of 10% on the WTG mean wind speed (a ratio of 0.9), translates into a reduction of 20% of the WTG site air density in the check against the design limit.

$$\rho_{\text{design}} \times V^2_{\text{ave,design}} \ge \rho_{\text{site}} \times V^2_{\text{ave,site}}$$

Equation (37) from [24] IEC 61400-1 ed. 4 (2019), adjustment criterion for the air density when the design air density is exceeded.

Section 11.9.3 Ultimate load assessment

The list of ultimate load checks for wind climate is extended to four explicit checks in IEC ed. 4, from only one explicit check on extreme wind speeds in IEC ed. 3. The three new ultimate load checks all refer to different aspects of extreme turbulence as seen from the list below.

a) Ambient 90% Turbulence [NTM]
b) Extreme Wind
c) Ambient Extreme Turbulence [ETM]
d) Max Centre-wake 90% Turbulence [ETM]

Check *(b) Extreme Wind* is adjusted slightly compared to IEC ed. 3. Firstly, the WTG extreme wind speed estimates must be corrected by an additional “safety factor” when the coefficient of variation of the WTG extreme wind Gumbel distribution exceeds 15%. Secondly, the WTG 50year extreme wind speed estimates may be air density corrected according to equation (39) in the standard (inserted below). This effectively reduces the WTG extreme wind speed by the square root of the ratio of the WTG air density and design air density of 1.225 kg/m^3.

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

Equation (39) from [24] IEC 61400-1 ed. 4 (2019), allowed air density correction criterion for extreme wind.

The new check *(a) Ambient 90% Turbulence [NTM]*, checks that the WTG ambient 90% of turbulence including turbulence structure correction (C_{CT}) is within the design Normal Turbulence Model (NTM) for wind speeds between 0.6 and 1.6 times the rated wind speed. One may wonder why this check of a non-extreme turbulence quantile against a non-extreme design turbulence is a part of the ultimate load checks. The reason is this checks link to a design load case, DLC1.1 where the resulting loads are extrapolated to extreme quantiles/return-periods. If this check fails, DLC1.1 and load extrapolation must be performed.

The new check *(c) Ambient Extreme Turbulence [ETM]*, checks the WTG ambient 50y extreme turbulence against the design Extreme Turbulence Model (ETM). No turbulence structure correction is required. An explicit wind speed check interval is not defined for this check, but the check is related to DLC1.3 in “Power production” group, defined for all wind speeds between cut-in and cut-out, hence this is the check range we have adopted.

The new check *(d) Max Centre-wake 90% Turbulence [ETM]* checks the WTG 90% turbulence including wake turbulence for the worst direction against the design Extreme Turbulence Model (ETM). This check bears a strong resemblance to the Effective turbulence check for fatigue loads, with the differences that the maximum centre-wake turbulence across all directions is used instead of the effective integration across directions for the effective turbulence. Another, difference is that this check (d) does not require turbulence structure correction (C_{CT}) to be applied as is the case for the Effective turbulence. An explicit wind speed check range is not defined, but with similar arguments as in check (c), the full power production range from cut-in to cut-out is adopted.

The two new checks (a) Ambient 90% Turbulence [NTM] and (c) Ambient Extreme Turbulence [ETM] both refer to the ambient turbulence. Since no wake affects are included, these checks are handled omni-directionally as this makes the statistical handling across wind speeds bins and the propagation to the WTG position much more robust. The omni-directional propagation of the turbulence is performed using the frequency weighted average wind speed and turbulence for the mast and WTG. An exception is for CFD/Flowres propagation where the full time series is propagated from the mast to each WTG and then binned omni-directionally there.

Effect of curtailment on fatigue and ultimate checks

If curtailment is applied to some WTG in a layout some of fatigue and ultimate checks may be affected. The curtailment does not change the ambient wind climate parameters, but will only affect the wake contribution to turbulence. The control of the WTG itself e.g. shut down or derating shall be handled as a part of the load simulation. Hence, only the checks which include wake effects will be affected by curtailment, this is the fatigue check (b) Effective turbulence and ultimate check (d) Max-centre wake 90% turbulence.

Connection to design load cases

The assessment of structural integrity based on the wind climate parameters is closely linked to particular design load cases (DLC), which depend on site specific wind climate parameters. For the group of checks related to fatigue loads and the ‘normal’ wind climate parameters, the primary relevant design load case is DLC1.2 ‘Power production’. Minor contributions to fatigue loads also occurs from DLC3.1 ‘Start-up ‘, DLC4.1 ‘Shut-down’ and DLC6.4 ‘Parked’, however, much less than the Power production part as summarized in the table below.

Fatigue Load Check	Design Load Cases (DLC)
(a) Wind Distribution	DLC1.2 + (DLC3.1,DLC4.1, DLC6.4)
(b) Effective turbulence	DLC1.2 + (DLC3.1,DLC4.1, DLC6.4)
(c) Flow Inclination	DLC1.2 + (DLC3.1,DLC4.1, DLC6.4)
(d) Wind Shear	DLC1.2 + (DLC3.1,DLC4.1, DLC6.4)
(e) Air Density	DLC1.2 + (DLC3.1,DLC4.1, DLC6.4)

Connections between ‘normal’ wind climate checks and fatigue load DLCs.

For the checks relating to the 'extreme' wind climate parameters and ultimate loads, the relations to DLCs are more complex as summarized in the table below:

Ultimate Load Check	Design Load Case (DLC)
(a) Ambient 90% Turbulence [NTM]	DLC1.1 + Load extrapolation
(b) Extreme Wind	DLC6.1 + DLC6.2
(c) Ambient Extreme Turbulence [ETM]	DLC1.3
(d) Max Centre-wake 90% Turbulence [ETM]	DLC1.3 alternatively DLC1.6

Connections between extreme wind climate checks and ultimate load DLCs.

DLC1.1 is 'Power production' using the normal wind climate via the normal turbulence model (NTM), but for the purpose of extrapolating the resulting normal operation loads to extreme loads. DLC1.3 is also 'Power production' but with the extreme turbulence model (ETM), where the alternative DLC1.6 also considers wake effects but in a more narrow wind speed interval. Finally, DLC6.1 and DLC6.2 are both 'Parked' during the extreme 50 year wind speed event, the latter with loss of grid connection.

Design loads

For a generic turbine model there are no explicitly defined design loads from a type certification, hence, the design loads are estimated as the loads which result from applying the load model (aero-elastic model or response model) to the design wind climate. IEC61400-1 ed. 3 explicitly mentions that the design load should represent the worst loading in regards to vertical inflow angles in span from -8° to +8°. Hence, for calculating design loads in load response the highest load of -8°, 0°, and +8° is always evaluated and the highest taken as the design load. In IEC61400-1 ed. 4, this requirement is no longer explicitly mentioned. For consistency, we interpret the intention to be same in ed. 4 in regards to inflow angles influence on deign loads although not explicitly stated.

Robust Weibull fit for turbulence

In the IEC61400-1 ed. 4 the design distribution of turbulence (wind speed standard deviation) conditioned on wind speed is described by a two-parameter Weibull, similarly to the annual wind speed distribution. In ed. 3, turbulence was assumed to follow a log-normal distribution. However, in all calculations relating to the site specific 90%-quantile of turbulence both ed. 3 and 4 uses an expression for the 90%-quantile, which assumes a normal distribution, i.e. $\sigma_{90\%} = \sigma_{\mu} + 1.28\sigma_{\sigma}$. In ed. 4 the Weibull parameters of the design turbulence (Normal Turbulence Model) are calibrated such that the Weibull based 90%-quantile matches the NTM 90% design turbulence. To be in-line with the ed. 4 standard we also allow the estimated site 90%-quantile to be based on fitted Weibull distribution of turbulence conditioned on wind speed. However, as the turbulence data are also binned on direction very few samples can be available for these fits. To ensure on the one hand a robust fit and on the other hand consistency with the standard equation based on the mean and standard deviation we have chosen a method of moments fit [25]. This solves two equations with two unknowns (i.e. the Weibull parameters) to find the Weibull with same mean and standard deviation as the data. This makes the fit quite robust even in bins with few samples.

Ambient extreme turbulence and the IFORM method

The IEC61400-1 ed. 4 introduces the Ambient Extreme Turbulence check and presents two alternative methods to estimate the 50 year extreme turbulence at each wind speed. One method is using a parameterized expression given in the standard based on peak factors (k_p) to be used similarly as for the estimation of the 90%-quantile, $\sigma_{50y} = \sigma_{\mu} + k_p\sigma_{\sigma}$ at each wind speed (k_p depends on wind speed). This method is said to be due to Leo Thesbjerg from Vestas in the IEC working group TC88 (no known publication). The alternative method proposed is the Inverse First Order Reliability Method, or IFORM [26], which progresses in a number of steps to estimate the 50 year turbulence conditioned on wind speed. Here the concept of IFORM is briefly sketched. The IFORM method performs the following steps for each wind speed:

1. Calculate the standard normal quantile (x_1) for the cumulative frequency of the wind speed
2. Calculate the target quantile (beta) for the target probability of exceedance of 50 years
3. Calculate the standard quantile of the turbulence (x_2) from x_1 and beta in the 2D standard normal space
4. Calculate the target 50y turbulence from its CDF such that it has the same cumulative probability as x_2

The IFORM is very sensitive to the estimated standard deviations of turbulence and is considerably less robust than the alternative method. Hence, IFORM is only recommended when data duration and quality is high so that turbulence distributions are well defined at most wind speeds and only little influenced by the fitting and extrapolation to higher wind speeds. The IFORM method is deactivated until industry guidelines to improve its robustness is established/published.

Appendix VIII - Lifetime extension DNVGL-ST-0262 (2016)

Many onshore wind turbines in Europe will be approaching the end of their design lifetime, traditionally 20 years. The operational lifetime may in many cases be extended beyond the original design lifetime – but this is typically subject to different national requirements mainly driven by inspection protocols and other such schemes. There is also an on-going effort to establish an international IEC standard 61400-28 for "Through life management and life extension of wind power assets", however, currently only two official standards on lifetime extension have been released by the commercial entities, DNV-GL and UL. The former entity has released the standard "DNVGL-ST-0262 Lifetime extension of wind turbines", which is a focused, concise and freely available standard [27] covering both the theoretical fatigue calculations of lifetime and the practical guidelines for inspection.

From windPRO version 3.5 lifetime calculations in LOAD RESPONSE have been aligned with the DNVGL-ST-0262 standard. The purpose is providing a very fast, easy and cost-effective tool for assessing the *structural potential* for lifetime extension prior to any further detailed and costly investigations and inspections. Physical inspections are always required for lifetime extensions and cannot be replaced by fatigue load calculations, only supplemented.

Methods in DNVGL-ST-0262

DNVGL-ST-0262 splits the lifetime assessment into an 'Analytical' calculation part (§2.2) and a 'Practical' inspection part (§2.3). Our focus is the Analytical part which is further split in to three alternative methods: 'Simplified' (§2.2.3), 'Detailed' (§2.2.4) and 'Probabilistic' (§2.2.5). The former two approaches are deterministic and covered by windPRO LOAD RESPONSE and described in the following.

'Simplified approach' (=generic response models)

This approach is used when the actual turbine design is not available and use of a generic model is necessary. Although this is a deterministic approach where uncertainties in general are not accounted for, the Simplified approach specifically requires assessment of the uncertainty related to use of the generic load model. Except for this uncertainty the Simplified approach is consistent with using LOAD RESPONSE with one of the module's generic turbine models. Further description of the uncertainty model and how to handle known load margins is provided in the following subsections.

'Detailed approach' (=specific response models)

The Detailed approach is used when the actual turbine design is available in the form of actual load calculations for the turbine model in question. In LOAD RESPONSE this corresponds to using a specific response model which also includes the actual design loads (certification loads) including any load margins. No uncertainty is considered for this approach.

Load margins (Simplified approach only)

Some specific turbine models are stronger than required for their design class, here referred to as 'load margins'. Some users may have knowledge of load margins for the components of specific models after several iterations with a manufacturer comparing load results for a generic model with those of a specific turbine. Such information may be included via a new option to combine known load margins with the use of generic models. Load margins as such cannot be handled as uncertainties as they are systematic biases from the design class basis introduced by each manufacturer for each turbine model.

Uncertainty model (Simplified approach only)

The uncertainty model relies on the IEC/ISO standard for uncertainty assessments [28] to calculate the resulting uncertainty on the lifetime. However, there is no simple or direct way to calculate the uncertainty due to the generic model, hence, the assessment is done as an order of magnitude. In general, the uncertainty related to using a generic reference turbine model depends on its similarity compared to the design of the actual turbine model for which the lifetime extension is conducted. An overall description of the reference turbines used in LOAD RESPONSE is found in the following subsection.

Initially, uncertainties are estimated for each component/sensor by analysing the variation in load index response across several different turbine models with moderate variations in their structural design. This is then simplified to a single baseline uncertainty across all sensors/components - in line with the largest variations observed for blades and tower loads – and therefore possibly conservative for other sensors/components. Three uncertainty categories are then defined via a doubling of the uncertainty when going one category up, as follows:

- High similarity / low uncertainty: 1 x baseline uncertainty

Moderate similarity / uncertainty:	2 x baseline uncertainty
Low similarity / high uncertainty:	4 x baseline uncertainty

The resulting uncertainties on the calculated component load indices are then propagated to uncertainties on the component lifetimes using the methodology of the ISO/IEC standard for uncertainty [28]. The relation between load index and lifetime is very non-linear and results in a significant amplification of uncertainties – this is inherent in the non-linear nature of fatigue damage accumulation and load calculations.

Reference models (Simplified approach only)

All generic models in LOAD RESPONSE are adapted from public reference models like NREL 5MW geared or direct-drive [29,31], Windpact 1.5MW [30] and DTU 10MW [32]. These all have a traditional standard design with the following main characteristics:

- Traditional upwind three-bladed design (fibreglass or carbon - choose appropriate model)
    - Max blade chord ca. 8% at ca. 25% of length, narrowing towards the root
- Geared or gearless (choose appropriate model)
- Standard “soft-stiff” steel tower
- Standard variable speed, collective pitch control (PI controller)

Special control strategies are not accounted for and is beyond the scope of the assessment as special control strategies could in principle result in arbitrarily large differences in the turbine load response.

Appendix IX - Siteres ambient climate files (from Resource, GASP, etc.)

From windPRO 3.5 a new resource data format “.siteres” has been introduced. Contrary to existing resource formats such as “.rsf” or “.wrg”, siteres files also include other site parameters in addition to the Weibull resource parameters.

These parameters are statistical parameters characterising ambient site conditions of extreme wind, turbulence, wind shear, air density, flow inclination and terrain complexity – sufficient to make a full IEC 61400-1 site assessment in SITE COMPLIANCE. Hence, from windPRO 3.5 siteres-files have been integrated as an alternative calculation basis in SITE COMPLIANCE supplementing the existing based on measurements and flow-modelling. The siteres format is described further in this reference: Technical Note - Siteres

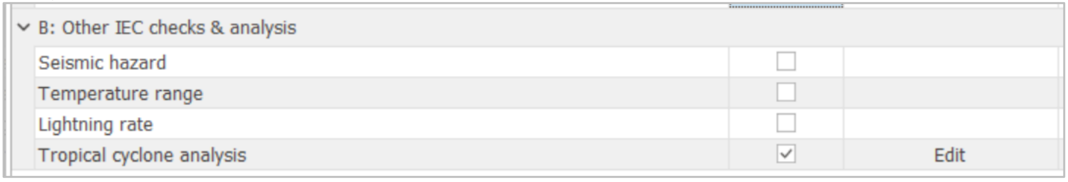
Siteres files may be obtained from several sources. The user may generate own siteres files in the windPRO RESOURCE module in a setup that inherits most calculation functionality from SITE COMPLIANCE (licence for SITE COMPLIANCE is required).

An alternative option is GASP - the Global Atlas of Siting Parameter - which provides a global atlas of siting paramers at 250m resolution and three heights 50m, 100m and 150m. GASP data may be downloaded directly from windPRO through the “Data / Siting Parameter (GASP etc.)” menu. This opens a download window which allows specification of the area of interest.

The same download window also includes another new concept, Regional Atlas of Siting Parameters (RASP), which is for atlases of siting parameters with regional coverage and considerably increased accuracy of the siting parameters compared to GASP. Currently RASP-SWE 0.3 (beta version) is available as a demonstration dataset for Sweden.

Appendix X - Tropical Cyclone Analysis

IEC 61400-1 ed. 4 (2019) includes in Annex J a method to quantify tropical cyclone extreme wind speeds. However, this theoretical method is not very practical, as it utilizes Monte Carlo simulation to predict tropical cyclone induced extreme wind speeds.
As a more practical alternative, from windPRO 4.0 SITE COMPLIANCE includes a screening tool to analyse historical cyclone tracks around a site. The Tropical Cyclone Analysis tool integrates the International Best Tack database (IBTrACS) [34] of historical tropical cyclone tracks with worldwide coverage going back to pre-1900. This analysis tool gives the user the possibility to analyse the sensitivity to size of region of interest and to the historical period of interest. The extracted tracks are visualized, and the important statistics are extracted and summarized. Finally, a Gumbel extreme wind model is fitted to the extracted data to quantify a 50-year extreme wind estimate at standard conditions. The Tropical cyclone analysis is added to the group *Other IEC checks & analysis.*



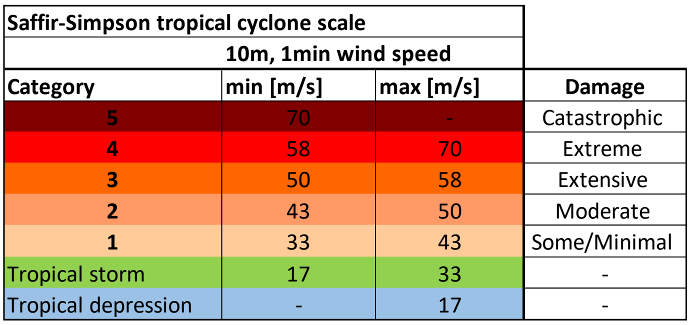
B: Other IEC checks & analysis

Seismic hazard	☐	
Temperature range	☐	
Lightning rate	☐	
Tropical cyclone analysis	☑	Edit

Tropical cyclones are also known as typhoons or hurricanes and are so-called warm core cyclones which can only be seeded and maintained when the temperature of the upper parts of the water column exceed 26°C. Exactly at the equator the Coriolis force is zero and tropical cyclones cannot form and will die out. North of the equator the Coriolis force make cyclones turn counterclockwise as winds veer to the right. The opposite is the case south of the equator, where wind veers left and cyclones rotate clockwise.

Tropical cyclones represent the fiercest weather and wind speed events on our globe, and, luckily, they are rare and relatively localized phenomena. This is also a reason for the difficulty when analysing extreme winds from tropical cyclones - getting a sufficient long-term record and sufficient spatial coverage to sample the variation in tracks. Even several years of data for a point location will rarely be enough to properly evaluate the risk of tropical cyclone winds.

Tropical cyclones are typically classified following the Saffire-Simpson hurricane scale, which uses so-called “1-minute maximum sustained wind speed” at 10m height. This simply means the highest recorded/modelled 1min averaged wind speed within the cyclone at a given time. Not all international cyclone agencies report cyclone data with the same averaging time, hence, IBTrACS contains data with both1min, 3min and 10min data depending on agency. To circumvent this problematic inconsistency, we use only wind speeds reported through the USA agencies which also incorporate data from the other agencies and convert them consistently to 1min data. The table below summarizes the Saffire-Simpson tropical cyclone scale with thresholds converted to m/s. The rightmost column indicates the typical damage incurred by each cyclone category.



Saffir-Simpson tropical cyclone scale			
	10m, 1min wind speed		
Category	**min [m/s]**	**max [m/s]**	**Damage**
5	70	-	Catastrophic
4	58	70	Extreme
3	50	58	Extensive
2	43	50	Moderate
1	33	43	Some/Minimal
Tropical storm	17	33	-
Tropical depression	-	17	-

Saffir-Simpson hurricane scale converted to m/s (see e.g. https://www.nhc.noaa.gov/aboutsshws.php).

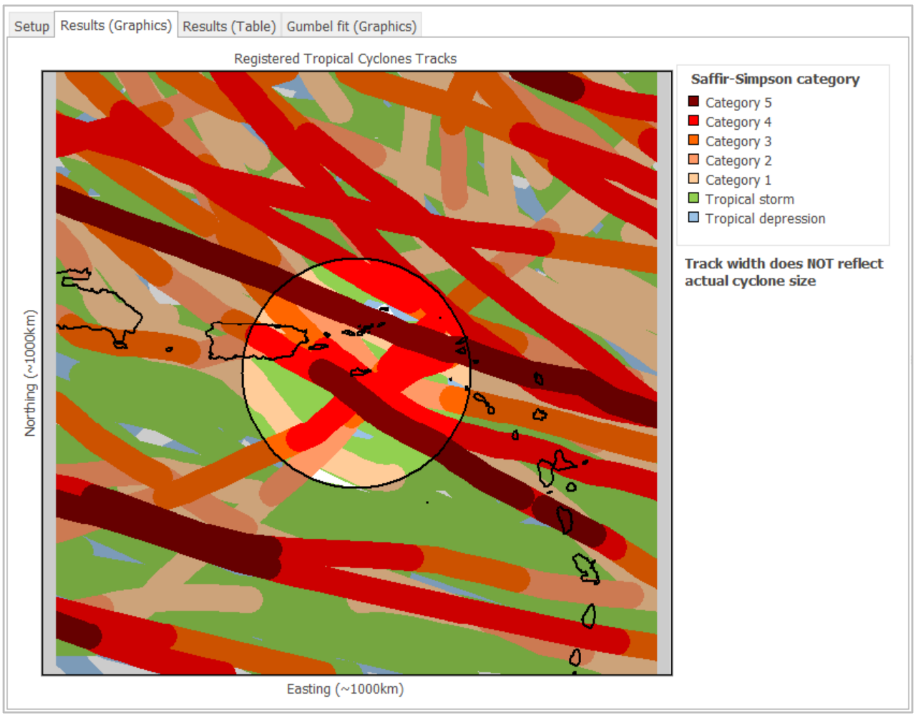
Setup - extraction of data from IBTrACS database

To extract cyclone events and statistics from the IBTrACS database the user needs to set three parameters, the start year of the extraction, the radius around the site centre to extract tracks within and finally a threshold wind speed below which extracted annual maxima are not included in the fitted Gumbel extreme wind model. By default, this threshold is set to 20 m/s however this should be specified site specific by the user.

Extract data from (year):	1980
Cyclone tracks represent site within (km):	200
Only fit wind speed events above (m/s):	20

Results (Graphics) – spatial plot of tracks using Saffir-Simpson scale

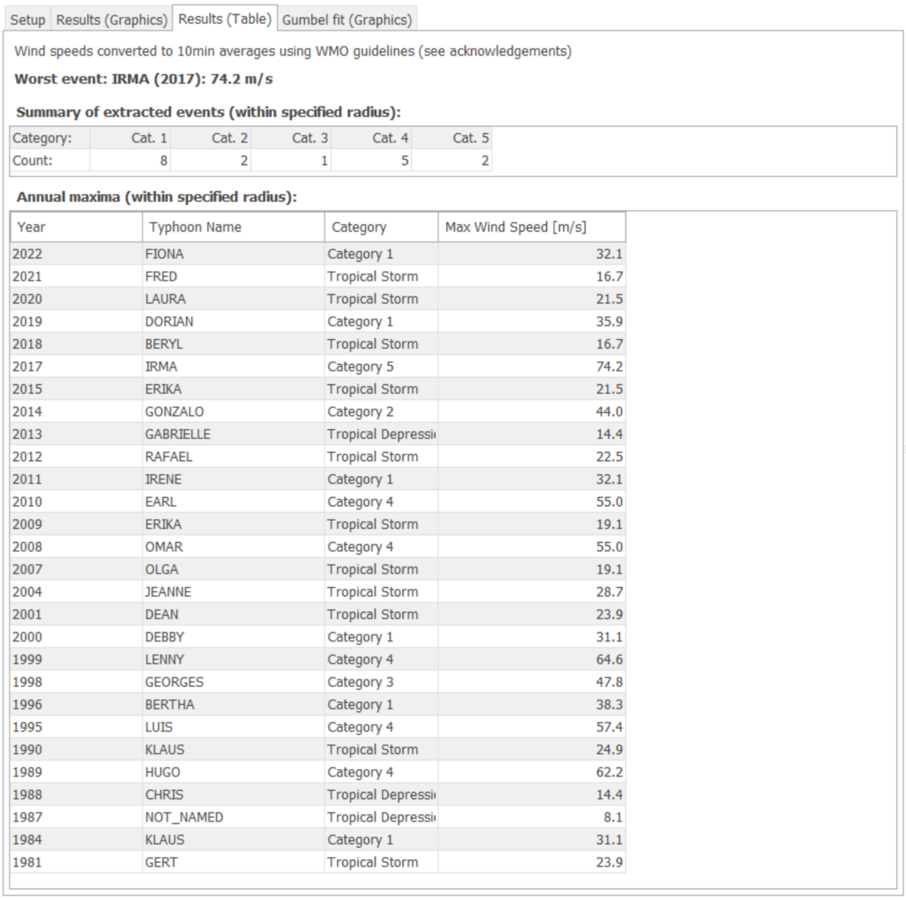
This track plot summarizes all tracks dating back to the user-defined start year within an area of ca. 1000km by 1000km. Track points are shown in the colour legend of the Saffire-Simpson scale and higher track category points/segments are always plotted on top to emphasize historical storm severity. The plot also highlights the user's selected radius of representativity around of the site centre.



Track width does NOT reflect actual cyclone size

Results (Table) – summary of extracted cyclone events and annual maxima

The first table on this tab summarizes the number of individual cyclone tracks of each Saffir-Simpson category within the user defined radius. The table below lists the annual maximum storm point/track for each year back to the user selected start year – within the selected radius. In this table all the IBTrACS 1min wind speeds reported by the USA agencies have been converted to 10min averages using the guideline provided by WMO for tropical cyclones [35]. This conversion is done assuming offshore/coastal exposure and will be conservative for inland locations, however, as tropical cyclones decay rapidly over land, they are mainly a concern for coastal regions or islands.



Wind speeds converted to 10min averages using WMO guidelines (see acknowledgements)

Worst event: IRMA (2017): 74.2 m/s

Summary of extracted events (within specified radius):

Category:	Cat. 1	Cat. 2	Cat. 3	Cat. 4	Cat. 5
Count:	8	2	1	5	2

Annual maxima (within specified radius):

Year	Typhoon Name	Category	Max Wind Speed [m/s]
2022	FIONA	Category 1	32.1
2021	FRED	Tropical Storm	16.7
2020	LAURA	Tropical Storm	21.5
2019	DORIAN	Category 1	35.9
2018	BERYL	Tropical Storm	16.7
2017	IRMA	Category 5	74.2
2015	ERIKA	Tropical Storm	21.5
2014	GONZALO	Category 2	44.0
2013	GABRIELLE	Tropical Depressi	14.4
2012	RAFAEL	Tropical Storm	22.5
2011	IRENE	Category 1	32.1
2010	EARL	Category 4	55.0
2009	ERIKA	Tropical Storm	19.1
2008	OMAR	Category 4	55.0
2007	OLGA	Tropical Storm	19.1
2004	JEANNE	Tropical Storm	28.7
2001	DEAN	Tropical Storm	23.9
2000	DEBBY	Category 1	31.1
1999	LENNY	Category 4	64.6
1998	GEORGES	Category 3	47.8
1996	BERTHA	Category 1	38.3
1995	LUIS	Category 4	57.4
1990	KLAUS	Tropical Storm	24.9
1989	HUGO	Category 4	62.2
1988	CHRIS	Tropical Depressi	14.4
1987	NOT_NAMED	Tropical Depressi	8.1
1984	KLAUS	Category 1	31.1
1981	GERT	Tropical Storm	23.9

Gumbel fit (Graphics) – extreme statistics and 50-year wind estimate (at 10m)

The annual maximum wind speeds listed on the previous tab are plotted on a Gumbel plot and fitted to a Gumbel extreme wind model (see Appendix 1). Wind speeds below the user selected threshold are not included in the Gumbel plot and fit, however, they still contribute in the calculation of the plotting positions on the y-axis (see Appendix 1). The Gumbel fit allows for the indicative calculation of a 50-year wind speed for tropical cyclones. This estimate represents 10m height and offshore/coastal conditions, hence, it may be used as the input base wind speed when using the EN1991-1-4 method in the Extreme wind check. In this case the reference roughness should be set to offshore roughness[15] z_0=0.0002m as the IBTrACS wind speeds represent offshore or coastal conditions.

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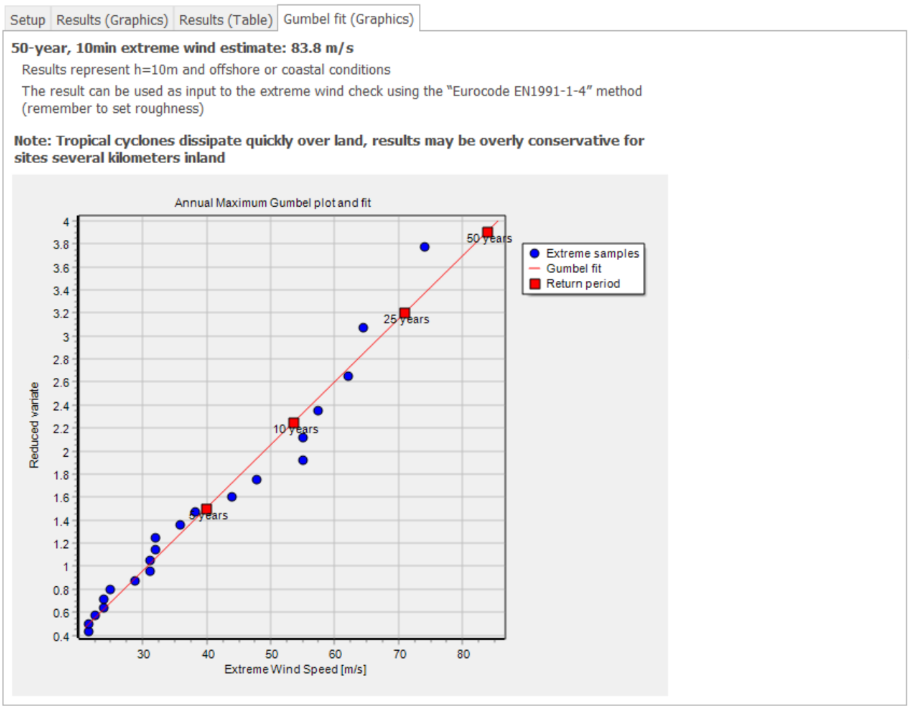
[15] The roughness will be increased offshore at higher wind speeds, but this 'charnock' effect is not modelled in models like WAsP, so to avoid artificial speed-ups/down, use of WAsP's offshore roughness length is recommended.



50-year, 10min extreme wind estimate: 83.8 m/s

Results represent h=10m and offshore or coastal conditions

The result can be used as input to the extreme wind check using the "Eurocode EN1991-1-4" method (remember to set roughness)

Note: Tropical cyclones dissipate quickly over land, results may be overly conservative for sites several kilometers inland

Disclaimer and limitations of the tropical cyclone analysis:

- Data provided from IBTrACS are provided *as is* with the conversions described above
- IBTrACS data before 1965 to 1980 have limited validity varying between regions
- Some wind speeds are coarsely discretized (e.g. 0.5m/s) visible as step-like artefacts in the Gumbel fit
- The tropical cyclone analysis is intended for offshore and coastal sites
  - The analysis may *not* be representative for inland sites and may be overly conservative
- The analysis does not account for *other storm mechanisms* - only tropical cyclones
  - Other extreme wind mechanisms (e.g. thunderstorms or tornados) may contribute significantly to the extreme wind conditions at a particular site.

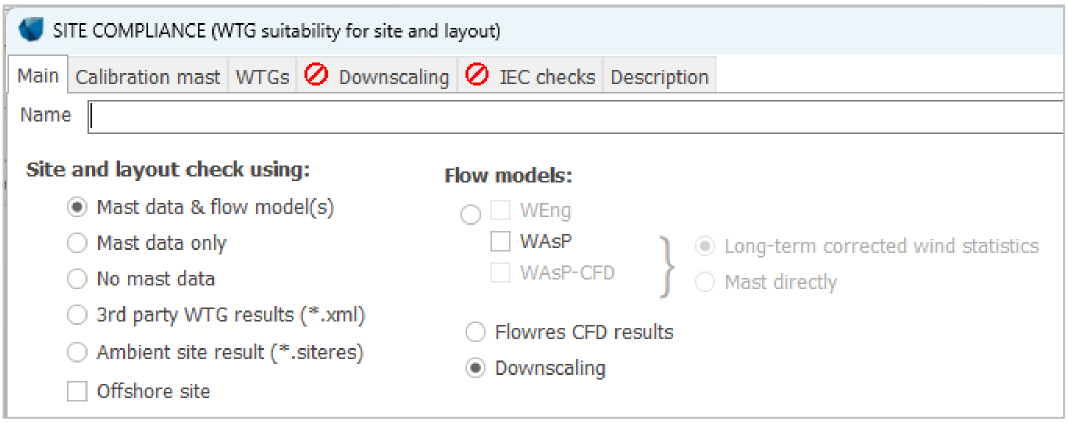
Appendix XI - Downscaling, Offshore mode & Spectral Correction

From windPRO 4.0 SITE COMPLIANCE includes the option to base site assessments on downscaling, that is, the combination of mesoscale data and microscale flow modelling. This functionality is based on the SCALER which is already well established and documented in windPRO.

The original motivation for the downscaling option was for offshore applications where mesoscale data mostly have limited bias and perform well, yet, with some limitations, particularly, regarding turbulence and extreme wind. Therefore, together with the downscaling option a new “Offshore site” option has been added to simplify setup for offshore sites in general.

Lastly, mesoscale data have a known bias with regards to extreme wind speeds, which may be sought corrected by applying a spectral correction which is available from windPRO 4.0. Unfortunately, no general correction model has been proposed for mesoscale TI, hence, this work is ongoing. However, in general results based on downscaled turbulence will be non-conservative.

The downscaling and offshore site option can be selected at the main tab in the SITE COMPLIANCE setup as illustrated in the figure below.



SITE COMPLIANCE (WTG suitability for site and layout)

Main | Calibration mast | WTGs | ⊘ Downscaling | ⊘ IEC checks | Description

Name

Site and layout check using:

- ● Mast data & flow model(s)
- ○ Mast data only
- ○ No mast data
- ○ 3rd party WTG results (*.xml)
- ○ Ambient site result (*.siteres)
- ☐ Offshore site

Flow models:

- ○ ☐ WEng
- ☐ WAsP
- ☐ WAsP-CFD
- ● Long-term corrected wind statistics
- ○ Mast directly
- ○ Flowres CFD results
- ● Downscaling

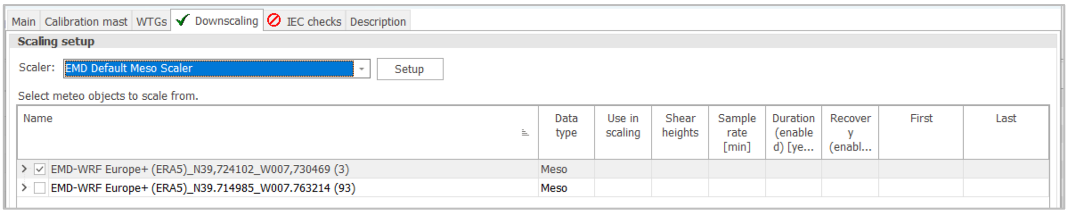
These three new options downscaling, offshore mode and spectral correction are briefly documented in the following.

Downscaling

As mentioned above selecting the downscaling option will allow for using the windPRO SCALER setup together with mesoscale data and a microscale model. In fact, by deselecting the *Terrain scaling* option in the SCALER setup, no microscale modelling is done at all, which can be justified offshore. Downscaling may be selected together with the main option *Mast data & flow model(s)* or *No mast data*. In the former case, two new tabs named *Calibration mast* and *Downscaling* will appear. In the latter case, only the *Downscaling* tab will appear.

Calibration mast
On this tab the user may select a meteo object holding measurements from a mast within the region or situated on-site. These measurements may subsequently be employed by the spectral correction method in the extreme wind check. Unfortunately, no calibration method is so far available for turbulence or other variables.

Downscaling
This tab provides access to the standard setup of the SCALER and selection of mesoscale data to be used by the selected SCALER setup.



Main | Calibration mast | WTGs | ✓ Downscaling | ⊘ IEC checks | Description

Scaling setup

Scaler: EMD Default Meso Scaler | Setup

Select meteo objects to scale from.

Name	Data type	Use in scaling	Shear heights	Sample rate [min]	Duration (enabled) [ye...	Recovery (enabl...	First	Last
☑ EMD-WRF Europe+ (ERA5)_N39,724102_W007,730469 (3)	Meso							
☐ EMD-WRF Europe+ (ERA5)_N39.714985_W007.763214 (93)	Meso							

IEC Checks

Each of the IEC Checks has a new option based on downscaling, named e.g. *Downscaled weibulls (via downscaled timeseries)*. The exceptions are the checks Terrain complexity and Flow inclination which have no new downscaling related method. The three checks related to extreme turbulence, introduced in IEC61400 ed. 4, are not allowed in downscaling mode as they require a higher quality of turbulence data.

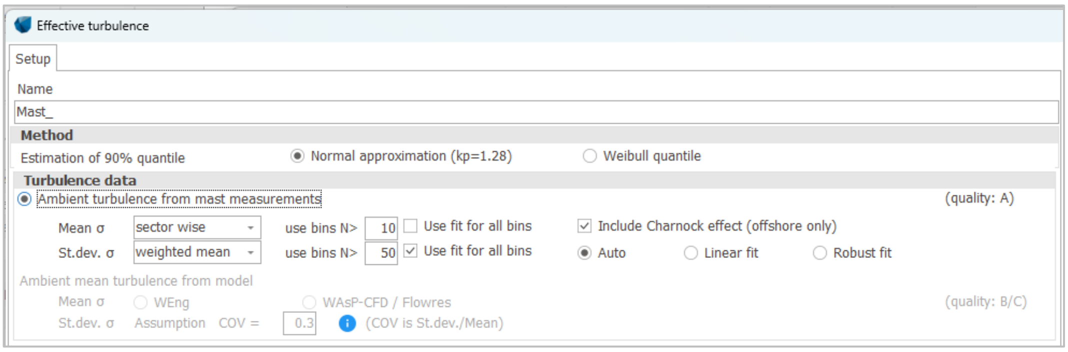
Warning:

- Be careful with assessments of Effective turbulence based on mesoscale turbulence intensity (TI)
- Even if the mean TI is well captured the variation of TI with wind speed may be significantly biased
- Standard deviation of TI within each wind speed bin is often too low, particularly at high wind speeds
- These biases may lead to underestimation of characteristic TI and component loads

Offshore mode

The offshore mode is mainly establish for the sake of better handling of offshore turbulence data and to avoid the need to calculate terrain complexity. Within the Terrain complexity check an offshore option has been introduced that avoids the need to actually establish terrain data via a DEM or TIN model.

In addition, the Effective turbulence check has a new option to include the *Charnock effect*. This introduces a second order term in the turbulence fits that extremely well captures the dynamic charnock effect, i.e. that higher wind speeds generate lager waves that in turn increase roughness and turbulence.



Name: Mast_

Method

Estimation of 90% quantile ● Normal approximation (kp=1.28) ○ Weibull quantile

Turbulence data

● Ambient turbulence from mast measurements (quality: A)

Mean σ: sector wise; use bins N> 10 ☐ Use fit for all bins ☑ Include Charnock effect (offshore only)

St.dev. σ: weighted mean; use bins N> 50 ☑ Use fit for all bins ● Auto ○ Linear fit ○ Robust fit

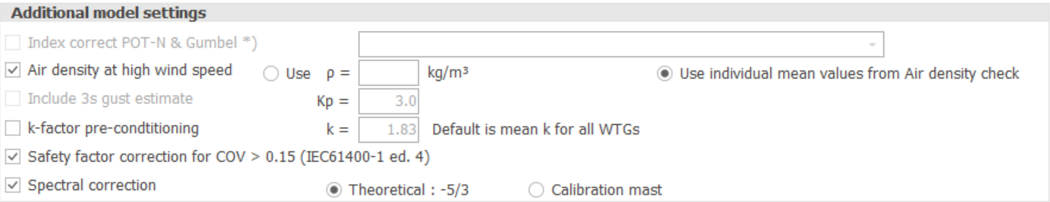
Ambient mean turbulence from model

Mean σ ○ WEng ○ WAsP-CFD / Flowres (quality: B/C)

St.dev. σ Assumption COV = 0.3 (COV is St.dev./Mean)

Spectral correction

From windPRO 4.0 SITE COMPLIANCE implements the extreme wind spectral correction method of Xiaoli Larsén et al. from DTU [36]. This method applies to reanalysis data and may be based on either theoretical assumptions of the spectrum or using an observed spectrum from a representative mast to quantify the relative damping of the reanalysis data's spectrum.



Additional model settings

☐ Index correct POT-N & Gumbel *)

☑ Air density at high wind speed ○ Use ρ = kg/m³ ● Use individual mean values from Air density check

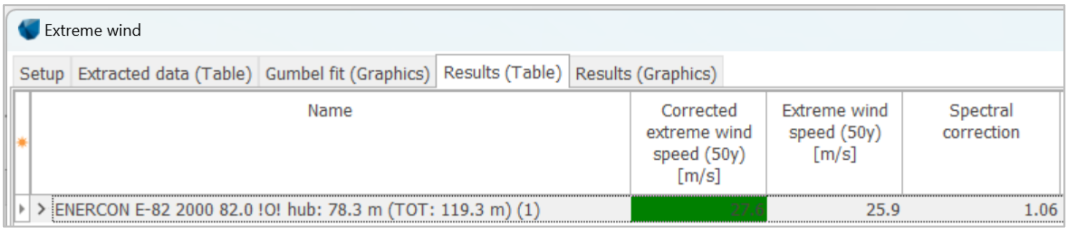
☐ Include 3s gust estimate Kp = 3.0

☐ k-factor pre-condtitioning k = 1.83 Default is mean k for all WTGs

☑ Safety factor correction for COV > 0.15 (IEC61400-1 ed. 4)

☑ Spectral correction ● Theoretical : -5/3 ○ Calibration mast

Fundamentally, the spectral correction method (hereafter SCM) seeks to compensate for the fact that the time series of reanalysis data are too smooth or equivalently put that the spectrum falls off too rapidly at high frequencies. The SCM simply quantifies the expected reduction of extreme wind speeds due to this error in the spectrum. The result is a simple correction factor that is applied to the extreme wind results based on reanalysis data as shown in the Results (Table) screen shot below, where the correction is +6%.



Name	Corrected extreme wind speed (50y) [m/s]	Extreme wind speed (50y) [m/s]	Spectral correction
ENERCON E-82 2000 82.0 !O! hub: 78.3 m (TOT: 119.3 m) (1)	27.6	25.9	1.06