3 Energy calculation

3 ENERGY CALCULATION

3.1 Introduction, step by step guide

Calculating the expected long-term Annual Energy Production (AEP) for a wind turbine or wind farm is one of the most important tasks when developing a wind project. The poorest wind sites (commercial turbines) have round 5 m/s in annual average wind speed. The best above 10 m/s. Since the energy content in the wind increases with power of 3, a 10 m/s wind site will provide 8 times more wind energy than a 5 m/s site. Due to the design of turbines, going for the best in cost efficiency, there will be limitations in utilizing the highest wind speeds. Therefore, the typical gain in production will “just” increase with a power of 2. This, however, still gives a factor of 4 increase in AEP for the 10 m/s relative to a 5 m/s site. And the increase in AEP just going from 6 m/s to 7 m/s is around 35%. Therefore, it is very important to know the wind speeds and thereby predict the AEP very precisely. The AEP, together with the price earned per MWh, are the two main deciding factors for the value of the project and if it is feasible. Project costs, maintenance costs, interest rates etc. are other deciding factors, but these vary typically not so much from site to site (except onshore vs offshore). Thereby, the wind speed and the MWh tariff mainly decide if the specific site is feasible to utilize.

To do a proper AEP estimate, there are several ways to go. In windPRO, the order of the calculation modules is lined up like this:

MCP – long term corrects the local wind measurements
PARK – do the AEP calculation based on the long-term corrected local wind data, including wake loss calculation and optional sector management or other curtailments
LOSS & Uncertainty – evaluate/calculate expected losses and uncertainties

OR, the “time varying energy calculation concept” based on mesoscale model data with time step calculation:

Meteo Analyzer OR Performance Check + PARK – Post calibrate the mesoscale data to match local measurements or turbine production for the period with data
PARK – do the AEP calculation based on recent 10-20-year mesoscale data (post scaled based on above), including wake loss calculation and optional curtailments
LOSS & Uncertainty – evaluate/calculate expected losses and uncertainties

Before the calculations can be performed, there are several steps to be taken:

3.1.1 Having local wind measurements:

1. Import the logger data in the windPRO METEO Object, do the data screening, and clean for bad data. Set up a terrain model for WAsP or WAsP-CFD and do analyses, like how does the measured shear compare to model calculated shear. And if more masts are on the site, how does the model cross predict – if poor, what could be the explanations and which possible model or data adjustments can improve the model setup. For instance, fine tuning roughness data and/or include displacement height (near forest) could be solutions.
2. Get long-term data, import in METEO object, analyze the quality, and compare different sources. Many long-term data sources are available for ON-LINE download.
3. Create long-term corrected wind statistics or long-term local time series with the MCP module OR use the new SCALER concept to calibrate long-term data using the local measurements.

3.1.2 Not having local wind measurements

a. Use mesoscale model data. This requires calibration since the mesoscale model data for most sites is not accurate enough for direct use. Calibration can be based on regional measurements or turbine production from operating turbines.
b. OR use one or more wind statistics (WAsP format) e.g., purchased from a meteorological department. The quality of these are often insufficient and they need to be validated e.g., by re-calculating already operating turbines near the new site.
c. OR use a wind resource map provided by an external source (WAsP format or .siteres format). Here again, it must be mentioned that quality assurance is the key.

Option A is very popular due to constantly improved mesoscale model data, which is fully integrated in windPRO's time varying calculation concept, described in Section 7.

Other aspects of wind farm development to consider
First step will typically be to establish the potential wind farm area in the WTG-area object, including restriction zones, buffers etc. Later, the SITE COMPLIANCE and LOAD RESPONSE modules can be important to find out which turbines are strong enough to survive at the site based on the wind conditions and the wind farm layout. Also, modules like METEO or WAsP interface can be useful for calculation of AEP for many different turbine variants and hub heights at "one spot" at the site to see which turbine comes out with the best AEP/Cost ratio for the site. Finally, the RESOURCE module is very helpful to get the spatial variations of the wind resource for the site and, thereby, a basis for designing a wind farm, eventually with help from the OPTIMIZE module.
Many other constraints can dominate the wind farm layout design. Noise restrictions (DECIBEL module) very often decide. Visual constraints (PHOTOMONTAGE and ZVI modules), shadow flickering (SHADOW module) and environmental constraints like bird corridors, just to mention a few others.

Set up a calculation model, which requires terrain data (elevation and roughness). With the terrain model and a flow model (WAsP, WAsP-CFD or flow result files from other model providers delivered in the generalized FLOWRES file format), vertical and horizontal extrapolations can be performed so the wind expectations at each turbine position and height can be calculated. windPRO offers full WAsP and WAsP-CFD integration and several terrain data sources for ON-LINE download.

Finally, yet importantly, it should be mentioned that windPRO has a large turbine database with the most important specifications for energy calculations. In addition, windPRO has numerous tools for wind farm design (eg. the OPTIMIZE module and the PARK design object), data validation, check etc. Specifically, the PERFORMANCE CHECK module shall be mentioned here, since it allows the user to set up detailed analyses comparing calculated and measured production for one or more wind farm(s) on a very detailed level. Comparing the measured and modelled calculated energy (PERFORMANCE CHECK module) on many operating wind farms, teaches the user much about how well the model calculations perform relative to real life operation. This gives unique feedback on setting up a calculation model for future projects.

3.1.3 Coordinate system auto selected for WAsP and PARK calculations

From windPRO 3.2 all WAsP and PARK calculations are performed in UTM WGS84 for the zone in which the Site Center is placed. This solves a problem when using Geographic coordinates (which cannot not be handled by WAsP), and problems arising from coordinate systems with large rotations relative to Geographical North. In former versions such systems could give doubtful results due to the rotation. By always using UTM WGS84, rotations are marginal.

3.2 Different concepts: wind statistics or time step calculation

3.2.1 Overview of the different concepts

Historically, the majority of AEP calculations have been calculated based on wind statistics. This is the native WAsP concept (Wind Atlas Method), where wind data is represented by a 3-dimensional matrix with Weibull distributions and frequency by height, direction sector and roughness. This concept is considered robust and fast – and it still is.

Calculations in the time domain do not really differ that much, but it gives many advantages. Getting a temporal dimension makes it possible to match up production with e.g. electricity prices and detailed curtailments. Another major reason for calculating in the time domain is that it is now possible to access good quality long term mesoscale wind data all over the world. But the method is not limited to usage of mesoscale data, as local measurements also can be used. An added benefit of the time varying concept includes the possibility for advanced interpolation of data from multiple masts - a feature which is well-sought after in the industry.

Table 1 Calculation/correction options: Wind statistics vs time domain

Calculation options		Wind statistics	Time step calculation
Power curve corrections:			
Different noise modes Day-Evening-Night		NO	YES
	Air density	YES, by annual average	YES, by time step
	Turbulence	NO	YES
	Shear and veer	NO	YES
Model corrections:			
	Displacement height by dir. sector	YES	YES
	RIX correction	YES	YES
Curtailment calculations in PARK			
	Sector management	YES	YES
	Other curtailments	NO	YES *6)
Resource map calculation:		YES	YES
Interpolation between more masts/mesoscale points:		Partly *1)	YES
Wake model options:			
	Alternative models to N.O. Jensen (WAsP, PARK1 and 2) and NO2005	YES	YES
	Special output like calculated turbulence and PPV model	YES	Partly *2)
	Advanced wake loss settings, like change WDC by upwind WTGs	NO	YES
	Turbulence controlled WDC	Partly, by direction sector average	YES, by time step
	Blockage	YES	YES
	Hub height dependent TI/WDC by terrain type selection	YES	YES
Utilization of WAsP CFD		YES	YES
Utilization of other CFD models		Partly *3)	Partly *4)
Utilization of mesoscale data from EMD		YES	YES
Utilization of mesoscale data from other providers		Partly *5)	Partly *5)

*1) Within a wind resource map calculation, interpolation between multiple wind statistics are possible. Afterwards the resource map can be used as input for the calculation.

*2) The calculated time series including e.g., calculated turbulence, can be copied to e.g., Excel and any aggregation can be made. Placing a small turbine at the mast position and including this in the calculation will give the output as calculated wind speed etc. at the mast position.

*3) Delivering output as resource map (WAsP format) can be used as input for the calculation.

*4) In the 2.9 "simple" variant of time step calculation handles resource map data as input. The new FLOWRES file format allows all model providers to generate output to be used from windPRO. The format also support turbulence, inflow angles etc. like it can handle different stability classes.

*5) So far, the advanced downscaling removing the Mesoscale terrain/applying the micro terrain and using the shear from the mesoscale data, is only an option for EMD mesoscale data. However, the datasets from other providers can be used as an "artificial mast" or with a simplified downscaling method.

*6) For Park1, Park2 and Eddy Viscosity 1988.

Below are some arguments and explanations related to the time step calculation concept, also called “the new energy calculation concept”. But remember, the old wind statistics based concept is still fully supported and also expanded with new features.

3.2.2 Why calculate in the time domain?

3.2.2.1 More accurate calculation

The validation of model calculation setup is much more precise. Instead of having only a single average value to check against, it is possible to do multiple checks by e.g direction, wind speed, time on day and month. Also, Weibull fit problems are avoided.

Corrections of power curves: Air density, turbulence, shear and veer are time step specific and higher accuracy can be obtained compared to average corrections. It is similar for wake models. It is known how the wake losses highly depend on turbulence, which varies in time.

Curtailment losses, like noise, flicker, birds, bats or load based (sector management) can be calculated very precise having the time series productions. It is possible to calculate based on different Day-Evening-Night noise reduction modes in one process. PARK can natively include most curtailments, which can dynamically influence the wake losses.

3.2.2.2 Improve the model setup

More detailed feedback recalculating operating turbines - learn about model problems, get better at setting up models for new projects. Get close to where the model calculation problems are e.g., by filtering data in high/low turbulence periods etc.

3.2.2.3 Value of turbine production

With volatile power markets causing electricity prices to fluctuate over time, it is key to know the production pattern to make sound investment decisions.
Output for time varying tariffs can be calculated. Similar if consumption pattern is known, own consumption covered from turbines can be calculated.
Grid systems and other production units can be designed better if the time varying production is known, e.g., how will the spatial distribution of wind farms affect the wind production variations in time.

3.2.2.4 Utilize Mesoscale wind data

Mesoscale wind data is not always precise - calibration with time domain data makes it possible to correct for e.g., directional and seasonal bias in the mesoscale model data.
Mesoscale data is complete, with no gaps or frozen equipment like with measurements. All relevant signals are available, like temperature, pressure, turbulence, shear, veer, humidity, solar radiation etc.
Mesoscale data opens up the ability for advanced corrections, like icing loss and heating requirements.

3.2.2.5 Huge future development potential

Manufactures are working towards more intelligent turbines that e.g., adjust to load conditions, meaning that the power curves will change by climate (load) conditions. MODEL can adapt these features.

3.2.3 How is it calculated in the time domain?

A transfer function between measurement points and calculation point is established by direction sector. The transfer function is used on each time stamp wind speed to extrapolate it to the calculation point.
Using Mesoscale model data, the calculation height is interpolated in the mesoscale data, thereby there is NO vertical model extrapolation, and the mesoscale data shear is used for each time step. The mesoscale model data is downscaled by an advanced methodology, see 3.4.2.
More mesoscale points or measurement masts can be used with advanced horizontal interpolation on the geostrophic wind level, which means that the mesoscale data is normalized (mesoscale terrain lifted off), before interpolation. Then, the interpolated, normalized values get the micro scale terrain applied at the interpolation point (calculation point).

3.2.3.1 The transfer function calculator (the SCALER) features

- Pre-procsessing mesoscale data, also called downscaling. Mesoscale terrain is “lifted out” and microscale terrain is applied. Utilization of traditional WAsP (ONLY ver. 11+), WAsP-CFD or the FLOWRES (open flow model output format) for the transfer function.
- Mast to turbine position scaling can be based on WAsP A-parameter ratio calculation OR the raw WAsP flow ratios (no stability correction). **Since windPRO 3.2 the WAsP A-parameter ratio calculation is made wind speed dependent and stability correction is thereby handled more correct. This can in case of large height extrapolations change calculation result from windPRO 3.0/3.1 to 3.2 or later significant.**
- RIX correction is optional.
- Displacement height calculation can be performed, based on an object’s displacement height OR the sector wise auto displacement height calculator.
- Turbulence can be moved from mast to turbine or calculated if the used model (e.g., CFD) supports this.
- Post calibration can be performed with wind speed scaling and/or offset + individual sector wise, seasonal, diurnal or wind speed scaling factors. The post calibration corrects for e.g., bias in mesoscale data.

3.2.3.2 The SCALER can be used from:

- PARK, time varying calculation
- METEO analyzer, for e.g., establishment of a calibrated SCALER for mesoscale data if measurement mast data is available.
- METEO object, “Add scaled time series” for e.g., downscaling mesoscale data within the METEO object to evaluate how the downscaling changes the raw mesoscale data.
- METEO object, Graphic/Profile, for scaling wind data within the METEO object (calculating the wind profile) for testing different SCALER settings, like displacement height.
    - Note: the aggregated calculated profile is directly comparable to measured when aggregation e.g., by season, while the filtering works on calculated as well as measured. A traditional WAsP calculated profile will always be based on all data.

3.2.3.3 The time varying concept features

Calculation in the time domain adds following features:

- Use the shear in the mesoscale data by time step
- Air density correction on time step basis.
- Turbulence correct the power curve by time step.
- Shear and veer corrected power curves by time step.
- Use time step turbulence to adjust wake decay constant in the wake model on a time step basis.
- Use different operation modes by time step.

Table 2 Establishment of calibrated long-term data time series

Wind used in calculations:

Local measurements (short term data)	
Tool to use:	**Long term correct with:**
MCP module	Mesoscale data

This "left side option" seem best if there are directional turn or nonlinear wind speed ratios, as these are handled well by MCP (Matrix method).

Alternative options

Mesoscale data (long term data)	
Calibrate with:	**Tools to use:**
Local measurements	Meteo analyzer + Scaler
Regional measurements	Meteo analyzer + Scaler
Regional Turbine wind	Meteo analyzer or Perf.Check module
Regional Turbine production	Performance Check module + Scaler
Added value: (partly for future utilizations, like Icing loss calculation)	
<u>More weather parameters:</u>	
Shear	Used by time step, optional Power Curve correction
Veer	Optional for Power Curve correction
Temperature	Optional for Power Curve correction
Pressure	Optional for Power Curve correction
Turbulence	Optional for Power Curve correction and wake correction
Solar radiations	
Humidity	
Cloud cover	
etc.	

Calibration can include direction and season scaling to compensate for bias in mesoscale data. This bias is dependent on where in the world and the local terrain features, like near shore, forest etc.

Having both mesoscale long-term data AND local measurements (blue arrow), there are two ways to go:

- Use MCP to create a long term local data series as input for the time varying calculation for getting the expected long-term AEP. This method has the advantage that it can utilize the more refined options in MCP to e.g., turn the mesoscale wind data to match the local measurements better.

- Use Meteo Analyzer to calibrate the mesoscale data with a SCALER to reproduce the local measurements accurately in the concurrent time period, and then calculate with the full mesoscale data period and the calibrated SCALER for getting the long-term AEP. This method has the advantage that the shear from the mesoscale data is used for the entire period, and it makes it possible to make power curve corrections on time step basis, based on the additional information in the mesoscale data. The present wind statistics based calculation concepts (WAsP) do not utilize the shear from local measurements, although it can be used in, for example, METEO object to calibrate the WAsP parameter settings, like heat flux.

3.2.4 Resource map, supports the design of the wind farm

A wind resource map is a calculation of the wind distributions (Weibull A and k for each direction sector) in a grid. The area to be calculated must be defined (e.g., by a WTG-area object) and the resolution and hub height(s) must be specified. A wind resource map (.rsf, .wrg or .siteres format) can be used as input for a PARK calculation or as input for an OPTIMIZATION.
Wind resource maps can also be calculated as well based on wind statistic(s) or based on the SCALER concept with calculation in time domain, where the output although won't include the time dimension. Both methods include interpolation between more wind datasets (masts or mesoscale data points).
Since 3.5 it is possible to rescale resource maps based on one or more measurement points within the resource grid area.
windPRO offers free access to the GASP dataset which is a global wind resource map. Documentation can be found here: GASP Global. The data format is .siteres, but can from result layer menu be exported to .rsf or .WRG.

3.3 Basic requirements, data & objects

A very large amount of data, as well a detailed description of the terrain, and numerous long wind data series, results in a huge data amount. windPRO is specially designed and developed over decades to handle larger and larger data amounts in a structured way and in a way where the user can keep track of the data, check them for errors and correct them. Here, the different data types and objects (data containers) for energy calculations are described. Note the more detailed description of some objects mentioned given in the BASIS chapter.

The fundamentals in an AEP calculation are:

1. Wind measurements/data (can be pre-processed data as wind statistics or model wind data).
2. Model extrapolations of the wind to each turbine position at hub height
    a. Vertical
    b. Horizontal
    c. In time (Long term correction)
3. Turbine data (Hub height, Power curve and Ct curve for wake loss calculation)
4. Losses
    a. Wake (depends on PARK layout, wind and terrain, and requires turbine positions)
    b. Electrical (can be calculated by eGRID module)
    c. Availability
    d. Other: like shut down due to environmental issues (curtailment) etc.

More "details", like temperature data for air density correction etc. are also relevant.
In the following, the fundamental data structures for the needed input are reviewed, then followed by a chapter describing the models and validation tools.

3.3.1 Wind measurements

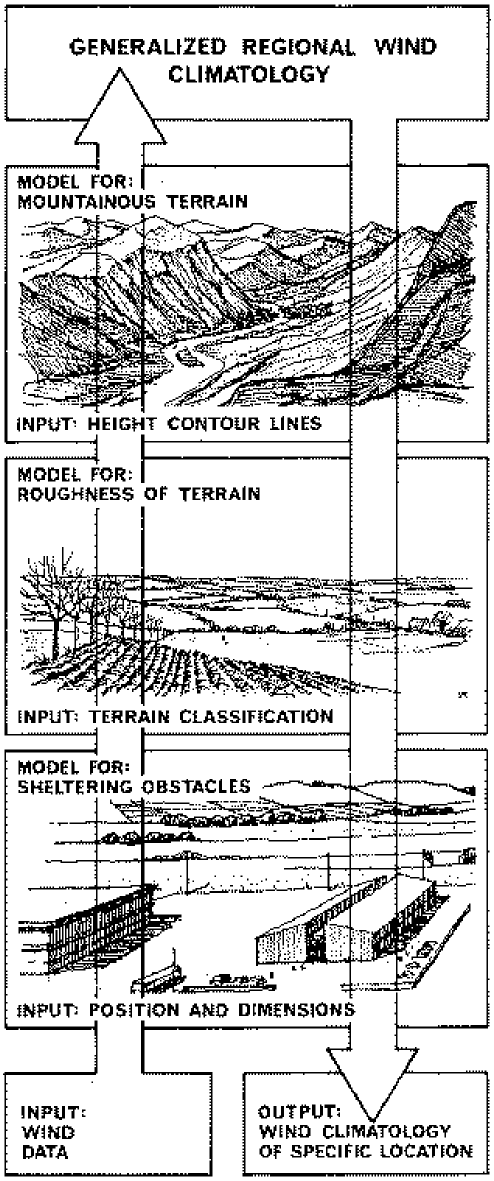
Wind measurements are the typical basis for calculations of expected energy production from wind turbines. Of high importance is partly seasonal variations, partly annual variations. Therefore, measurements should normally be performed for at least one year to capture not only seasonal variations in wind speeds and directions but also like variations during the seasons. The annual variations should be handled by long-term correction based on long-term data for at least 10 years, preferably 20 years. Measured wind data and optional additional data like temperature and pressure can be imported in the METEO object where data can be screened and cleaned for errors or other problems like icing events etc.

Measuring at multiple heights makes it possible to evaluate how the shear is handled by the model and if model adjustments are needed. Measuring at the expected hub height for the turbines to be installed takes out an important uncertainty component - the vertical extrapolation. Measuring with more masts (or other measuring devices, like Lidar), reduces the horizontal extrapolation uncertainty and gives, in general, an important feedback on how well the model handles this. The Cross Predictor in Meteo Analyzer is a tool for checking both the vertical and horizontal extrapolation accuracy of the model. More measurement points can also be handled in windPRO, where the new time step-based calculation concept with SCALER allows for interpolations between more measurement points. This is an expanded feature not included in the native WAsP software.

3.3.2 Wind statistics based energy calculations

Historically, the majority of AEP calculations have been calculated based on wind statistics. Even though the new time-varying energy calculations has many benefits, the wind statistics based energy calculation is still supported by windPRO.

A wind statistics is a structured collection of wind measurements processed with terrain and holds, thereby, the information of the wind speed distributions as a function of roughness, direction and height.



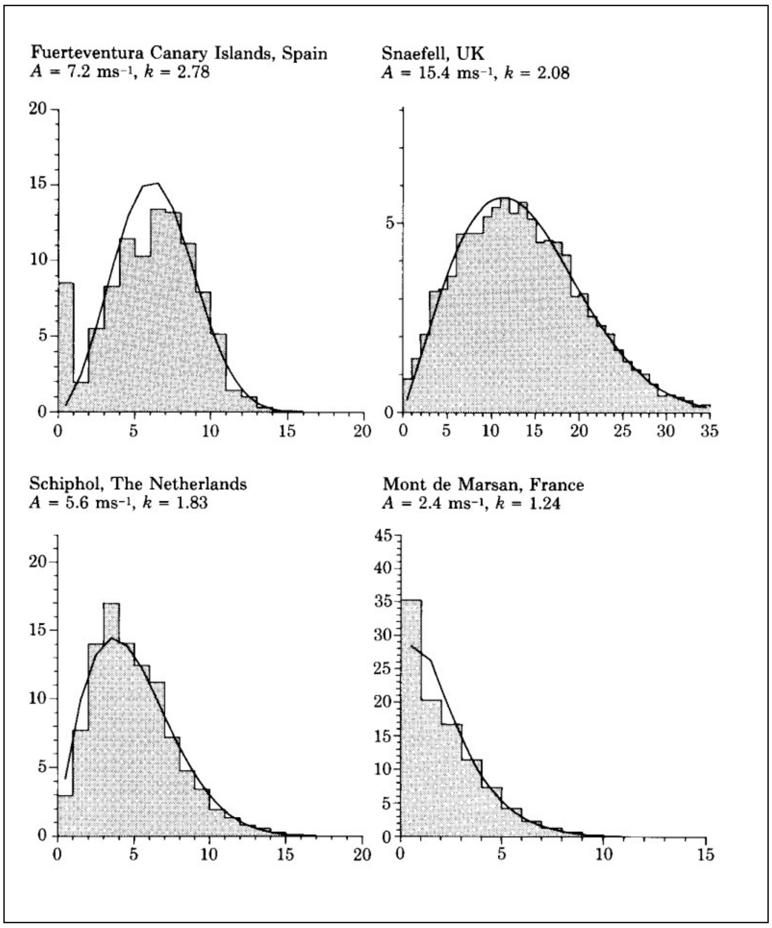


Figure 1 Wind Atlas Method

The left graphic illustrates the wind atlas method: "cleaning" the wind measurements of local terrain effects and establishment of a generalized wind climate, the wind statistics. This is then used with the local terrain at the calculation point to establish the expected "terrain corrected" wind climate. To the right, different wind distributions (frequency versus wind speed) are shown partly as measured (grey) and as weibull fitted representations (black line)[Source: European wind atlas, Risø/DTU].

A wind statistics is a file with a multidimensional matrix with the following dimensions:

- Height (typical: 10, 25, 50, 100, 200 m)
- Wind direction (typical 12 sectors of 30 degrees)
- Roughness (typical 5 classes; 0, 1, 2, 3, 4, corresponding to lengths; 0.0002, 0.03, 0.1, 0.4 and 1.5)

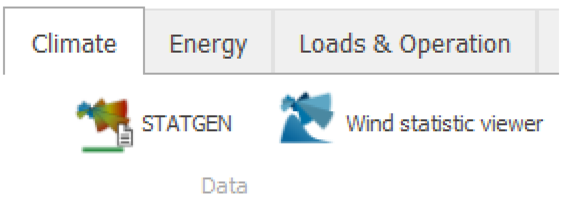
For each dimension, a Weibull distribution describes the wind distribution. This is represented by an A and k parameter. For each roughness, a frequency by direction sector gives how often the wind comes from this direction.
A wind statistics can be generated via WAsP from windPRO modules STATGEN or MCP. It is based on a Weibull distribution, a histogram (table data) or a time series in METEO object with wind speed and direction for each time stamp (ONLY 1 height) AND a terrain description (elevation, roughness, local obstacles and, eventually, displacement height). The WAsP model, popularly spoken, lifts off the terrain influence on the wind and creates "neutral" wind distributions. When generating a wind statistic from MCP, the local measurements are long term extrapolated based on a long-term time series (see more in MCP section).

The native format for wind statistics in WAsP is called a Library file (*.LIB). However, since WAsP 11, it is called "New *Generalized Wind Climate* (*.gwc) file format replaces the *Wind Atlas* (*.lib) file format. Vertical wind profile model and parameter settings are now part of the *Generalized Wind Climate* file; A number of model parameters, which in WAsP 10 and earlier versions were saved with the WAsP project, are now saved with the Generalized Wind Climate file." (from www.wasp.dk)

In windPRO, the file extension for a wind statistics is .wws. This file contains a number of additional parameters, like coordinates, information of the time series used, the WAsP parameters, WAsP version etc. The number of parameters has expanded over time by different windPRO versions. From an energy calculation, a report page "wind statistics information" is available, showing which data and parameters are included in the .wws file. Note windPRO supports both .lib and .gwc files while .lib files can be generated directly and both types can be used in calculations from windPRO.

An important part of a wind statistics is the shear: how does the wind speed change with height. This is partly based on the roughness, but also on an advanced stability model, which is part of the WAsP model. The stability model can be invoked by changing the heat flux parameters in WAsP. This will typical be needed in very warm (dessert) regions or very cold climates. With measurements at more heights, the METEO object can be used to calibrate the stability settings.

3.3.2.1 View/evaluate/edit a wind statistic



It is possible to view wind statistics with the **Wind statistic viewer** which can be found in the Climate tab. Below an example:

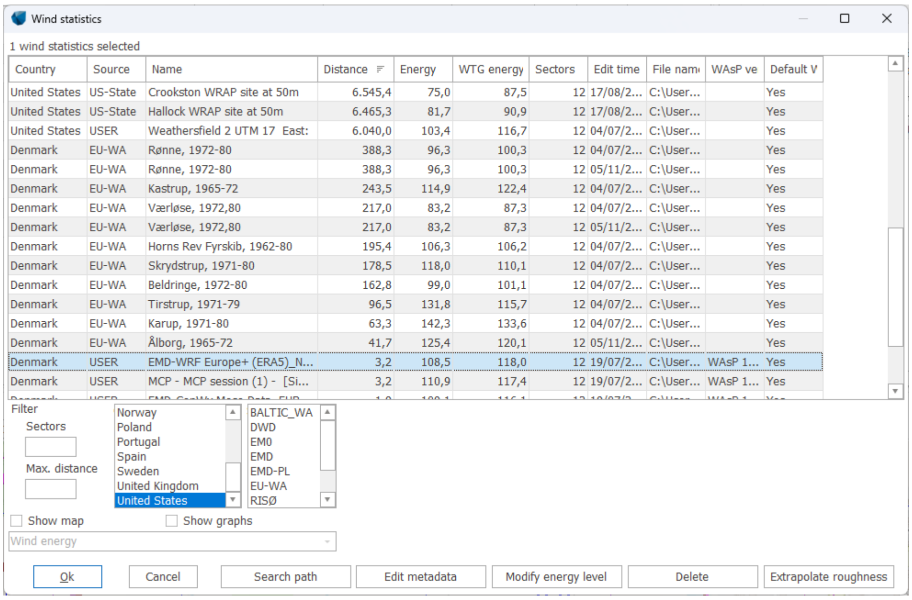


Figure 2 Wind statistic view.

The window shows some basic info as well as some evaluation figures. These, based on Danish average site, are:
Energy – the "raw" energy as a percentage of 3300 kWh/m².
WTG energy – the power curve filtered energy relative to 1025 kWh/m², where the calculation is based on a WTG with specific power: 0.45 kW/m².
The energy levels arbitrary chosen to correspond to an average Danish site with round 6.5 m/s at 50m a.g.l.
For both variants, a hub height of 50m and roughness class 1 is used for the key value calculation.
The energy key values are very useful for checking if the wind statistic seem to be "reasonable". Comparing with other wind statistics in the region, only smaller differences should be seen, otherwise it is most likely that the data quality is too poor. It can although be related to mesoscale wind differences in e.g., mountainous or coastal regions.

In addition to the energy key values, it is possible to show direction graphs and maps with wind statistics, see example below:

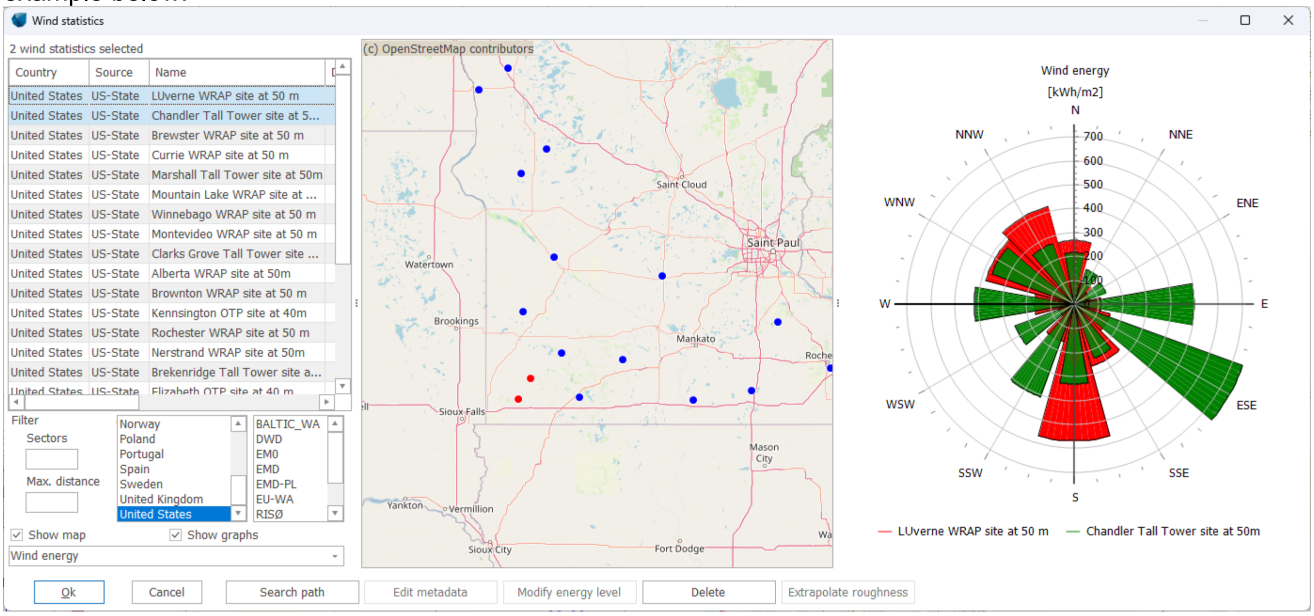


Figure 3 View of wind statistics on map and as rose graphs.

As seen above, multiple wind statistics are selected in the list, and to compare e.g., the directional energy level. The selected are marked yellow on the map.

Edit metadata button give access to modify different information's, like coordinates.

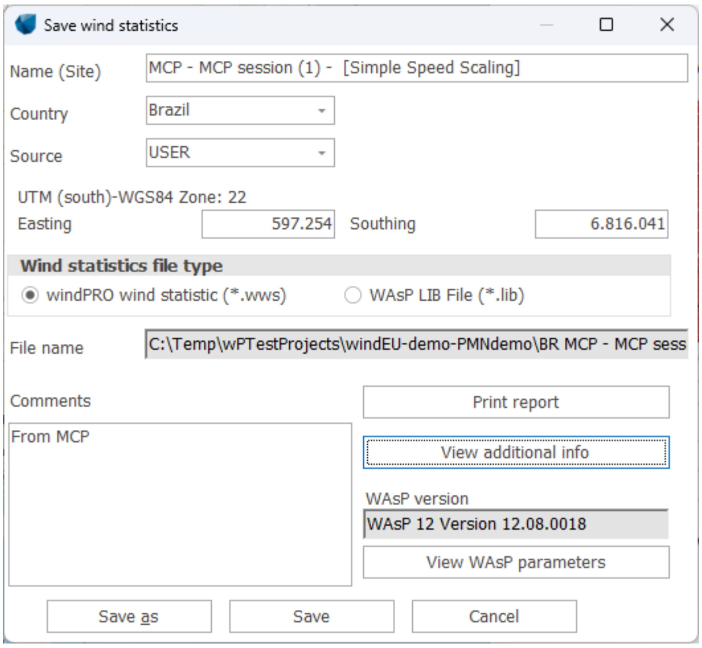


Figure 4 Edit wind statistic metadata

It also gives access to print report with all relevant information's on the wind statistic.

The "View additional info" shows the following:

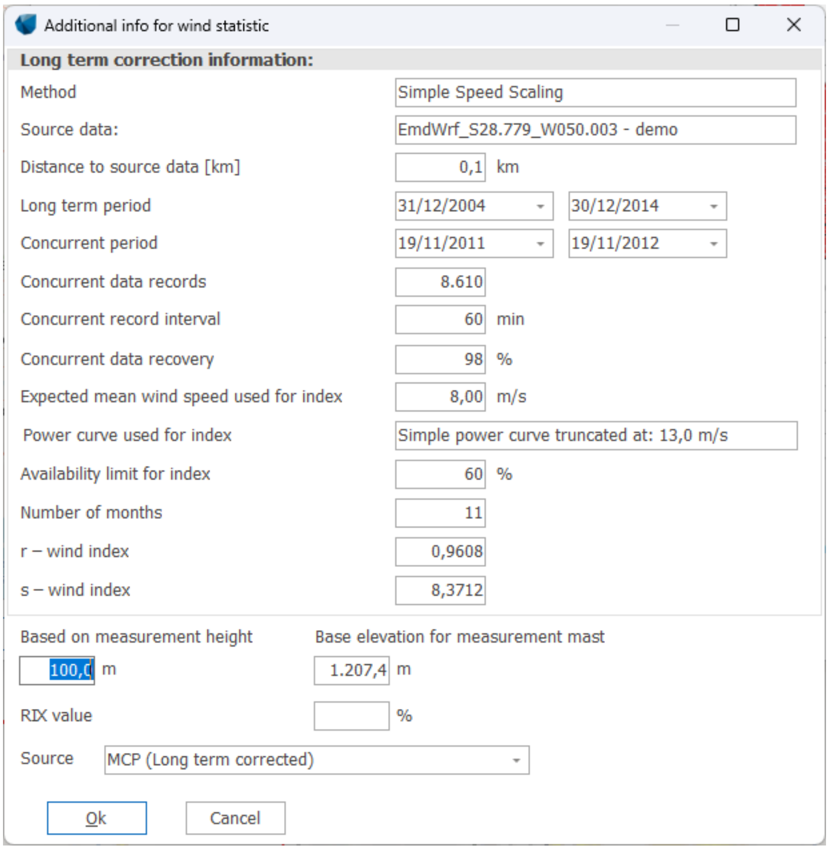


Figure 5 View additional wind statistic info.

Modify energy level is a special feature allowing for manipulation of the data within the wind statistic, in case it is known that it provides too high or too low calculation results, e.g., if used on an operating project with good long-term expectation knowledge.

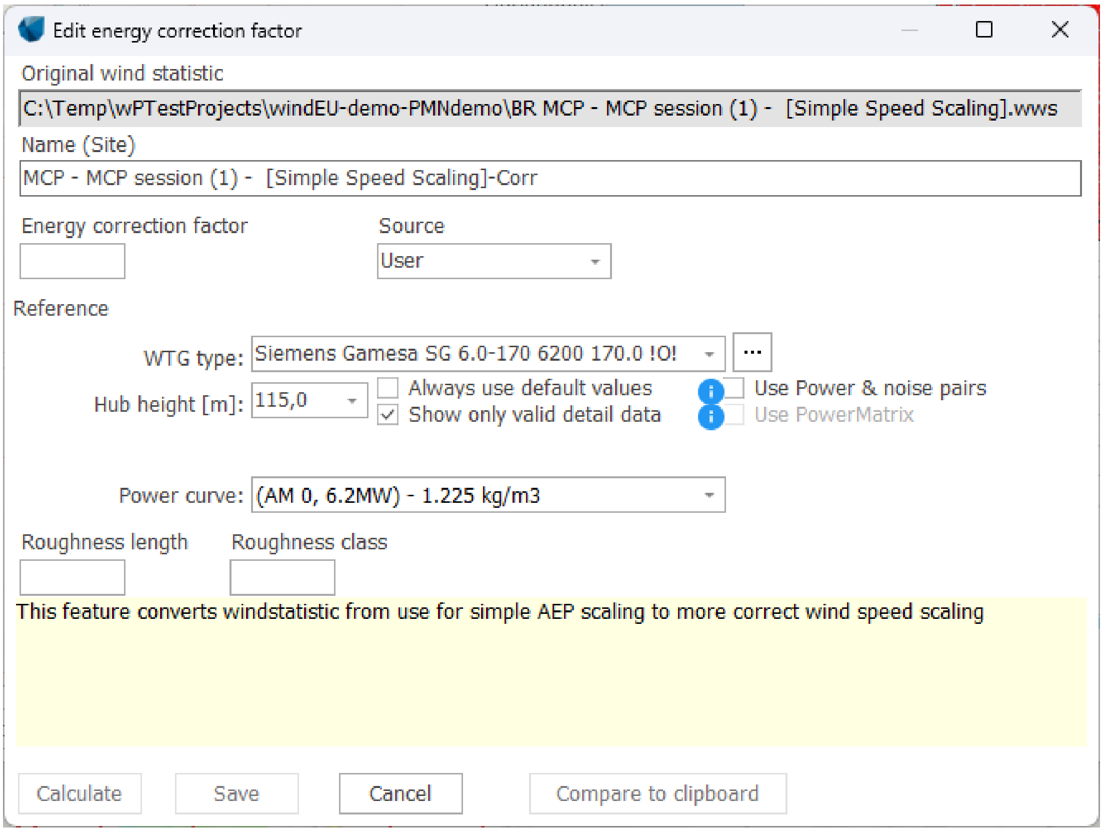


Figure 6 Modify energy level for wind statistic.

For a given:

- Power curve
- Height
- Roughness

The energy correction factor can be entered.

For each sector, an optimizer finds the A and k parameter adjustment (scaling factor) needed for adjusting the calculated energy production that respects the desired energy correction factor. These scaling factors are then used on ALL A and k parameters within the wind statistic.

From windPRO 3.6 a measure has been introduced to stop the optimizer from finding an increased A-parameter, when the energy is scaled down. If the power curve ramps down at higher wind speeds, this ramp down is removed in the power curve used in scaling. In practice, the energy correction optimizer uses the highest power value for all wind speeds up to 100 m/s. This avoids the A-parameter being scaled in the opposite direction of the energy correction. In addition, there is a limit to how much the k value is allowed to be modified, so this always will stay within the range 1.0 to 4.0. However, if the k in the windstatistic to be scaled is outside this interval, then the limit is expanded to this value.

For a site with terrain features (different speed ups by direction at different locations etc.) the calculation result may not change exactly as expected. If the goal is to match a certain value, then one must try out different correction factors experimentally.

With the modification of the correction factor, the wind statistic would serve as a better input for the calculation of new wind turbines in the near region, compared to using a wind statistic that has a known bias.

An illustration of the energy scaling compared to wind speed scaling, and why it is important to not just scale energy, is shown below.

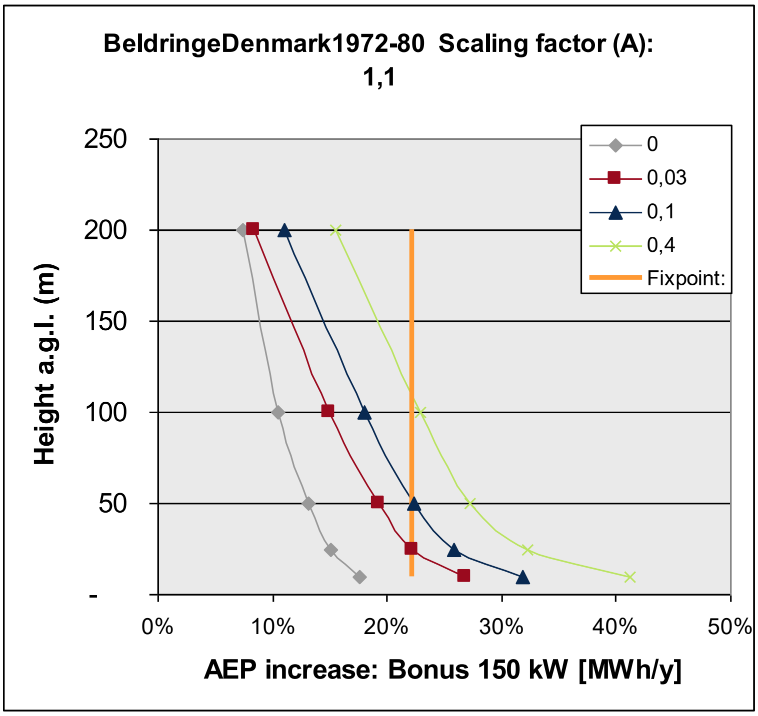


Figure 7 Illustration of energy vs wind speed scaling.

With energy scaling, the correction on AEP in any calculation will be as shown with the "fixpoint" line, here approximately 22%. With wind speed scaling, the AEP correction will be the same for the fixpoint, which was basis for the creation of the wind speed scaling, here 25m hub, roughness length 0.03m (Rcl. 1) and a Bonus 150 kW turbine. With wind speed scaling as example for a 100 m hub height, same roughness length 0.03m (Rcl. 1) and the same power curve, the AEP correction will now be approximately 15%.

The methodology is used in the Danish DK'07 wind statistic, which is based on regional correction curves created back in 1992 mainly based on 25 m hub height turbines. This wind statistic is still much used for calculations in Denmark 25+ year later. The methodology will although not work well in complex terrain regions, where the wind can change radically just within few km.

Extrapolate roughness button gives access to add extra roughness in the wind statistic. This is needed for later WAsP versions, that do not allow for roughness extrapolations. Especially older wind statistics will often have an upper roughness length of 0.4 (class 3.0), which then not will work on sites with roughness values above this.

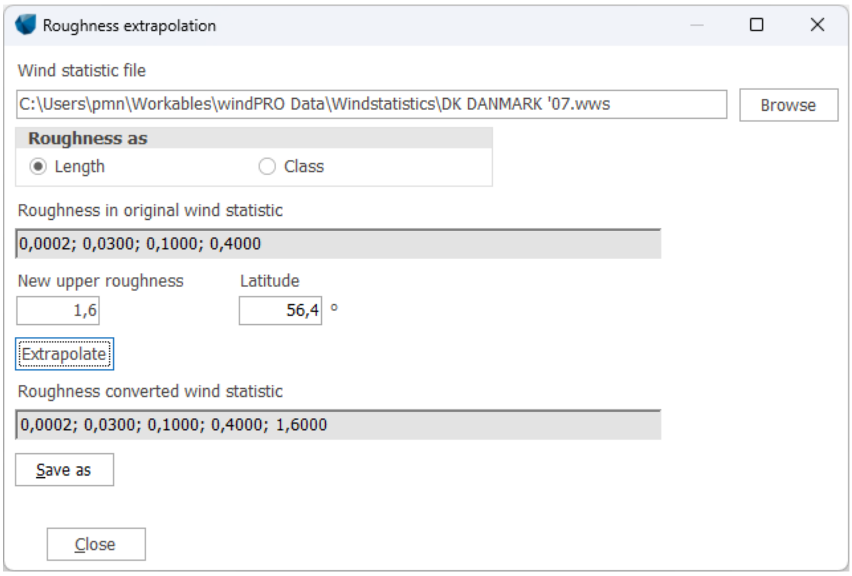


Figure 8 Extrapolate roughness.

Here a new upper roughness value of 1.6 (class 4) is added, and the extrapolate button creates the new data. Entering "Edit meta data" gives access to print a wind statistic report, in which the added data can be seen.

Mean wind speed [m/s]

Height [m]	Roughness class/Length 0 (0,00 m)	1 (0,03 m)	2 (0,10 m)	3 (0,40 m)	4 (1,60 m)
10,0	7,2	5,0	4,4	3,5	2,2
25,0	7,8	6,0	5,4	4,5	3,4
50,0	8,4	6,9	6,3	5,4	4,3
100,0	9,1	8,0	7,4	6,5	5,4
200,0	9,9	9,8	9,0	7,8	6,7

Figure 9 Results with extrapolated roughness.

3.3.2.2 Global Wind Atlas wind statistics, download and use.

At the web page: https://globalwindatlas.info/ there is access to wind statistics worldwide based on World Bank sponsored project.

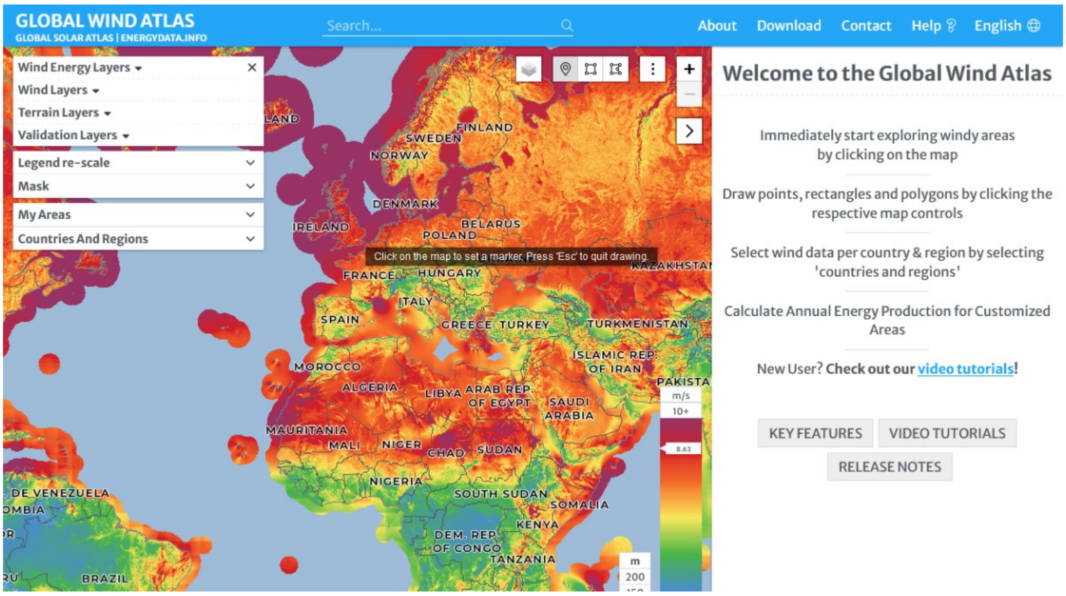


Figure 10 Global Wind Atlas web page.

Zooming into a specific location and placing a marker, gives access to downloading a .LIB file (GWC file):

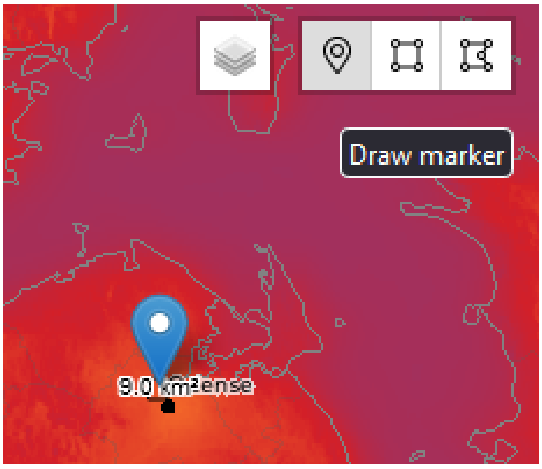
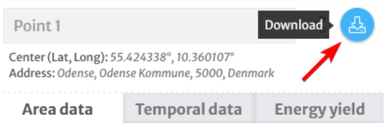


Figure 11 Place a marker at the specific location for the wanted GWC file.

After placing the marker, a download button appears in the right pane:



Then select GWC:

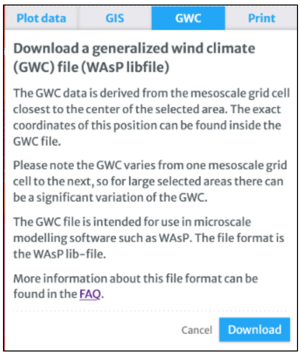


Figure 12 Download the .GWC file for selected location.

Save the file like here:

Figure 13 Save GWC file in folder below "WindPRO Data\Windstatistics" or in project folder.

If your search path setting for wind statistics includes this path, the file is ready to use in windPRO and can be found by the wind statistic browser:

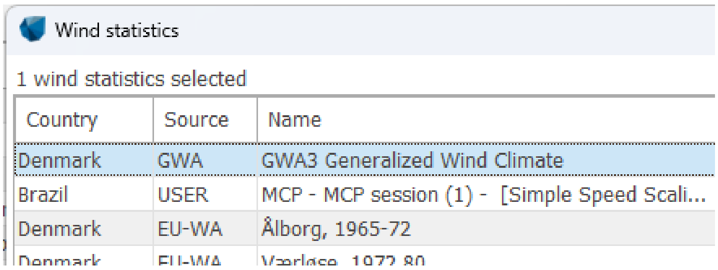


Figure 14 The GWC file is seen in the wind statistic browser.

To see the GWC file requires the file location is included in the search path setup. The naming is taken from the file, and will always be the same, but also coordinate information is included, making it possible to distinguish between more downloaded files.

Mean wind speed [m/s]

Height	Roughness class/Length 0	1	2	3	4
[m]	0,00 m	0,03 m	0,10 m	0,40 m	1,50 m
10,0	7,6	5,4	4,7	3,8	2,5
50,0	8,9	7,4	6,8	6,0	4,9
100,0	9,7	8,7	8,0	7,2	6,1
150,0	10,7	10,0	9,3	8,3	7,2
200,0	11,2	11,0	10,1	9,1	8,0

Mean wind speed [m/s]

Height	Roughness class/Length 0	1	2	3	4
[m]	0,00 m	0,03 m	0,10 m	0,40 m	1,60 m
10,0	7,2	5,0	4,4	3,5	2,2
25,0	7,8	6,0	5,4	4,5	3,4
50,0	8,4	6,9	6,3	5,4	4,3
100,0	9,1	8,0	7,4	6,5	5,4
200,0	9,9	9,8	9,0	7,8	6,7

Figure 15 Comparing GWC file (left) with EU-WindAtlas file (right).

By “Edit meta data” in the wind statistic browser, there are acces to printing a wind statistic report. Above the mean wind speeds from the report. As seen, the GWC file has essential higher wind speeds than the “old” EU-Wind Atlas data for the same location.
This would also be seen in the browser, where the WTG energy level, a very useful check, is seen. In this case the GWC file located at same spot as the “Danmark” wind statistic (Beldringe from EU-WindAtlas) has an WTG energy level ~15% higher than the “Danmark” files, which has proven to calculate quite precise. This mean that at this location, the GWC file probably will calculate round 15% too high energy, so the results will not be more precise than this. Below a small test is performed with the GWC data.

Scale 1:100.000

* Existing WTG

Figure 16 The locations of the 13 WTGs in test calculation.

Note the forest in main wind direction for WTG 11-13, this is not handled in the calculation setup, where displacement height or better the ORA tool should be used.

A calculation based on standard DK roughness maps and elevation is set up with default wake model.
The results of the calculations are below compared to actual wind index corrected production based on 15+ operation years, where months with larger availability problems are filtered.

WTG type	Valid	Manufact.	Type-generator	Calculated prod. without new WTGs [MWh/y]	Actual wind corrected energy [MWh/y]	Goodness Factor [%]	Calculated prod. without new WTGs [MWh/y]	Actual wind corrected energy [MWh/y]	Goodness Factor [%]
1	No	VESTAS	V44-600	1.675,5	1.342,0	80	1.465,0	1.342,0	92
2	No	VESTAS	V47-660/200	1.763,9	1.326,0	75	1.542,0	1.326,0	86
3	No	VESTAS	V47-660/200	1.766,7	1.326,0	75	1.544,4	1.326,0	86
4	No	VESTAS	V44-600	1.732,7	1.398,0	81	1.508,0	1.398,0	93
5	No	NEG MICON	NM48/750-750/200	1.959,3	1.589,0	81	1.705,2	1.589,0	93
6	No	NEG MICON	NM48/750-750/200	1.921,4	1.589,0	83	1.683,7	1.589,0	94
7	No	NEG MICON	NM48/750-750/200	1.925,1	1.589,0	83	1.694,9	1.589,0	94
8	No	NEG MICON	NM48/750-750/200	1.904,0	1.517,0	80	1.680,2	1.517,0	90
9	No	NEG MICON	NM48/750-750/200	1.895,0	1.517,0	80	1.652,2	1.517,0	92
10	No	NEG MICON	NM48/750-750/200	1.890,7	1.517,0	80	1.657,4	1.517,0	92
11	No	NEG MICON	NM48/750-750/200	1.950,0	1.489,0	76	1.690,6	1.489,0	88
12	No	NEG MICON	NM48/750-750/200	1.968,9	1.458,0	74	1.701,6	1.458,0	86
13	No	NEG MICON	NM48/750-750/200	2.052,6	1.571,0	77	1.773,7	1.571,0	89

Figure 17 Testing GWA (left) versus EU-Wind atlas wind statistics (Beldringe), rightmost.

The GWA data overpredict by 17-26%, the EU-WindAtlas data overpredict by 6-14%. Worth to note that “normal” availability losses and possible noise reduction modes (not known here) justifies an overprediction of 5-10%. The most overpredicted WTGs 11-13 has heavy forest in main wind direction, SW, which not is handled in the calculation setup. Conclusion is that at this location, the EU-WindAtlas works quite well, with a few percent overprediction if all corrections were made, whereas the GWA data overpredicts by at least 10%. The reason is probably a known bias from mesoscale modeling where for Denmark it is in the order of 3-5% on wind speed, which converts to 10-15% on energy. This bias is seen much worse, in e.g., southern Germany, up to 20% on wind speed is seen. Offshore in North sea, the bias is close to zero.

3.3.3 Mesoscale wind data

Mesoscale wind data are time series output from a mesoscale model, like WRF. The concept is that data from global climate simulation models (ie, at a 100 km resolution) is used as the input together with terrain (elevation and roughness) to create a grid node resolution of ie. 3 km. The mesoscale model thereby adds the regional terrain effects not included in the global climate simulation models.

Mesoscale wind data can be downloaded from a database with pre-run datasets for selected areas using windPRO by establishing a METEO object. It is also possible to run the WRF mesoscale model from windPRO for any place in the world (see further details in Chapter 4). A special feature added in the windPRO mesoscale data is the used mesoscale terrain, which is stored in the METEO object. This is used when downscaling the mesoscale data (lifting off the mesoscale terrain and applying the micro terrain). But even when downscaling the mesoscale wind data, there will be a need for calibration. Mesoscale data does not have a fully accurate wind speed level all over the world, and the bias will be different depending on where the point is. Therefore, a post scaling/calibration is needed. In windPRO, there are comprehensive tools for performing this post calibration.

VERY IMPORTANT: The use of downscaling near a coastline is problematic. The reason is partly the coarse resolution of the mesoscale model runs (including coarse roughness data resolution) and partly the different stability conditions between land and water. Lifting off mesoscale terrain (downscaling) from two data points near the coastline - one onshore, another offshore - can, thereby, give large differences in wind speeds when calculating e.g., right at the coastline. And which one tells the truth? It is so far recommended NOT to use mesoscale data within +/- 3 km from a coastline. Instead, take the next point further offshore or further inland, depending on where the calculation shall be performed (on- or offshore).

3.3.4 Elevation data

Elevation data describes the terrain elevation. In windPRO, elevation can be handled as grid data or as contour data with conversion options between the two formats. There are more free datasets available for download that can be directly accessed via windPRO ON-LINE data services, making it easy to establish the elevation data. Also, comprehensive tools are available within the Line object for manually digitizing the elevation data based on contour lines on background maps. (See more details in Chapter 2 Basis)

For a wind farm site, elevation should be established for a distance of around 7 km in all directions from the edge of the site (can also depend on turbine height). For WAsP-CFD calculations, the data should cover a 20 km radius. The needed resolution of the elevation data depends on the terrain. For WAsP calculations, 5 m resolution contour lines are normally considered sufficient.
A special issue to consider is when using surface data (top of forest etc.), like SRTM data. These data can create large errors, especially if turbines are placed inside or near forests and the calculation model, thereby, places the turbines on the top of the forest instead of on the ground. The only way to proceed in this case is to digitize the wind farm area manually based on background maps with the correct terrain elevation. Visit the knowledge base for online data to read more about the available datasets.

3.3.5 Roughness data

The surface roughness is very important for describing how the wind profile is dragged. It describes the friction created by the landscape elements like houses, trees, and the surface of the ground. There are more free datasets available for download. These can be directly accessed via windPRO ON-LINE data services, making it easy to establish the roughness data. Also, comprehensive tools are available within the Area Object for manually digitizing the roughness data based on polygons on background maps. The Area Object exports the polygons to Roughness Lines, which is the format required by the WAsP model.

The line object can import roughness data from these file types, where the .tif is new from windPRO 3.4:

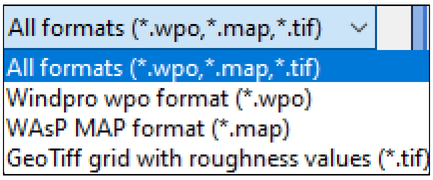


Figure 18 Import file formats for roughness from line object.

The Area object can import polygons from Autodesk DXF file (*.dxf) ESRI shape file (*.shp) as well as gridded data from Open grid file (*.grd;*.asc;*.tif).

Using older WAsP versions (< 10.2), or the simple ATLAS model, roughness can be handled as roughness roses, which can be established within Site Data Objects (see windPRO 2.9 manual for details). But todays standard is to use roughness line maps. One reason for this is that newer WAsP versions (from 10.2) use the roughness maps for calculation of the stability corrections on a more refined way than previous WAsP versions. Therefore, the use of roughness roses is no longer supported.

3.3.5.1 Using Online data for roughness line maps

Roughness lines can be downloaded direct from EMD's On-line service. It is only recommended for initial calculations or, for example, the calculation of resource maps for larger regions for finding areas of interest. When a specific site shall be calculated, the fine-tuning of the roughness data is very important. This is very difficult based on roughness lines, and, thereby, it is recommended to perform this within the Area Object. The roughness data sources are in a rapid development, more new datasets appear every year, with different resolution and quality. Below is described a procedure for manual edition as ONE example based on Data4Wind roughness data. Other datasets might not require this process, but it is still good to know the features available for editing.

- Import the data into an area object.
- Delete the "open farmland" areas. While these normally cover the most, and they will be treated as background roughness. In non-farmland regions, like deserts, heavy forested regions, or water, it can be more convenient to let these dominant area types be associated with the background roughness.
- In a dataset like "Data4Wind", the open farmland is the class range of 1.8-1.9 .
- Set the background roughness to the dominating roughness of "open farmland" (or whichever class is dominate), which can be from class 1 up to class 3 if there are many wind breaks (see figure later). If the farmland areas varies much in surface roughness (seen, e.g., by looking at the areas on google maps, preferably combined with a site visit), manual digitization of parts of the open farmland areas might be required to establish a reasonably accurate roughness map.
- Take the roughness areas given as > class 3.2, and merge these into the class 3.2 layer. It can be discussed if there are areas with higher class than 3.2, but typically not for a standard farmland site (although, mountains could be). Forest areas are recommended not to be set higher than class 3.2 but, instead, use the displacement height calculator for compensating for the effect of the forest (see chapter related to this).
- Finally, export the processed roughness areas to lines. A line object with the data can automatically be created.

3.3.5.2 General information about roughness

For a wind farm site, roughness should be defined for a distance of around 20 km in all directions from the edge of the site (can also depend on turbine height). The needed resolution of the roughness data depends on the terrain. It is important that surface roughness shall be seen as a property of a larger portion of terrain. E.g., a farmland with many wind breaks should not be digitized wind break by wind break, but as the entire farmland region where the distance between and heights of the wind breaks decides the roughness (see figure later in this paragraph).

Roughness can be handled by either roughness classes or roughness lengths (see next table).

Table 3 Roughness definitions

Roughness class	Roughness length	Relative energy %	Description
0	0,0002	100	Water areas.
0,5	0,0024	73	Mixed water and land area or very smooth land.
1	0,03	52	Open farmland with no crossing hedges and with scattered buildings. Only smooth hills.
1,5	0,055	45	Farmland with some buildings and crossing hedges of 8 m height and about 1250 m apart.
2	0,10	39	Farmland with some buildings and crossing hedges of 8 m and 800 m apart.
2,5	0,20	31	Farmland with closed appearance and dense vegetation – crossing hedges of 8 m height and 250 m apart.
3	0,40	24	Villages, small towns, very closed farmland with many or heigh hedges, forrest, many abrupt orographic changes, etc
3,5	0,80	18	Large town, cities with extended build-up areas.
4	1,6	13	Large cities with build-up areas and high buildings.

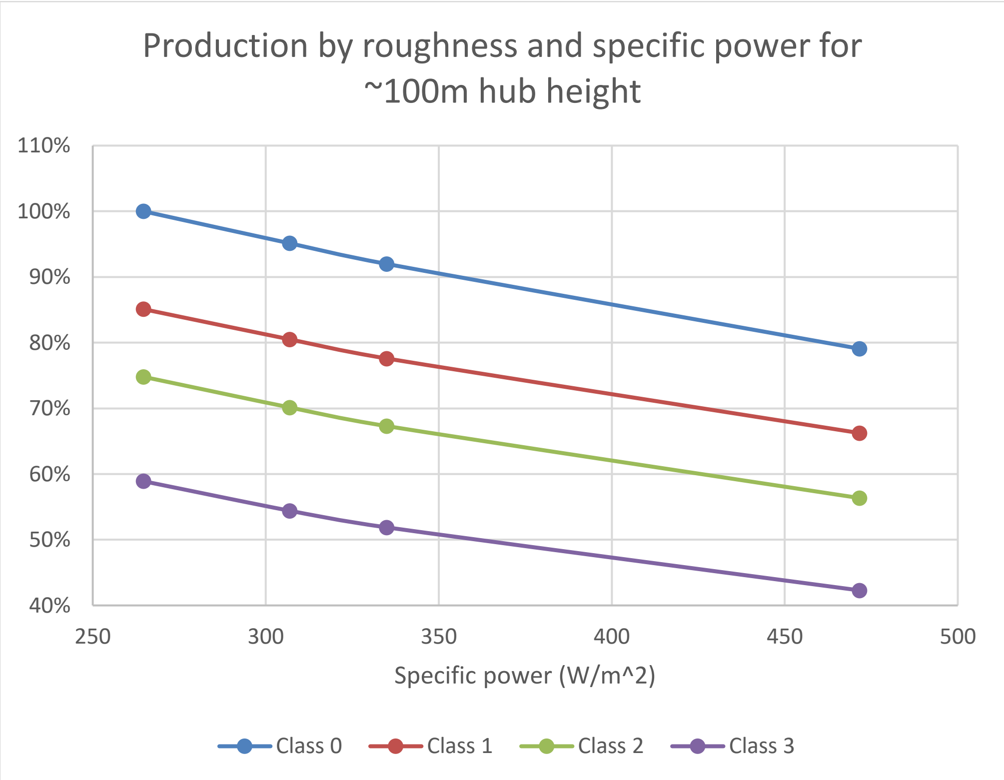


Figure 19 Production variation by roughness and specific power

The deciding factors for AEP in flat terrain are the roughness, the specific power and hub height. Above is illustrated how the first two mentioned invoke AEP for Danish wind conditions- more than a factor of 2.

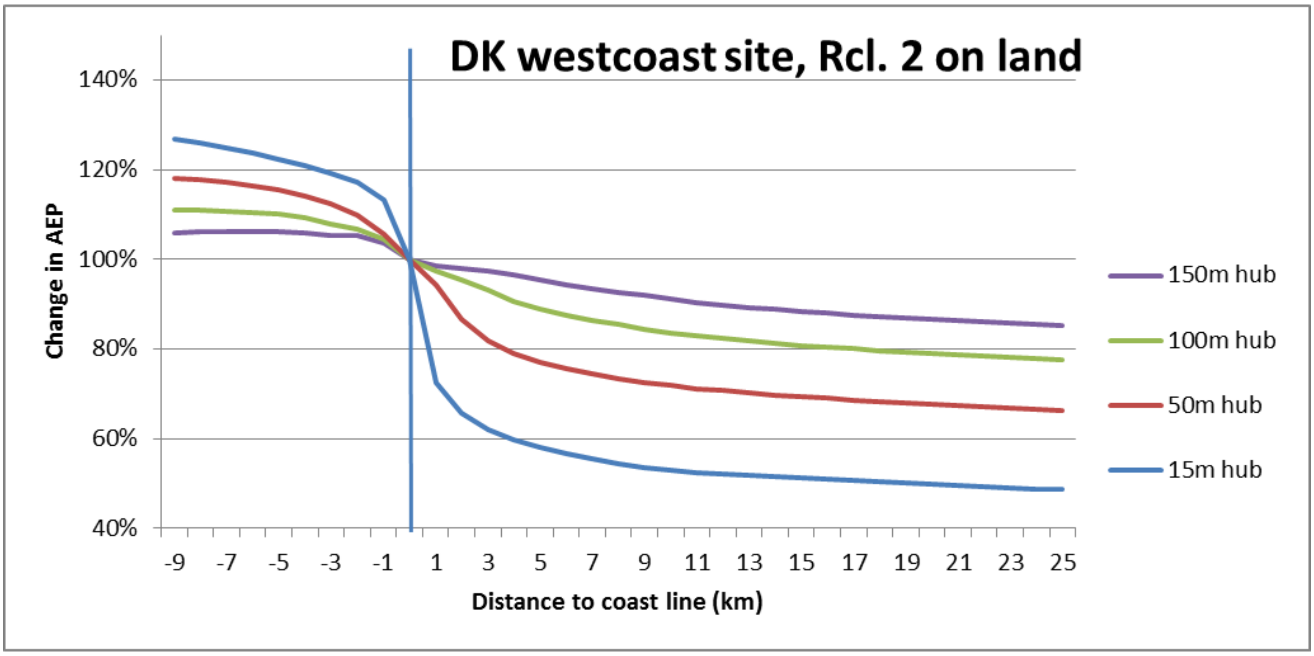


Figure 20 AEP change vs distance to coastline and hub height

Illustrated in the figure above is the very large influence the roughness has on the AEP, even at high hub heights. A 100m high turbine loses 20% in production, when moving 15 km from shore inland – even with a relative low inland roughness of class 2. An only 15m high turbine loses 50%, so larger hub heights do compensate a fair for roughness influence but are still heavily influenced themselves.

In areas with hedges (windbreakers), the graphs in the following figure, based on formulas from "Danish wind atlas", Risø/DTU 1979, can be used to estimate the roughness class or length. Notice the non-linear impact of the hedge height on the roughness class. Normal farmland is assumed to lie between the hedges. This is incorporated into the figure by adding 0.03 m to all specified roughness lengths. A porosity of 0.33 is assumed.

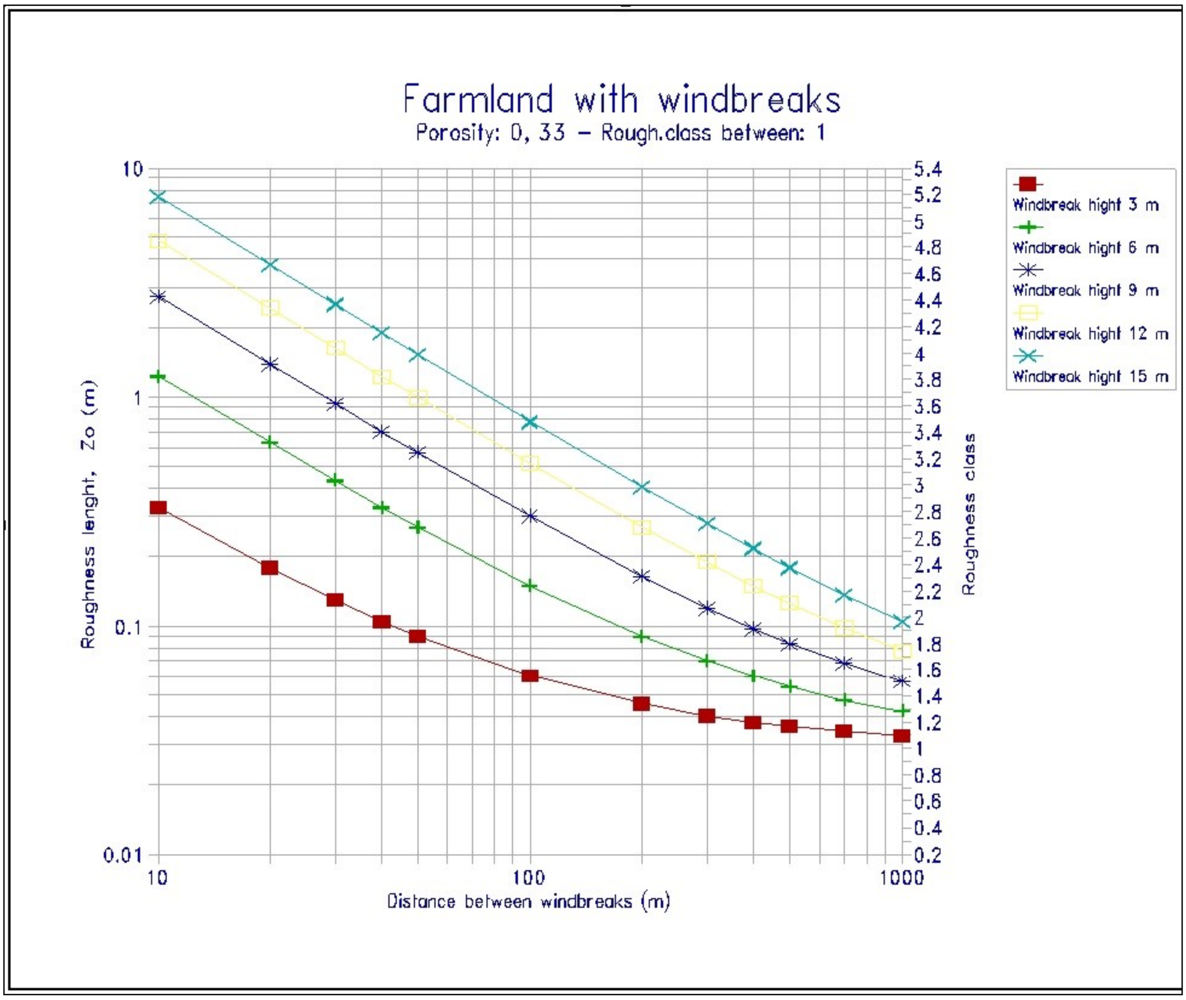


Figure 21 Roughness in farmland with windbreaks

In an area with many buildings, the roughness length can be estimated by using the following equation from "Danish wind atlas" Risø 1979:

$$z_0 = 0.5 * h^2 * b * n / A$$

Where:
- **h** = height of building
- **b** = width of building
- **n** = number of buildings
- **A** = total area within which the n buildings are situated

NOTE: The roughness length of the area between the buildings must be added to the roughness length, which has been determined based on the above equation, e.g., add 0.03 m to the calculated roughness length for normal farmland.

The relation between roughness classes and roughness lengths is shown in the next figure.

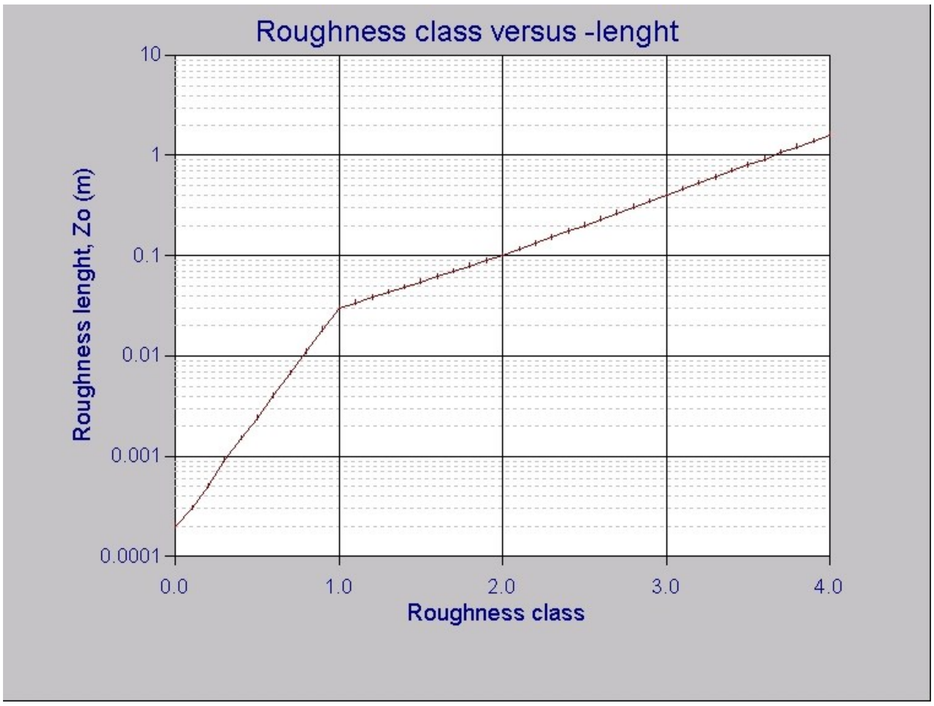


Figure 22 Roughness class vs length

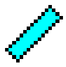
By applying roughness sector wise (roughness roses), it may be necessary to decide on one roughness value when, that sector consists of more than one roughness class. It is then recommended to make a simple weighting of the roughness classes in that sector. For example, if the area consists of 1/2 Roughness Class 2, 1/4 Roughness Class 1 and 1/4 Roughness Class 3, the resulting Roughness Class becomes: (2*2 + 1*1 + 1*3)/4 = 2. It is, again, important to note that the use of Roughness Roses is a legacy practice/option that is only viable with WAsP versions before 10.2.

It's important that a roughness classification covers an entire roughness area (belt), i.e. a roughness belt with a width 1000 m with one crossing hedge of 10 m heights should be assessed to the roughness class 2. It's often seen that such an area has been classified as roughness class 1 all the way to the hedge, with a shift to roughness class 3 for a few meters along the width of the hedge, and with a final roughness class of 1 just after the hedge. *This is incorrect*! The "European Wind Atlas" recommends doubling the width of every new roughness belt when moving outwards from the WTG.

Another important rule: Even if an area is located at a ground level, which is lower than the turbine site, the roughness classification is not affected by this fact. *The differences in terrain heights are included in the elevation model.*

In practice, it's important to visit the site and take preliminary notes regarding the roughness and the distances between the roughness changes. Furthermore, notes should be taken regarding local obstacles and their dimensions. Having completed the site visit, the exact distances between the roughness changes and the final design of the roughness classifications can be determined at your desk by using the map and the above-mentioned tools. However, much of the measuring work can be avoided by using digital background maps in windPRO. An efficient option is the Google synchronization view, where the objects are shown on top of Google Earth maps.

3.3.6 Obstacles – displacement heights (forest handling)

Single obstacles, e.g., buildings, hedges etc. (of more than ¼ of the hub height) near the WTG (within approximately 1000 m from the turbines) should be included as  local obstacles **OR incorporated by displacement height.**

A displacement height calculator was introduced in windPRO 3.0, because experiences showed the obstacle model does not handle the combination of forest and larger turbines sufficiently. It is, therefore, recommended to use the displacement height calculator when having forest areas near (within approx. 1 km) the turbines when they have a 40 m hub height or higher. For smaller turbines (<40 m), the obstacle model seems to handle the reductions sufficiently, although there are problems when the obstacles are very close to the turbines (within the shaded region shown in the figure below).

If the obstacle is lower than ¼ of the hub height or farther than 1000 m away, it should not be included in the calculation as an obstacle as it will have little or no influence on the calculation result. However, it must be included as a roughness element in the roughness classification. In addition to the dimensions of the obstacle, its porosity must also be estimated. The following figure shows how the WAsP model handles obstacles.

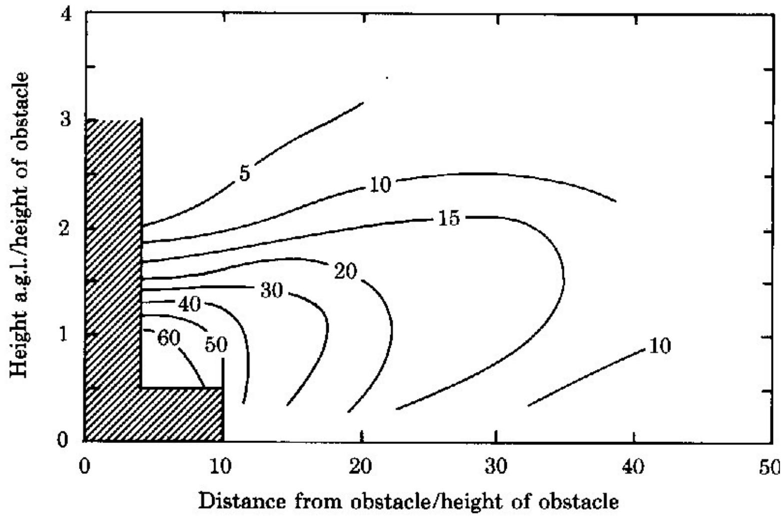


Figure 23 Obstacle model

The displacement height calculator works like this:

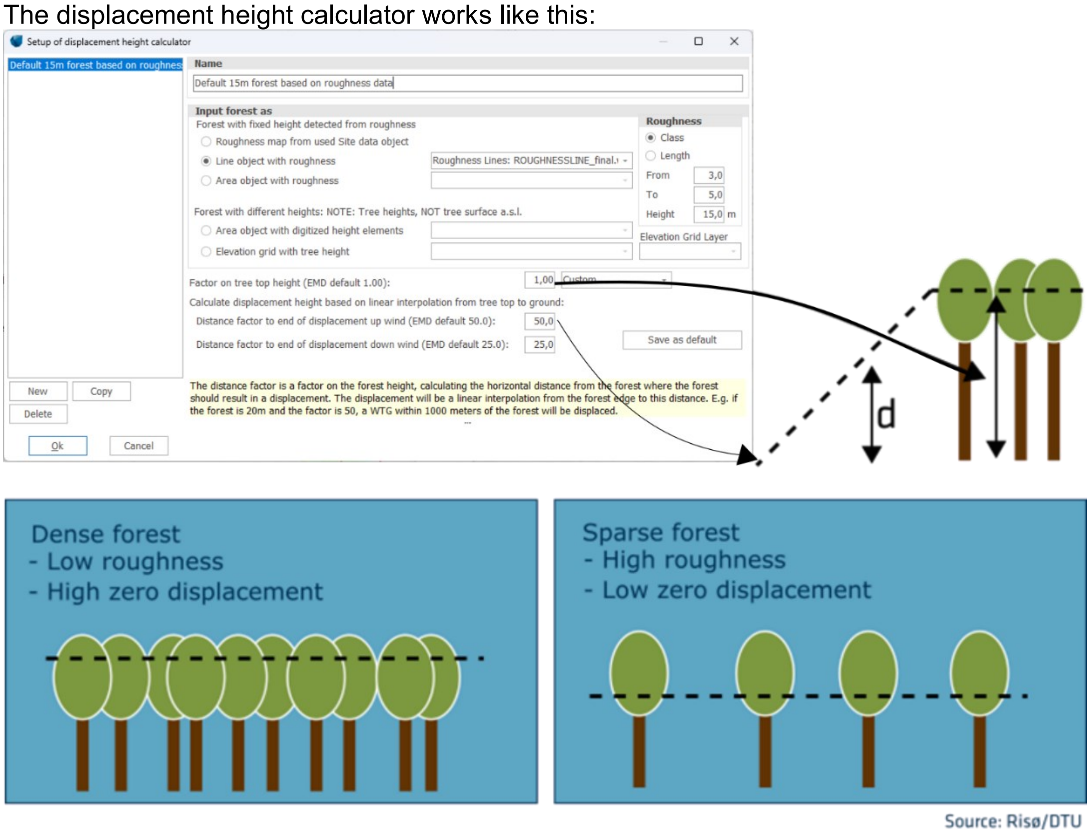


Figure 24 Displacement height calculation

With the displacement height calculator, a height is subtracted from the hub height in each direction sector based on the height of the forest and the distance to the forest. Various input data to describe the forest can be used (see more detailed documentation later).

3.3.7 Site Data Object: the terrain (and wind) data container

The Site Data Object is a multi-purpose object for definition of how the terrain shall be handled. It can, e.g., merge multiple elevation or roughness data files, or be used to point out a specific combination of files, which makes experimental calculations more structured. Thus, when setting up, e.g., a PARK calculation, all the input data is defined just by a link to a Site Data Object.

Depending on the data provided to the Site Data Object, the symbol will change color on the map:

- Orange – Only terrain information (elevation and/or roughness) is defined.
- Blue – also has a wind statistic attached.
- Green – also has an area defined for a RESOURCE calculation.
- Purple – has an area defined for WAsP-CFD.
- Black – for ATLAS calculations.

3.3.8 Turbine data

New WTG

Existing WTG

Wind turbines can be established as new or existing. Both hold links to the turbine catalogue with information on power curve, Ct curve, noise data, visualization data etc. User defined parameters such as coordinates, hub heights etc. can be input as well. New from 3.2 is handling of paired Noise and power curves. (**More details are in Chapter 2 of the Basis module).**

Existing WTGs can be marked "Treat as PARK WTGs": ☐ Treat as Park WTG
The feature basically identifies if the existing WTG is part of the project, or just a reference turbine that might give wake and noise additions, but is not part of the project that is calculated. The PARK calculation will then calculate the production with and without new WTGs. Grid curtailment calculations ignores non-"Treat as Park" WTGs.

Start-stop dates can be set on turbine objects. This is a very convenient option in time varying calculations, as one long time series can be calculated with turbines with different (de)commissioning dates, which is respected in the PARK calculation.

For existing turbine objects, information on actual production can be included, partly as the long-term expected production (statistic tab) and/or as time series (see more details in Chapter 11, Operation – Performance Check).

Since 3.1, the noise reduced power curves can be utilized based on Day-Evening-Night settings and thereby a PARK calculation can handle different noise modes by time of day.

From 3.2 there is an option to choose "Shut down" in power curve choice, if e.g., Night mode is to stop the turbine. It can also be used for taking out a turbine of a re-calculation, if this e.g., is an experiment, then it is not needed to open the PARK calculation to deselect the turbine.

3.3.8.1 Handling of power curve cut-out

If a power curve is set to cut out at a specific wind speed, production is included up to the cut-out wind speed. Decimal cut-outs (e.g., 22.8 or 22.9 m/s) are even handled when calculating in e.g., 1 m/s bins. Here, the end will be calculated a little higher in the 23 m/s bin covering production from 22.5-23.5 m/s. For time step calculations it is simply the time step wind speed which decides if it is below cut-out.

3.4 Tools (data/MODEL validation/calibration)

Models have uncertainties; data have uncertainties – and even errors.

One of the most important disciplines within energy calculations is to justify that both the data and the models used are reasonably correct. This means that the calculated wind distribution at each turbine location is as close as possible to what the project will show. There are plenty of possible mistakes. The more comprehensive the evaluation of the data and the models, the higher the safety that no major mistakes are made. The validation/calibration tools therefore, always have had a high focus in windPRO.

3.4.1 Overview of model and wind data validation tools

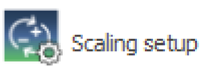
The data tools are described in separate paragraphs in this chapter, with METEO object and Meteo analyzer as exception. These are described in Chapter 12. Also, the Performance Check module is described in separate Chapter 11. Here an overview is given.

Table 4 Model and data validation tools

Model and wind data validation tools in windPRO
Meteo object: Compare more measurement heights, disable (flag) erroneous data, merge "free directions"(remove mast shadow if more anemometers in same height), calculate shear 24-12 matrix and based on this create synthesized data in other height and many more options. (See Chapter 12).
Graphic tab, profile: Validates the shear by showing measured shear together with model-calculated shear from ONE height. Can be shown by direction sector. The model calculated shear can be based on: A) WAsP OR B) WAsP-CFD for aggregated data (wind statistics based). Thereby, annual average calculated shear is shown which by season or day/night aggregation of measurements not give a real comparison. OR C) SCALER. Here it's possible to do real comparisons by, e.g., season or day/night. Although the model "behind" (WAsP) does not yet have the option to run with different day/night heat flux settings, then only when using Meteo object with EMD mesoscale data, the day/night shear differences be compared between measured and calculated.
Meteo analyzer: *General:* Compare more masts/mesoscale data on time series level or aggregated with concurrency optional. Disable functionality available - written back to Meteo objects. (See Chapter 12). *Cross predictor:* Validates the horizontal (and vertical) model extrapolations between more masts and heights based on concurrent data
SCALER: Creates a SCALER based calculation (e.g., from mesoscale data or other mast) in an existing mast (Meteo object) for comparison to measured data – then optional: Change SCALER setup (Post calibration) and recalculate to get a match.
MCP: Creates long-term corrected wind data based on transfer model set up from concurrent local measurements and long-term data. The module holds comprehensive tools for comparing the modelled and measured data in the concurrent data period and gives quality indicators.
Performance Check: The most comprehensive tool (module) for validating the "full way" from wind data to energy output from the wind turbines (when in operation). Checking performance turbine by turbine, direction by direction, month by month, power curve by power curve etc. can give the full understanding of where data or models fail or need tunings. (See Chapter 11).

Extrapolation of the wind data, e.g., coming from a measurement mast, will, in most cases, be needed, as measurements will not be available at each planned turbine position, are often not in hub height, and not long enough to be sure data is long-term representative. This is where the models come in, like the WAsP flow model for horizontal and vertical extrapolation, and MCP models for long-term extrapolation.

3.4.2 SCALER - downscaling/post scaling/interpolation



A SCALER is used for "moving" wind (and other climate parameters) from one location (mast) to another (turbine) in the time domain. It is a very comprehensive interpolation and book keeping tool utilizing different flow models, that makes it capable to use multiple masts with multiple heights, even with direction dependent displacement heights.

Besides being able to transfer wind data at each time step sample, the SCALER also includes functionality to transfer data from one terrain to another. This unique feature of the SCALER means that it can be used for downscaling meso-scale data. So, in other words, the SCALER can take in to account the terrain used in mesoscale models and transform wind to the micro scale terrain, illustrated below:

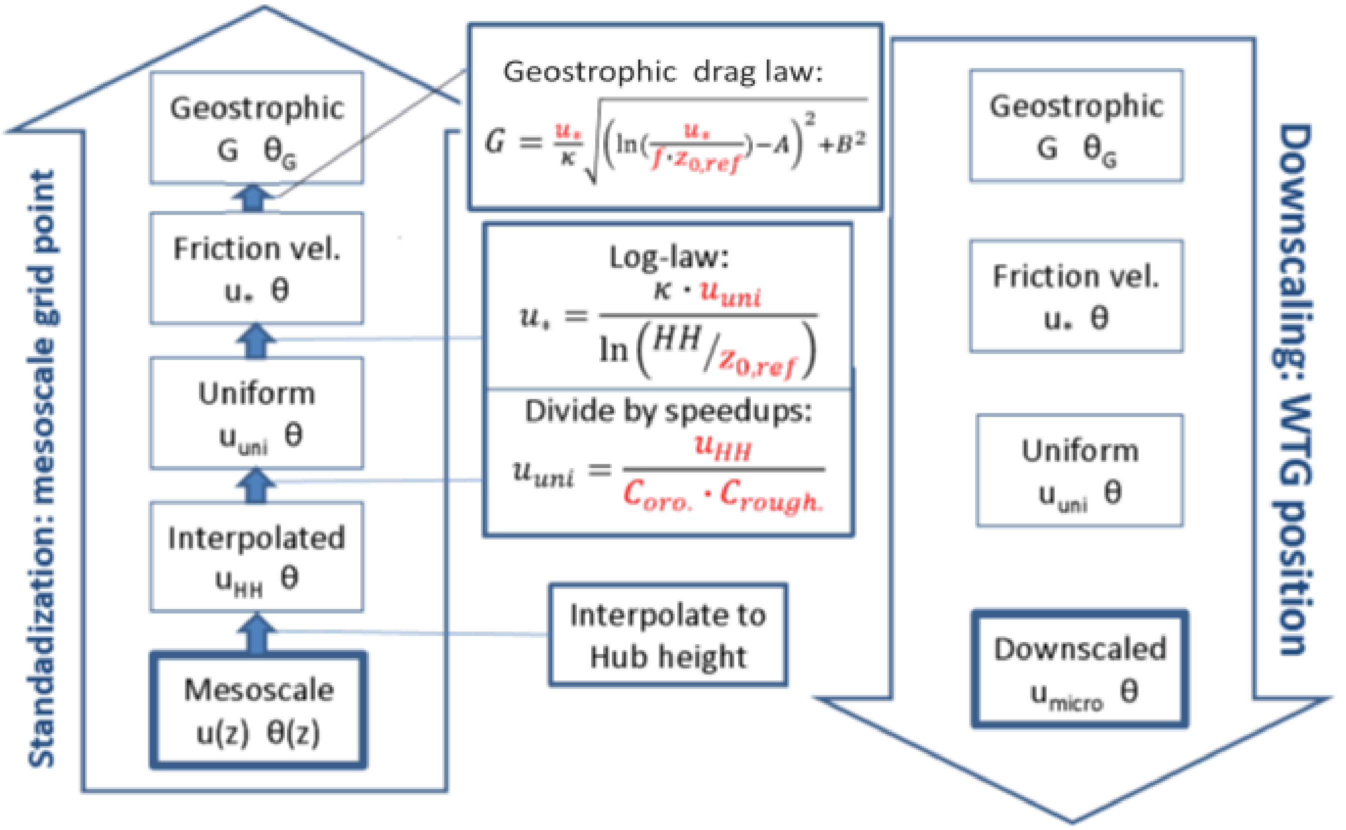


Figure 25 Mesoscale terrain used for Standardization of Mesoscale wind data.

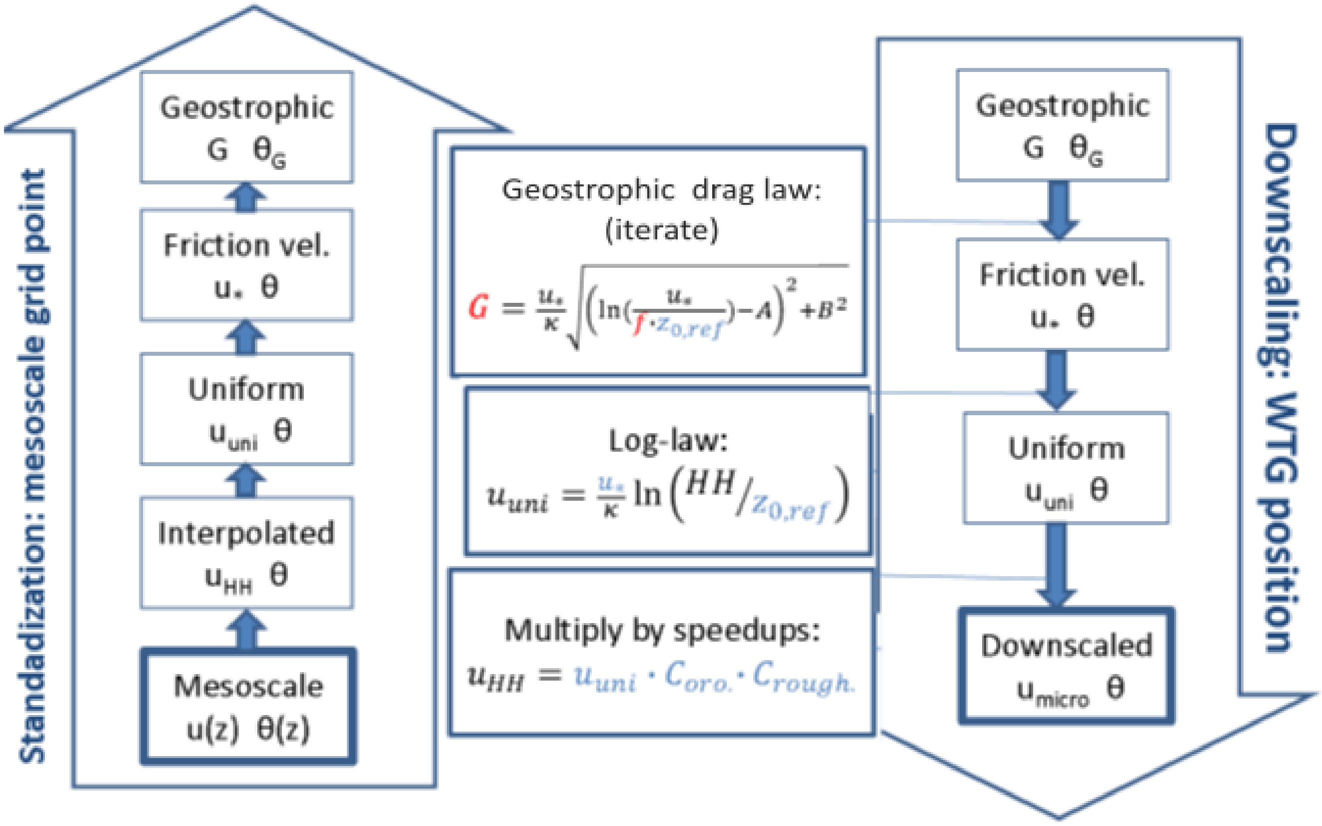


Figure 26 From Standardized wind to micro scale wind.

As a windPRO user, think of the SCALER as a component that can “scale” wind from one position to another using results from a flow model (orography, roughness, obstacles, stability, etc.). So the SCALER “moves” wind from source data to turbine positions on a site for each time step sample, but, on top of that, it is also able to calibrate each sample according to user defined post-scaling parameters. This is especially important when down-scaling meso-scale data, because such data will often include a bias that has to be calibrated against real measurements from masts or existing turbines. Similarly, e.g., nacelle wind measurements often need a post calibration.

A SCALER incorporates other important features, such as RIX correction where the complexity of the terrain can be used to compensate the WAsP IBZ linear flow model problems. Another important feature is that the SCALER is able to scale the results from the flow-model based on displacement heights for each sector. This feature is relevant in forest areas where sector-wise displacement heights can be used to simulate the forest “lifting” the wind profile. For windPRO 3.0, it is important to note that sector-wise displacement heights are only used at the calculation points and not at the mast positions (points where data are scaled from). For meso-scale data downscaling calculations, this is not important since forests will not affect the meso-scale data like it will for real measurement masts.

Starting from windPRO 3.1, displacement heights at mast positions is included in the SCALER, and masts near forests, will be handled with this feature (unlike in 3.0), which might call for recalculations in specific projects.

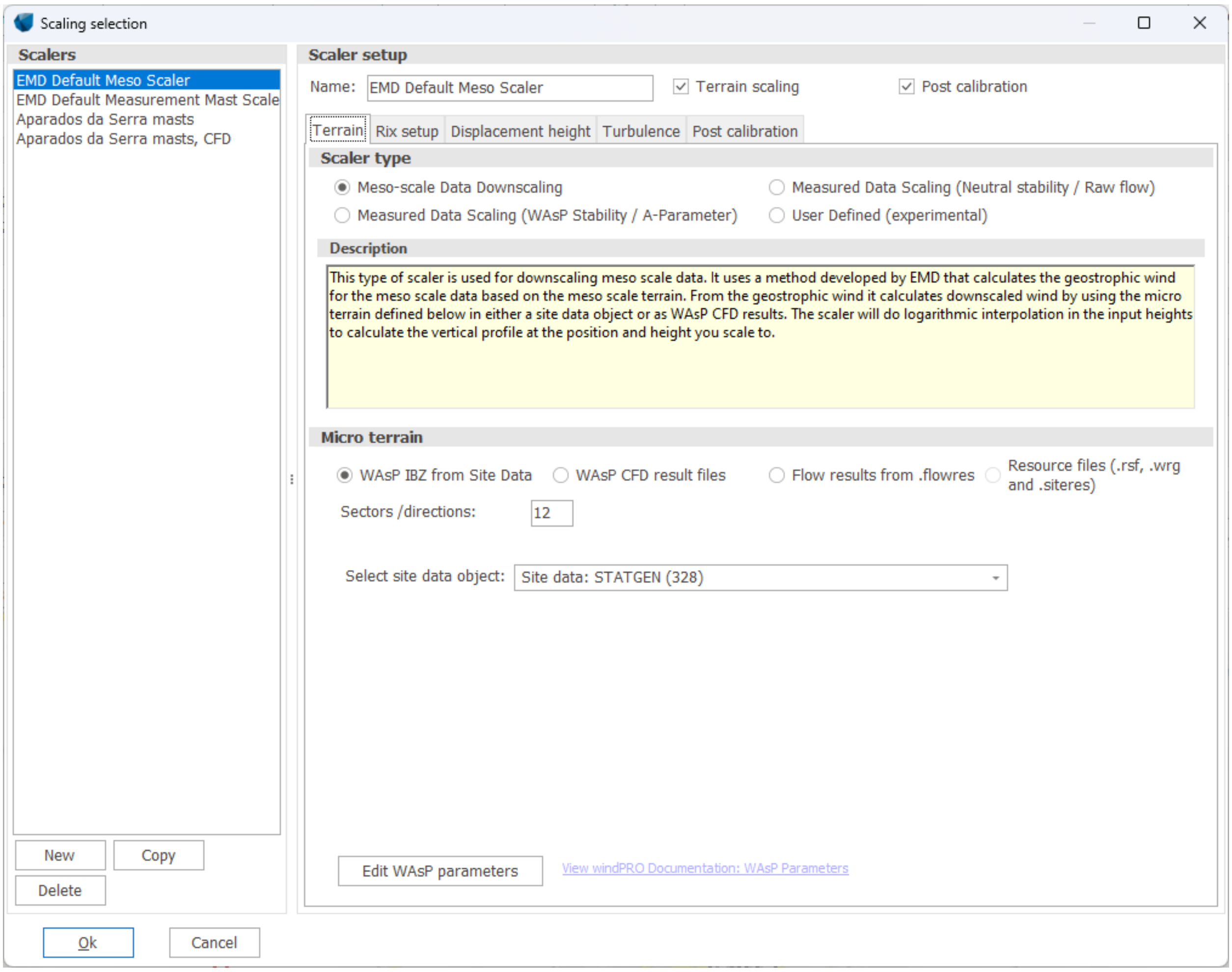


Figure 27 SCALER setup

The SCALER setup can be reached from the relevant parts in the software, like a PARK calculation, METEO object, Meteo Analyzer etc.

The tabs to be explained are:

- Terrain scaling
- Rix setup
- Displacement height
- Turbulence

- Post calibration

All 5 correction types are optional. The first 4 are all of the category "terrain scaling" and can be unchecked at the [ ] Terrain scaling checkbox. The values behind are kept but not used when unchecked. The Post calibration can, likewise, be unchecked. Rix correction and displacement height can individually be checked/unchecked within the definition tab.

3.4.2.1 Terrain scaling

Terrain scaling is divided into these main types:

- Meso-scale Data Downscaling
- Measured data scaling
- The "user defined" allows for any mix and to change predefined choices

Meso-scale Data Downscaling assumes the mesoscale model terrain data is part of the METEO object that holds the mesoscale wind data. Therefore, the "standard" downscaling method only can be used with EMD mesoscale data in the present version. For the more specific downscaling predefined choices, press "user defined".

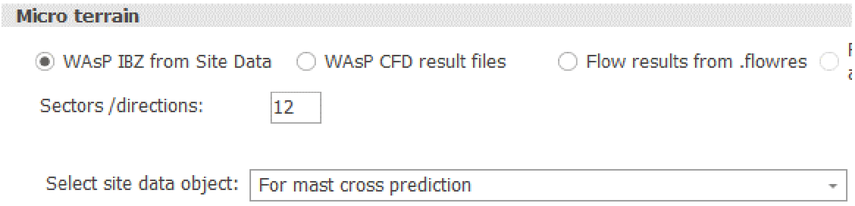


Figure 28 Micro terrain in SCALER

When using EMD mesoscale data as a wind data source, the mesoscale terrain is included in the METEO object and automatically used as the terrain for the source data.

The only necessary user input is, therefore, the Micro terrain. The options are:

- Site Data Object – use WAsP 11+ for terrain scaling
- WAsP-CFD results – use WAsP-CFD result file(s) for terrain scaling.
- FLOWRES files – use external e.g., CFD models that support the .flowres file format
- Resource files (.rsf, .WRG, .siteres) since in 3.6

Using WAsP, the number of direction sectors can be specified (default 12, max. 36).

Measured data Scaling is a "simple" variant of the above, where only the Micro terrain is used. Just as specified above, where instead of downscaled mesoscale data, the data comes from a mast (or an "artificial mast" coming from other Mesoscale data providers). Here are two variants:
<u>WAsP Stability /A-parameter:</u> The speed up's are calculated as Weibull A parameter ratios between mast position(s) and the calculation points.
Important: From windPRO 3.2 the ratios are calculated for more wind speeds and the ratios becomes wind speed dependent. This can change calculation results
<u>Neutral stability / Raw flow</u>: The speed up's are calculated based on the raw WAsP speed up output (roughness, orography and obstacles), including the turns of the wind directions, but NOT including stability correction, while this is not a part of the WAsP speed up output. This method is therefore ONLY recommended if measurements are close to hub height, and it is also checked by the software that the height differences are less than 20m. But due to the more correct handling of the speed up's and turns, this method is recommended if the stability correction not is needed.

User defined terrain scaling explains partly the terrain scaling principles and partly gives access to experimental settings.

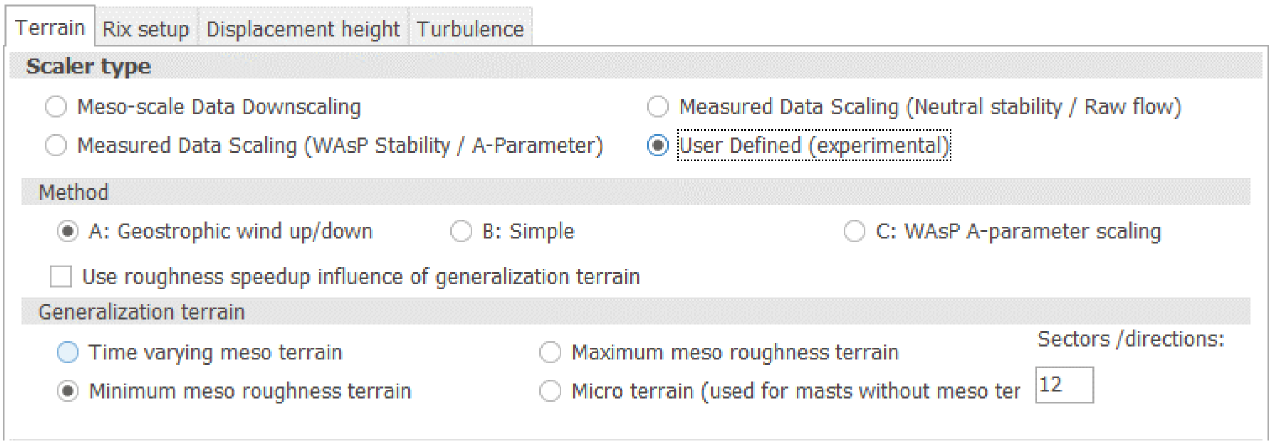


Figure 29 terrain scaling in SCALER

The SCALER includes different methods intended for different user cases.

•**A: Geostrophic wind up/down**: This method uses the geostrophic wind laws to generalize each sample to geostrophic wind from the generalization terrain and then applies micro-scale terrain effects using flow perturbations from the micro-scale terrain. The method does not include modelled stability corrections in vertical scaling, but relies on interpolation in the input heights to do the vertical interpolation.

•**B: Simple (no mesoscale terrain effects**): This method does not take in to account the terrain effects from the generalization terrain (normally meso-terrain), but only corrects the source data by orography effects in the micro-terrain. The eventual roughness differences in mesoscale and micro terrain is, thereby, not considered. This assumption will be unproblematic offshore. It is similar in mountain regions, where the dominating effect is the orography. But in terrain where the varying roughness dominates the terrain effects, this method will not be a good choice.

•**C: WAsP A-Parameter Scaling**: This method scales wind from one location to another by the ratio between the A-parameters from a WAsP calculation at the two locations. This method accepts more source height for interpolation if relevant (if there are measurements both below and above calculation height) but uses the WAsP model to do the vertical extrapolation if calculation height is outside measurement height range. **From 3.2 the WAsP A-parameter ratio calculation is made wind speed dependent and stability correction is thereby handled more correct. This can in case of large height extrapolations change calculation result from windPRO 3.0/3.1 to 3.2 significant.**

As seen, the SCALER includes different methods intended for different user-cases, but, essentially, they all have the same purpose of “moving” wind data from one location to another. As a windPRO user, it is normally not needed to decide since method A is chosen for EMD Mesoscale data, by default, and method C for measured data. Only for experimental purposes or if using mesoscale data from other sources, the choice of method can be relevant. A special case could be where mesoscale data is used, but the user wants to control the stability correction by WAsP heat flux parameters instead of taking the shear from the mesoscale data. In this case, method C must be used together with the mesoscale data from one height.

[ ] Remove roughness in mesoscale terrain is an option when selecting method A: in user defined mode, explained here:

The first step in downscaling is to remove the terrain effects from the mesoscale terrain. In order to do that we use WAsP to get the speedups from the meso-terrain. WAsP will return an orography speedup and a roughness speedup. So the first step is to divide the wind speed with the orography speedup (always done) and if the “Remove roughness in mesoscale terrain” is enabled it will then divide by the roughness speedup as well. So why is this option disabled in the default downscaler? Because tests have shown that the way WAsP sees roughness (as changes) is not how the meso-scale model sees it. During downscaling the effects of roughness is still taken into account since the equations going to and from geostrophic wind includes a z0 (meso-scale roughness or reference roughness) which comes from the meso-terrain when going up and from the micro terrain when going down.

3.4.2.1.1 Standardize using mesoscale terrain in scaler

As mentioned above the unique feature of the SCALER is that it is able to differentiate between the terrain in which the source data is located and the terrain at the calculation points (WTGs/masts). Therefore, it is important for a SCALER to know where the source data is located.

A SCALER accepts, in general, two types of terrain for generalization, namely:

- **Meso-terrain**: This terrain type represents the terrain used in the model, the source data originates from. So, for meso-scale data the terrain would be the terrain used in the meso-scale model. In windPRO, the meso-scale terrain is associated to the METEO object holding the meso-scale data. For the SCALER setup, you do not point directly to a meso-scale terrain, but simply indicate that the SCALER should use the terrain from the METEO object(s) used.
- **Micro-terrain:** If the SCALER is setup to use the micro-scale terrain as the generalization terrain, it simply means that the source data is also located in the micro-scale terrain. This is true for, e.g., masts, LIDARS, or modelled data that are downscaled to micro terrain (artificial masts).

3.4.2.1.2 Micro terrain in scaler

The micro terrain in a SCALER can be defined in following ways:

- **Site Data Object** when using the classical WAsP IBZ linear flow model. The SCALER only uses the terrain from the Site Data Object so any wind statistics in the Site Data Object will not be used in the SCALER calculations.
- **WAsP CFD result files** that have been calculated for relevant area(s). When using WAsP CFD result files, all flow perturbations used in the SCALER come from the CFD results instead of the WAsP IBZ model.
- **FLOWRES file,** from external model calculations.

3.4.2.2 Rix setup

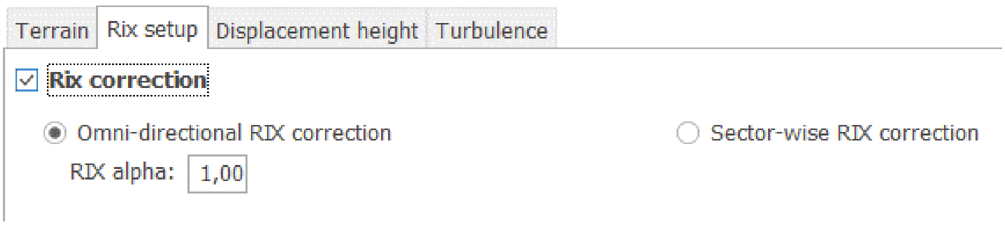


Figure 30 RIX correction in SCALER

The RIX correction is explained in Section 3.4.2.2. Within the SCALER, the RIX values are calculated by WAsP 11+ default settings:

The default configuration of the RIX calculation is:

calculation radius [m]	3500
threshold slope	0.3
number of sectors	12
number of subsectors	6

3.4.2.3 Displacement height

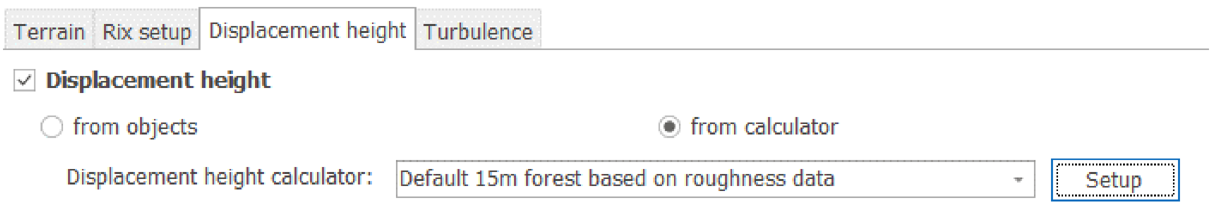


Figure 31 Displacement height in SCALER

The displacement height calculation is explained in Section 4.9. Note that the displacement height calculation using calculator is NOT used on the mast position in windPRO 3.0, but will be used from windPRO 3.1. Updating calculation using this feature thereby will result in changes in results if mast is near a forest and the “calculator” used.

3.4.2.4 Turbulence in scaler

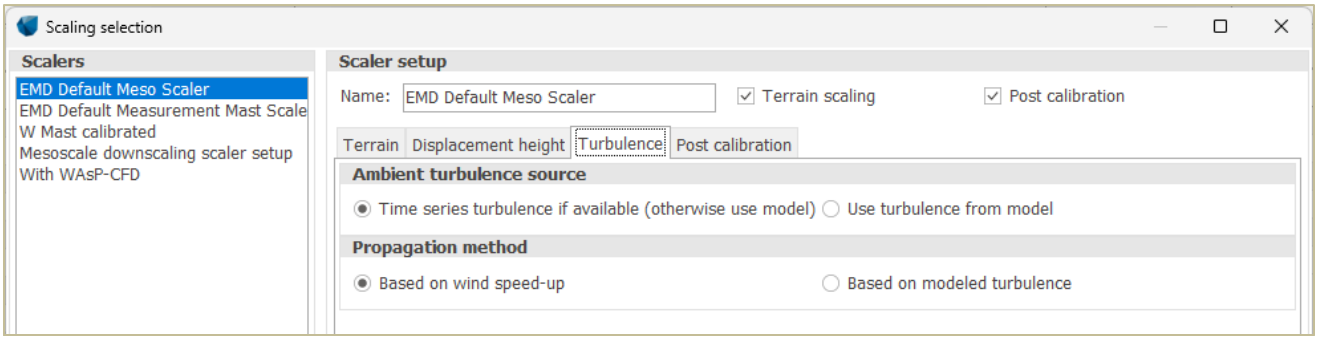


Figure 32 Turbulence scaling.

The ambient turbulence can come from the meteo data series (if loaded). If so, this measured turbulence can be moved to each turbine position by two different propagation methods:

Based on wind speed-up
The St.dev. is assumed constant at all turbine positions. Then the mean wind speed calculated at each turbine position defines the turbulence by formula: TI = St.Dev(u)/u, where u is the wind speed at the given time step, and the St.Dev(u) is found at the measure point by same formula.
This method is also used if the turbulence is taken direct from a meteo object (not from scaler). The difference is that when using the feature within the scaler, interpolation from more meteo objects is supported along with the features described below.

Based on modelled turbulence
If modelled turbulence exists for the site, e.g., from WAsP CFD result file or by other model by use of FLOWRES files (can come from WENG or other models, e.g., external CFD models supporting the FLOWRES file format), the turbulence is propagated from the measurement point to the turbine position by the model turbulence ratio.

Use turbulence from model
The model calculated turbulence is used at each calculation point found by interpolation in the model data. This require the used model include turbulence calculation, like WAsP-CFD or FLOWRES files from external model with turbulence calculation.

When using the feature WDC controlled by turbulence in time step calculation, each turbine will get individual WDC for each time step. This WDC is then used to decide the wake expansion for each turbine. Similar when using turbulence corrected power curve.

3.4.2.5 Post calibration in scaler

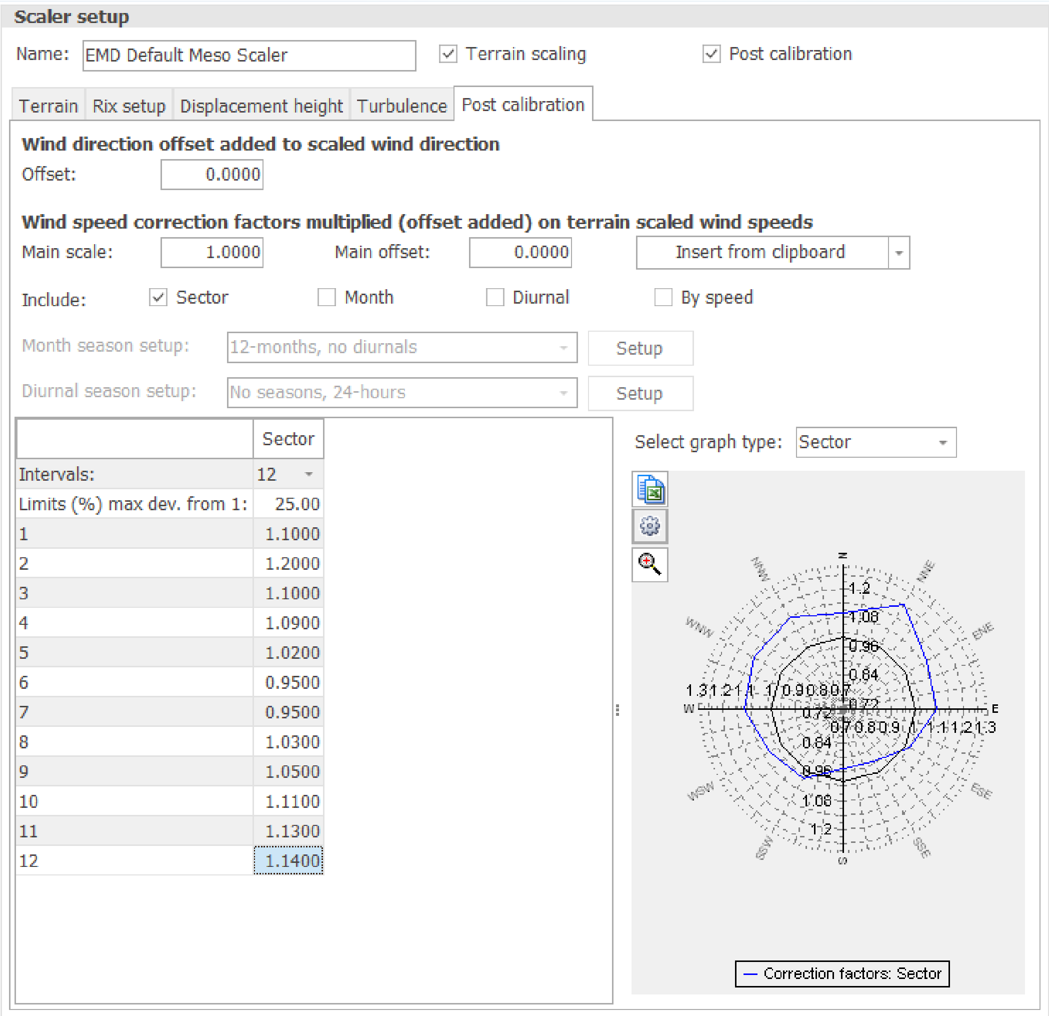


Figure 33 Post calibration in SCALER

Post calibration is a very important part of the SCALER. Using Mesoscale wind data for a calculation cannot be assumed accurate. The post calibration is required to unbias the mesoscale wind data. For measurements, post calibration can be used for correction of tower shadow or, in the case of nacelle measurements, for correction of calibration problems. Calibration of measurements should typically only be performed if production data is available to calibrate against using the Performance Check module. It must, although, be mentioned that a calibration, in this case, could be biased due to a wrong power curve or a wrong wake model calculation (see details in the performance check chapter).

Having Mesoscale data, the Post calibration can also be based on local wind measurements (Meteo Analyzer) as well as turbine production (Performance check).

The proposed calibration process is:

1. Adjust the main scale (see Section 4.6.2)
2. Include, if needed, a main offset (and readjust the main scale)
3. Calibrate by direction sector
4. Calibrate by month
5. Redo calibration by sector
6. If needed, include diurnal correction

Ad. 1 – The main scale is adjusted to get the data within a reasonable range. Up to 25% adjustment is needed at some locations. This is simply a problem in the mesoscale modelling. Offshore regions seem, in general, very precisely modelled, but, the further inland, the higher the over prediction by the mesoscale models. It is important to get the data within a reasonable range before starting the more detailed calibration. Comparing the scaled mesoscale data against measurements, or calculated turbine production based on the mesoscale data, against real turbine performance often shows that low wind speeds are too low and high wind speeds too high in the mesoscale data. This bias can be corrected by an offset.

Ad. 2 - Offset corrects for skewness in mesoscale data. For most examples tested, an offset of around +1 m/s has given the best match. This will then require the main scale to be decreased.

Ad. 3 - Having a reasonable match between scaled mesoscale data and measurements (or turbine production), the fine tuning can be established. It is described in detail in the Meteo Analyzer section (Section 4.5) and in the Performance Check chapter on how to perform calibrations by variables like direction and month (**). The direction calibration is important since a direction bias can result in wrong long-term estimates, even when the average between measured and scaled match for a specific period (e.g., one year, if this year has a non-typical direction distribution).

Ad. 4 - Calibration by month can be used to take out seasonal bias coming from the terrain (roughness). The surface roughness changes by season, in some places a lot (especially where tall crops are grown, like maize) It can also occur in regions where e.g., the winter season has snow. The mesoscale model does, partly, compensate for this, but the micro terrain is fixed by present calculation methods. The difference in how the mesoscale model compensates and the fact the micro terrain does not change in time in the model can create a seasonal bias when comparing model data to measurements. This can be unbiased by the Post calibration.

Ad. 5 - By calibrating seasonally, the direction calibration will be invoked, as some directions are more frequent than others are in specific seasons. While the direction calibration is assumed very important, it is recommended to remake the direction calibration after a seasonal calibration. It is important to notice here that the new found direction calibration factors must be MULTIPLIED with the previously found values before putting the calibration factors into the SCALER. It is a multiple of the used calibrations and the new deviations that gives the final calibration.

Ad. 6 - A diurnal calibration can be performed as the last step. This is especially important if the diurnal variation is used for reasons like PPA negotiations, having tariffs that vary by hour or for dimensioning of storage systems, etc.

Calibration by speed is tricky and should be handled carefully. An example of where this can give unforeseen effects is if the same factor is multiplied on,e.g., 8 m/s, no matter if the 8 m/s is in 30m height or in 80m height. Thereby, the shear will be modified, which might not be a desired effect of the calibration. But in a situation like dealing with nacelle measurements, a scaling by speed could be the method that corrects best for the needs of a non-linear calibration of the measurements.

3.4.2.6 Selection of wind data - Interpolation

With the SCALER it is possible to use data from multiple masts, assuming a gradual change of the wind speeds between the masts. This is utilized directly by the PARK calculation, instead of having to calculate a wind resource map up front (as in previous versions before 2016). Similarly, when using mesoscale wind data, multiple mesoscale data points can be used and interpolated.
In PARK, the data selection for data to be used with a SCALER looks like this:

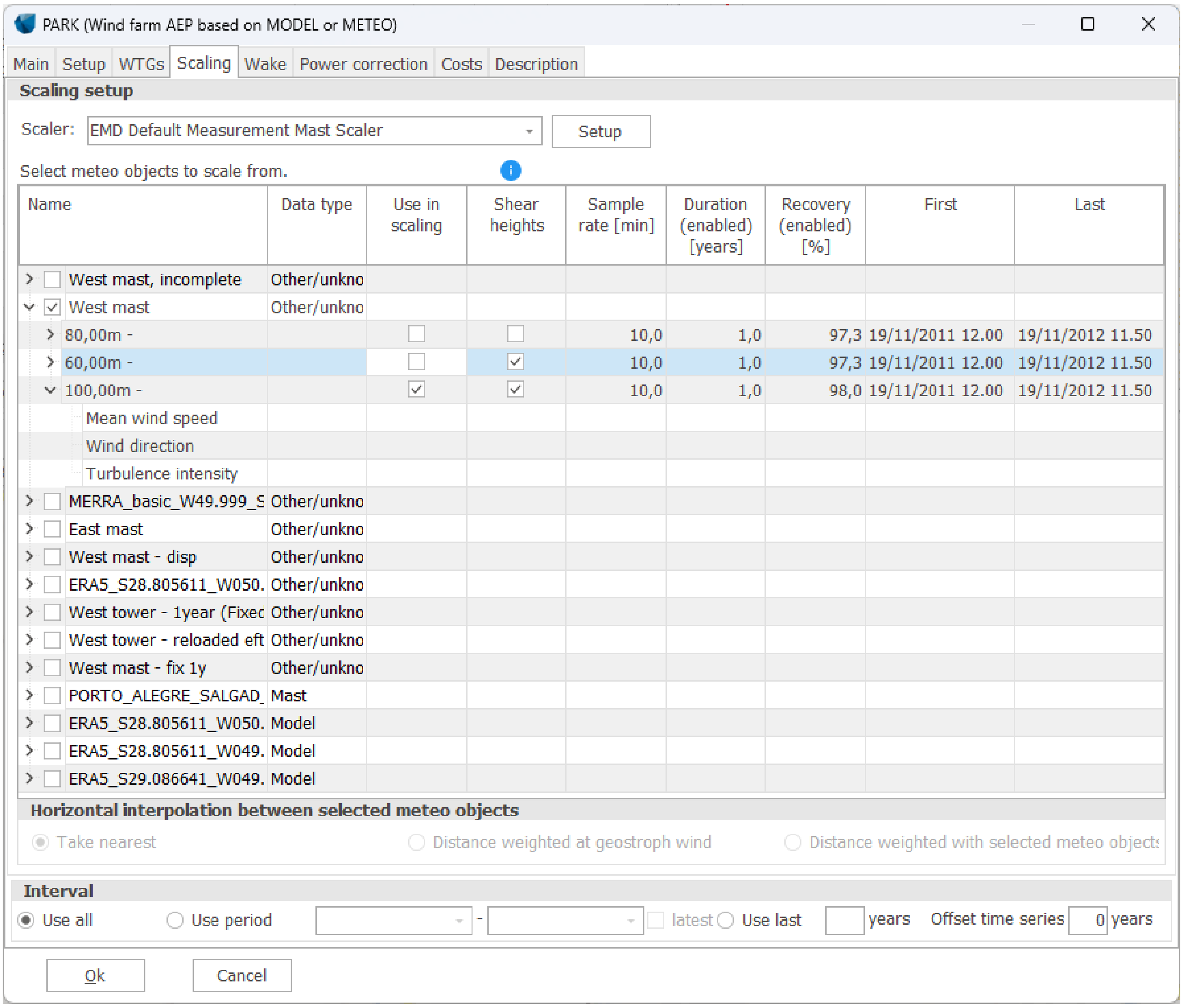


Figure 34 Wind data selection in SCALER

A list with the available METEO objects is seen. Each “mast” can be expanded to see the different heights and signals. The following rules apply to the “use in scaling” column:

Using mesoscale data, there must be at least a height above and below the calculation height, where calculation height could be displaced. (Mesoscale data wind profile/shear is used, no vertical model extrapolation).

Using measurements, multiple heights from each mast can be selected for the calculation and interpolation is done. If calculation height is outside the mast height interval, the WAsP model does the vertical extrapolation.

Shear heights column does not affect the calculation of the wind speeds for the energy calculation. It is used for calculating shear for other purposes, like power curve correction based on shear or curtailment based on shear. When selecting shear heights top mounted anemometers should not be used with side mounted, while this would distort the shear calculation in the mast direction. If there are very few mast shaded data or these are corrected, it will although be ok.

For as well mesoscale data as measurement data, MORE horizontal data points (mesoscale points or masts) can be used. Horizontal interpolation will be performed. Either by taking the nearest (if one mast is, e.g., in the valley and one on the ridge, this would be best as it adheres to the similarity principle) or by distance weighting at geostrophic wind level. The latter one means that wind data has the terrain influence “lifted off” before the interpolation, then the micro terrain is applied at the calculation spot to the interpolated value. The distance weight is based on the **inverse squared distance.**

When more masts are selected, there MUST be concurrent data with wind speed and wind direction. Up to 50% deviation of the time step (e.g., 5 minutes if having 10 min. data) is allowed in the concurrency check, so the clock does not need to be completely synchronized at the different masts.

When selecting distance weighting, it is possible to define minimum and maximum thresholds:

- Maximum weight: The maximum weight that any meteo object is allowed to have in the horizontal interpolation. Setting the threshold to 100% is equal to not setting a limit.
- Weight function: Choose between Distance and Distance squared
- Maximum points: In case you don't want to allow all meteo objects to influence the interpolation, you can limit the number of points to 1 or 2 (or more) meteo objects. Setting the value to 0 is equal to not setting a limit
- Maximum distance: In case you don't want to allow all meteo objects to influence the interpolation, you can limit how far away a meteo object is allow to be from the WTG. Setting the value to 0 is equal to not setting a limit

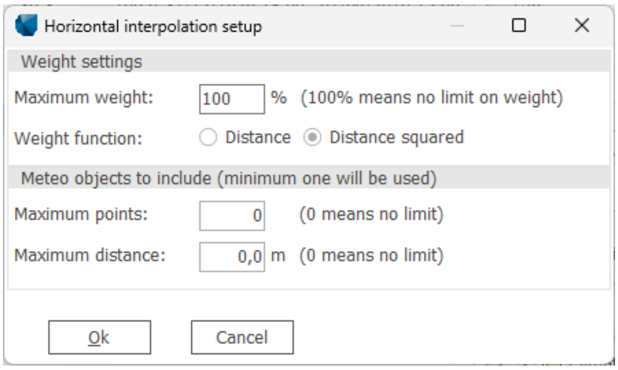
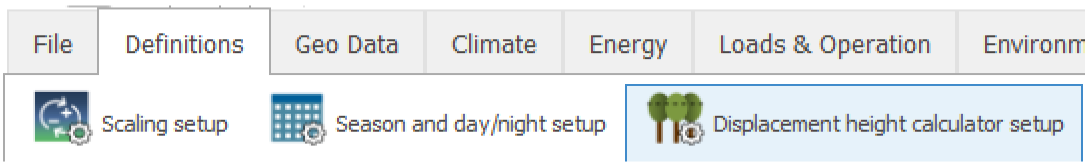


Figure 35 Setting limits on the horizontal interpolation

3.4.3 Displacement height calculator

The Displacement Height Calculator can be found inside the SCALER and as a separate tab in the PARK and RESOURCE calculations. It can also be accessed from the **Definitions** tab:



Forests near turbines is a known issue. Experience shows that handling the forests with a displacement height works reasonably well. A tool that calculates sector wise displacement heights is incorporated since windPRO 3.0.

Theoretically, the displacement height is an offset in the wind profile lifting the perceived ground level off the ground and treating the forest top as the ground. The offset effectively cuts the bottom part off the turbine and/or met mast towers, thus reducing their heights in the calculations. An illustration of the effect can be found in the METEO object in a situation where WAsP may be unable to predict the observed wind profile above forests. However, if the mast is reduced in height with something close to tree height, the profile may fall into place.

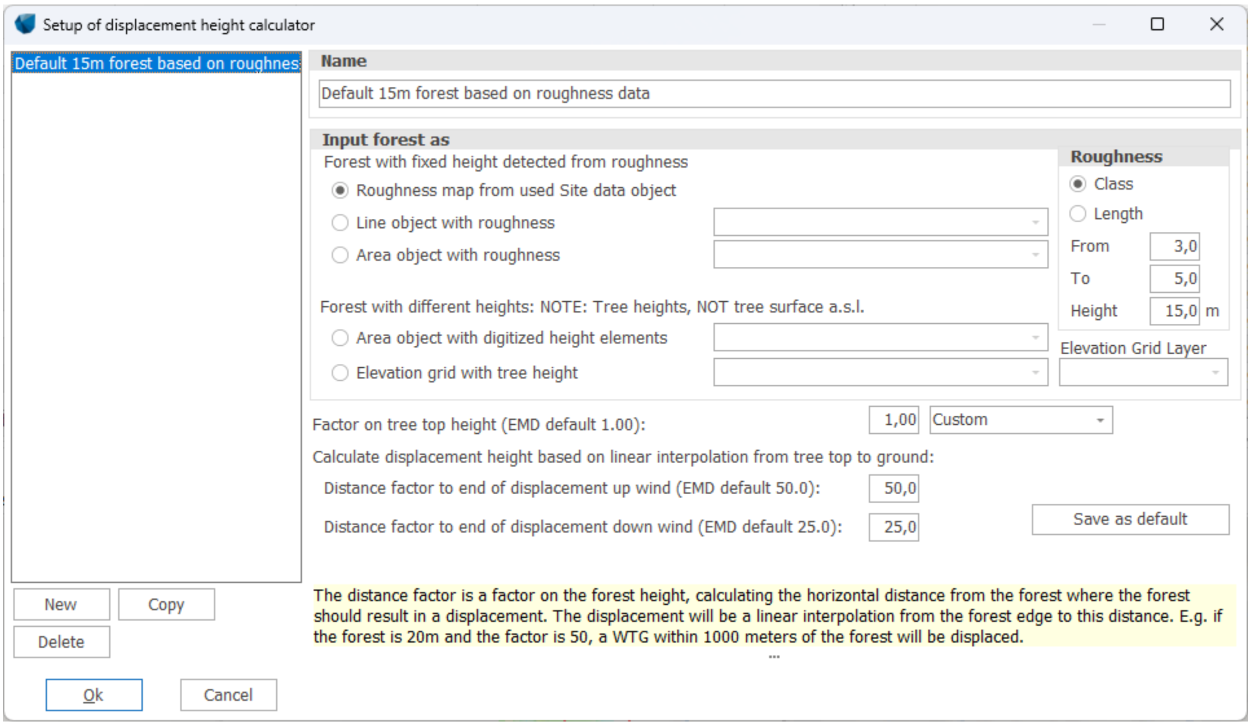


Figure 36 Displacement height input data

The input form for the displacement height calculator is shown above. The ”input forest as” section is a setup form on how to input the forest information.

The very simple approach is to use the roughness map for defining the forest areas. The input choices are:

- Use the roughness map as used in the energy calculation (selected in Site Data Object), OR
- Point out a specific line object with roughness lines, OR
- Point out an Area object with roughness areas

In each case, it must be decided which roughness class (or length) that defines to the program what is a forest area and what the typical forest height is.

The more refined approach makes it possible to work with varying forest heights:

- Area object with digitized height elements (the height property must be used in the area object)
- Line object with tree heights
- Elevation grid with tree heights

NOTE: For all 3 options, it MUST be the height of the forest, NOT the elevation + height (some data sources provides the surface elevation. These cannot directly be used but must first be pre-processed, subtracting the terrain elevation).

It is possible to tune the displacement height calculation with the following:

- Factor on tree height – general experience seem to shows that using the actual forest height works best, meaning this factor should be kept to 1.0, although for some test cases a factor of 1.5 is seen to work best.
- Distance factor to end of displacement up wind – e.g., having a forest height of 15m and a factor of 50 means that forest in a distance up to 15 x 50 = 750 m in up wind direction from the turbine will create a displacement height, linearly decreasing from 15 just at the forest edge to 0 at 750 m distance.
- Distance factor to end of displacement down wind – same as above, but where the wind hits the turbine before it hits the forest.

Considering the two last ones, the result returned is conservative, taking the largest displacement height between the two.

The calculation is based on 3-degree “beams”. For each beam a displacement height is calculated, and the average from all beams in a sector is taken. Thereby a forest that only covers part of the sector will give a reduced displacement height. If the beam hits more forest parts (at different distances with different heights), the largest displacement height is used.

Several scientific papers regarding this issue are available, and several test cases have been set up by EMD showing that the concept works well. It is, of course, not a very precise calculation, since issues like density and size of the forest, etc. not are handled, but is still a better evolved process than was available previously.

See also the validation chapter; 8.4 with tests of the Displacement Height Calculator.

3.4.4 ORA (Optimized Roughness Approach)

Forests in energy calculations is complicated. Therefore several approaches are seen. One of the more promising, intensively tested is the Optimised Roughness Approach (ORA).

This approach consists in defining the roughness value of forested areas according to the height and type of trees. Higher trees will give higher roughness value, and, for the same height, coniferous forests will have a higher roughness than deciduous forests.
The ORA model is implemented in windPRO as an "add on" tool to the already implemented displacement calculation tool in windPRO:

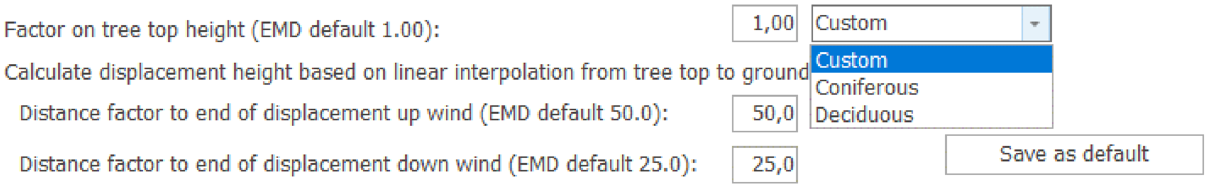


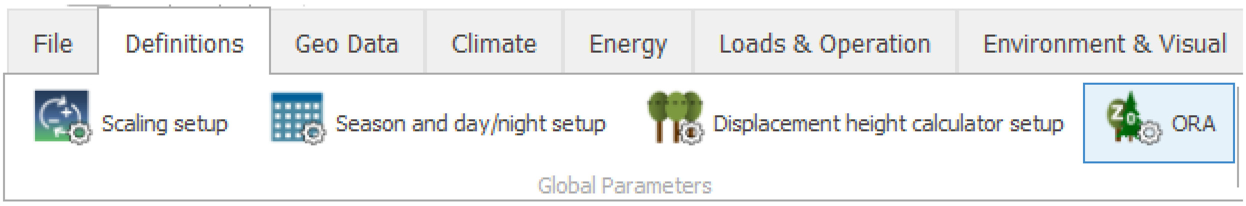
Figure 37 Displacement height calculator, part of ORA

The displacement height calculator based on different input sources (line, area or elevation grid objects) calculates the displacement height at any position in the terrain in any direction sector. The base concept is that the distance to the forest and forest height decide the displacement height by a linear decrease by distance. Inside the forest, the displacement height is given by the forest height with a multiplier. New in windPRO 3.2 is that the factor can be selected based on forest type:

- Coniferous: 0.66
- Deciduous: 0.7

These factors will be proposed modified in the displacement height calculator to these defaults from the ORA tool. Thereby the combined increased roughness values and factors on tree heights in displacement height calculations are aligned to match the experimentally found best combinations based on several sites. For specific sites other combinations might work better, but this requires quite good data, e.g., more measurement masts at site, to be able to find best working combinations.

The ORA tool is started from the **Definitions** tab:



The ORA tool allows to:
1) Calculate the roughness value of forest areas according to the tree height and type
2) Combine these new forest roughness areas to the original roughness map so that it can be used for energy calculation.

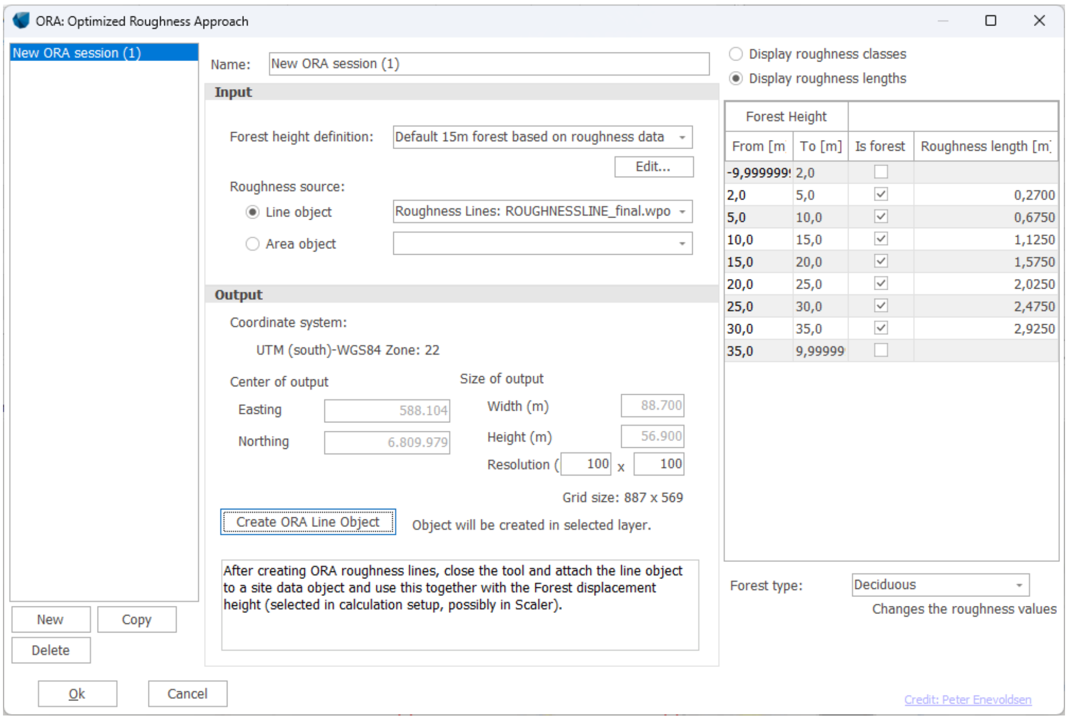
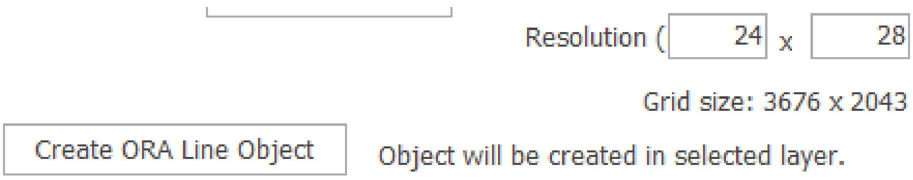


Figure 38 ORA setup

The ORA tool setup.
Besides choosing/defining a displacement height calculator setup, the ORA tool creates a roughness map based on the shown settings by pressing the "Create ORA line object". The line object will be created in the active layer.

The conversion from forest heights to roughness values can be edited manually. The defaults values depend on the selected forest type Coniferous/Deciduous. These values are experimentally found by Peter Enevoldsen, (PHd, Aarhus University), based on several test cases. The values of roughness are found together with the previous mentioned factors on forest height. Therefore, windPRO suggest changing these factors in the displacement height calculation setup, if the forest type is changed.

An important input is the selection of the original roughness source (Non forest roughness), where forest are included based on "traditional" assignment of roughness to forest, e.g., coming from On-line roughness datasets as Globecover. This is the starting point for the ORA modified roughness map, where the forest data overrule the roughness in the forested areas based on tree heights. The basic concept is that the roughness data are converted to a roughness grid, where the grid cell values with forest are replaced based on the ORA values. Then the grid is converted back to a line map. The resolution for the temporary grid must be given as input:



If the resolution is set to a too low value (high resolution) in combination with the size of the roughness map, a warning is shown, and the creation of roughness map is not possible. If the resolution value is too high to capture the forest areas reasonably well (seen by visual inspection of the created line map), the workaround is to limit the size of the initial roughness map, eventually dividing it into more map files and running the process more times. In this case, it shall although be payed attention to the borders between the line maps. The best will be to combine these into one line object (by "add" function) and thereby inspect and correct inconsistencies along borders. Inconsistent roughness maps do violate WAsP calculations and must be taken very seriously, while WAsP do not produce any error message, it just creates unrealistic results near the inconsistent lines.
After creation of ORA roughness map, the method to use it is described in the yellow box in the ORA setup form.

The validation results have been presented at the Resource Assessment Workshop in Edinburgh 2017 (A Uniform Approach for Wind Simulations in Forested Areas: Examining the Importance of Data Inputs

(Enevoldsen, 2017)), where it was demonstrated that 3 different industrial CFD forest simulations had an average error in wind speed cross prediction of ~6.5% where the ORA/WAsP model error were as low as 2%.

The Optimized Roughness Approach was developed by Peter Enevoldsen. Further info can be found in Managing the Risks of Wind Farms in Forested Areas: Design Principles for Northern Europe (Enevoldsen, 2017)

3.4.5 Rix correction

From windPRO 3.0, it is possible to include RIX correction in the AEP calculation. Previous versions had the possibility to perform a RIX calculation, but no correction.
Rix correction is a separate tab in the setup of the PARK and RESOURCE calculations based on wind statistics. Using SCALER, the setup is performed within the SCALER setup. Here RIX correction is treated as a model feature, meaning the WAsP model handles the RIX correction based on the WAsP parameter settings.

RIX is the Ruggedness Index, defined as the percentage of the area around an object that has a steepness above a given threshold value. At 30% steepness, flow separation typically starts, which means that the WAsP model assumptions are no longer valid. Experiments show that the RIX values can be used to fix WAsP model calculation problems in steep terrain – or at least reduce the error introduced by flow separation. It is even seen in research papers that RIX correction can also improve CFD calculation results. But The RIX correction is, however, not currently offered as a correction option using WAsP-CFD results for a calculation.

The Latest research by DTU/Risø/ shows that the threshold in a RIX calculation typically works best with 40% steepness (new default), and that, with a delta Rix within +/- 5%, corrections should not be performed. Cross predictions based on more masts can fine tune the threshold (see Cross predictor tool in windPRO Meteo Analyser). In the windPRO LOSS & UNCERTAINTY module, RIX correction can be calculated automatically as a bias based on the most recent recommended correction formulas, which can be found in EWEC2006 & 08 papers on Rix from DTU/Risø, see extract below:

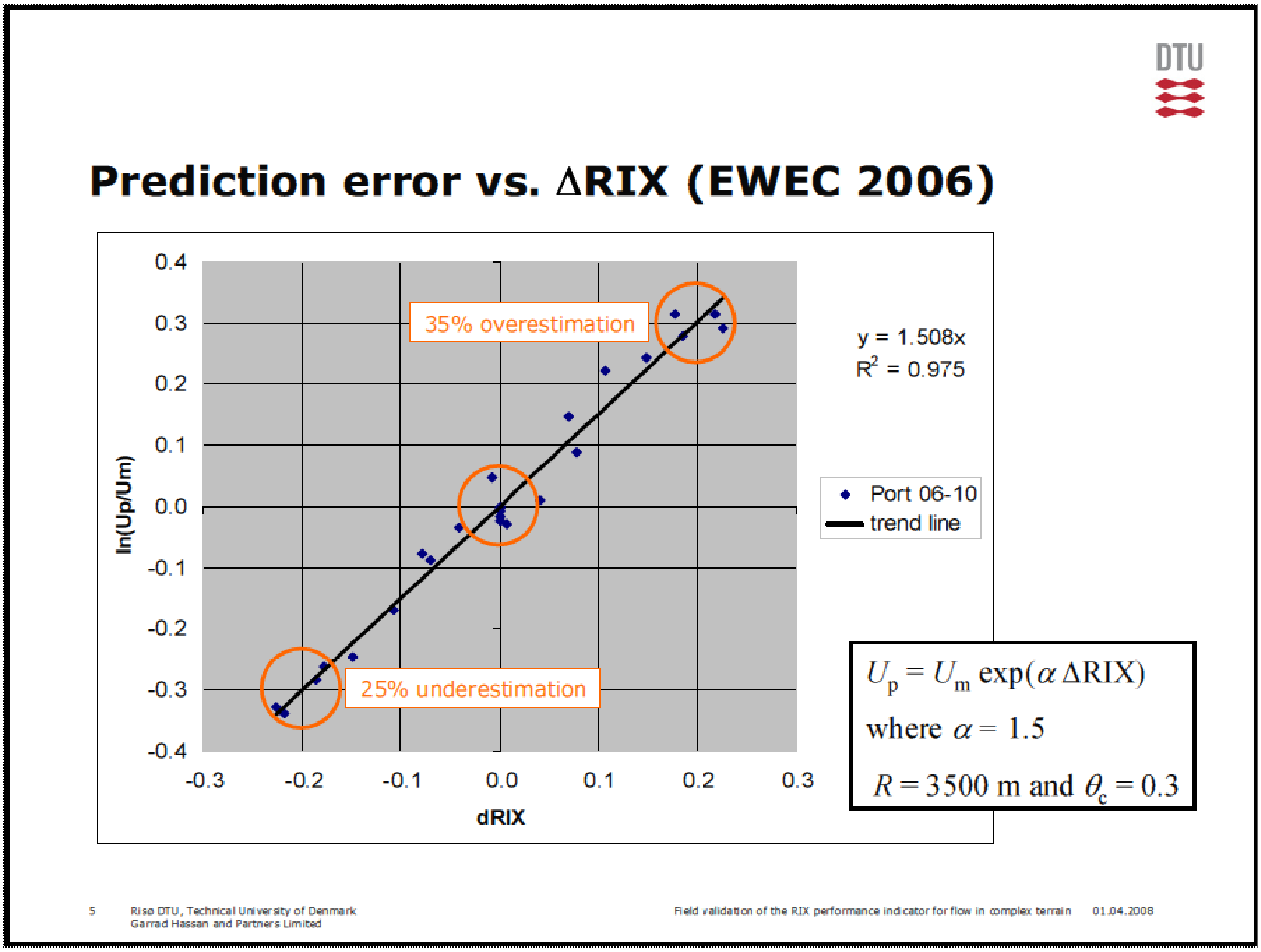


Figure 39 RIX correction EWEC 2006 results

The main conclusion, based on the use of the RIX method, is that if both reference site (measurement mast) and predicted site (WTG) are equally rugged (Delta RIX < 5%), very small calculation errors are expected.

If the reference site (measurement mast) is very rugged (e.g., RIX = 0.2) and the predicted site (WTG) is less rugged (e.g., RIX = 0), Delta RIX will be -0.2 and, according to the graph, a 30% too low wind speed prediction could be expected at WTG site. This could lead to around 60%[1] under-prediction of the calculated energy production.

If the reference site is less rugged (e.g., RIX = 0) and the predicted site (WTG) is very rugged (e.g., RIX = 0.2), Delta RIX will be +0.2, and, according to the graph, a 30% too high wind speed prediction could be expected at WTG site. This could lead to around 60%[1] over-prediction of the calculated energy production.*[1]

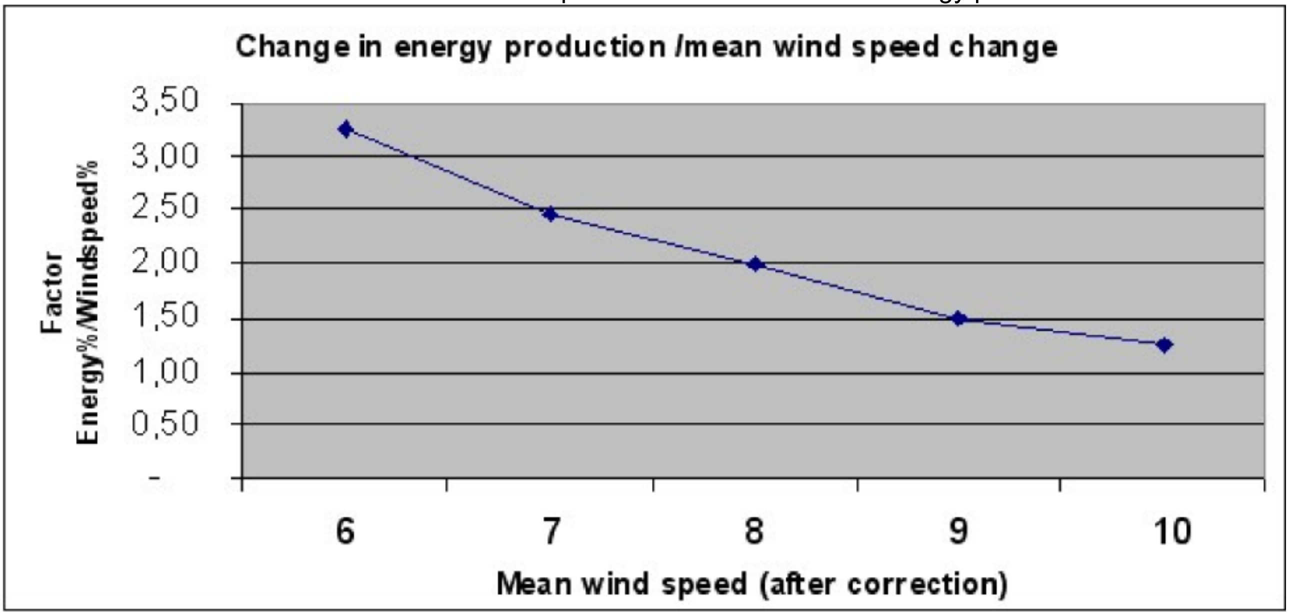


Figure 40 Change in AEP% per change in wind speed %

Source: EWEC06 paper:

IMPROVING WAsP PREDICTIONS IN (TOO) COMPLEX TERRAIN
Niels G. Mortensen[1], Anthony J. Bowen[2] and Ioannis Antoniou[1]
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[2]Mechanical Engineering Department
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Christchurch, New Zealand

[1] Doubling of the energy prediction error based on the mean wind speed error is a rough conversion, which holds for wind speeds around 8 m/s. At 6-7 m/s, tripling the value is more accurate and only 1.5 factors should be used for 9 m/s (see graph above based on a typical WTG).

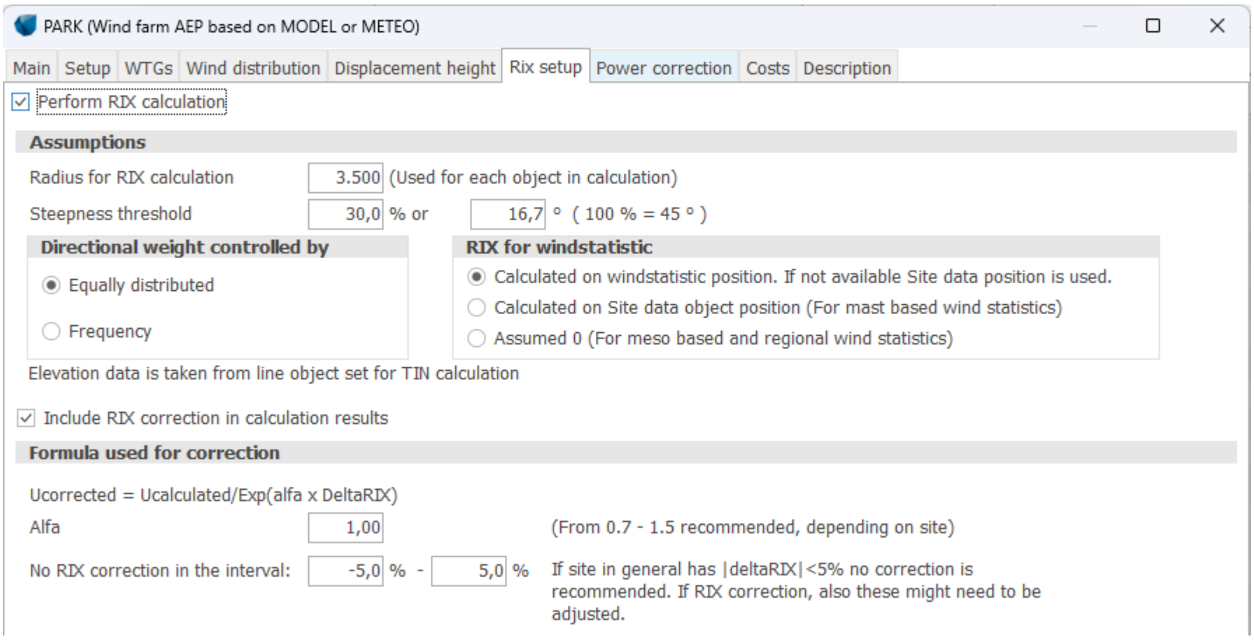


Figure 41 Input data for RIX correction in statistical based calculations.

The form above shows the RIX setup when the traditional wind statistic based PARK calculation is selected.

The Steepness threshold is, in some papers, recommended to start at 30%, while others say at 40%. It depends on the site characteristics. In the Meteo Analyser, it is possible to do experiments, if more masts are available, to judge which method works best. Here, it also can be judged if the RIX correction should be weighted by direction (Frequency) or omnidirectional (Equally distributed).

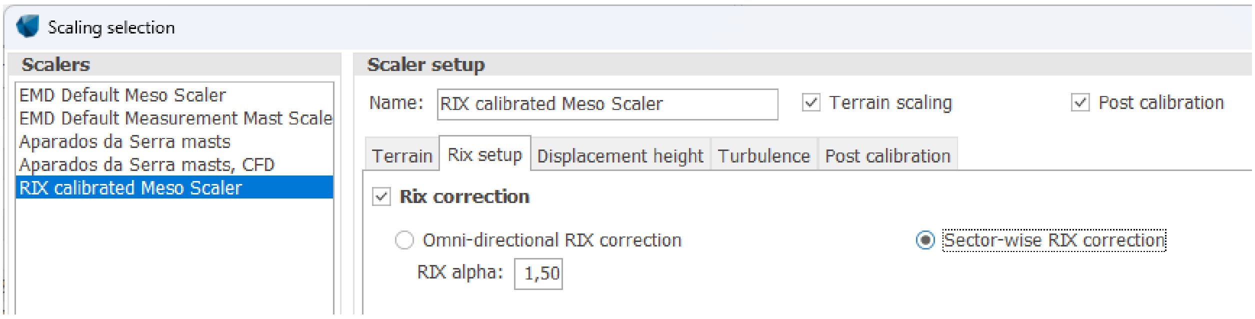


Figure 42 RIX correction input in SCALER

Within the SCALER, a simpler approach is used since the SCALER uses the internal WAsP RIX calculation where the settings are defined within the WAsP parameter file. This does not allow for frequency weighting, but steepness threshold and radius can be set.

In the Result to file output, the RIX correction is included. Note the sector wise **result to file** gives the sector corrections, where the standard result to file just gives the aggregated results.

The RIX report page in the PARK calculation, statistical based, is shown below.

PARK - RIX calculation

Calculation: Std. PARK lt meso data

Assumptions

Radius for calculation	3.500 m
Steepness threshold	30,0 % / 17 °
Directional weight	Frequency distributed
RIX for wind statistic	Calculated on Site data object position (For mast based wind statistics)
Height contours used	
Alfa	1,5 m
No RIX correction for delta RIX in interval	-5,0 % - 5,0 %

Reference sites

Terrain	ITM X(East)	Y(North)	Z [m]	Name of wind distribution	Type	Reference site RIX [%]
A	584.140	923.899	160,0	MEso lt data calibrated at local mast	WAsP (WAsP 11 Version 11.02.0068)	0,5

WTG sites

	Links	ITM X(East)	Y(North)	Z [m]	Reference site RIX [%]	WTG RIX [%]	Delta RIX (WTG site - Reference site) [%]	RIX correction [MWh]
1	A	586.508	924.094	332,3	0,5	2,0	1,5	-24,33
2	A	586.300	924.194	335,0	0,5	1,6	1,1	-29,95
3	A	586.196	924.374	340,0	0,5	1,7	1,2	-31,52
4	A	586.182	923.976	293,4	0,5	1,6	1,1	-23,91
5	A	586.382	923.863	290,9	0,5	1,5	1,0	-11,43

Figure 43 Report output with RIX correction

In the report from a wind statistic based calculation, full RIX correction documentation is available. But note, this is the total. If sector wise correction is used, the result shown is the sum of the sector corrections and, thereby, there can be a RIX correction even if the average delta Rix is within +/-5% and this interval is set to no correction. This is due to the fact that some sectors have a delta Rix outside the +/-5% intervals.
For the Scaler based RIX correction report, only the RIX values for each WTG is shown, while the correction is an integrated part of the model calculation.

3.4.6 Result layer

The result layer offers a presentation of the spatial distribution of calculated wind data, production etc. It even allows for presentation of differences by the Compare feature, where, e.g., a CFD calculation can be compared to a WAsP calculation by ratio or difference or a formula. This gives unique options for checking different models against each other – or the same model with different data assumptions. The use of the result layer is described as part of the BASIS chapter.

3.4.7 Performance Check module

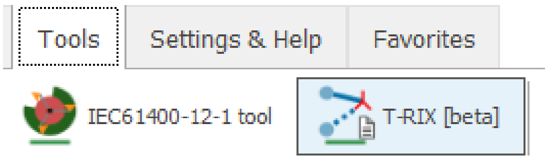
The performance check module is an important module for calibration of the SCALER. Having turbine production monthly, hourly or 10 min. based, gives unique possibilities to calibrate the wind data so the calculated production, time step by time step, matches the measured production (filtered for downtime), and thereby establishing a wind data time series reflecting the “real wind” at the site. Also, having turbine production data for more or many turbines at a site makes it possible to calibrate/test wake model settings, roughness, forest model, Rix correction, power curve corrections etc.

The unique thing about using turbine production for model and data calibration is that there, typically, are many more calibration points than having measurement masts, and the transformation from wind to power can be included in the calibration.

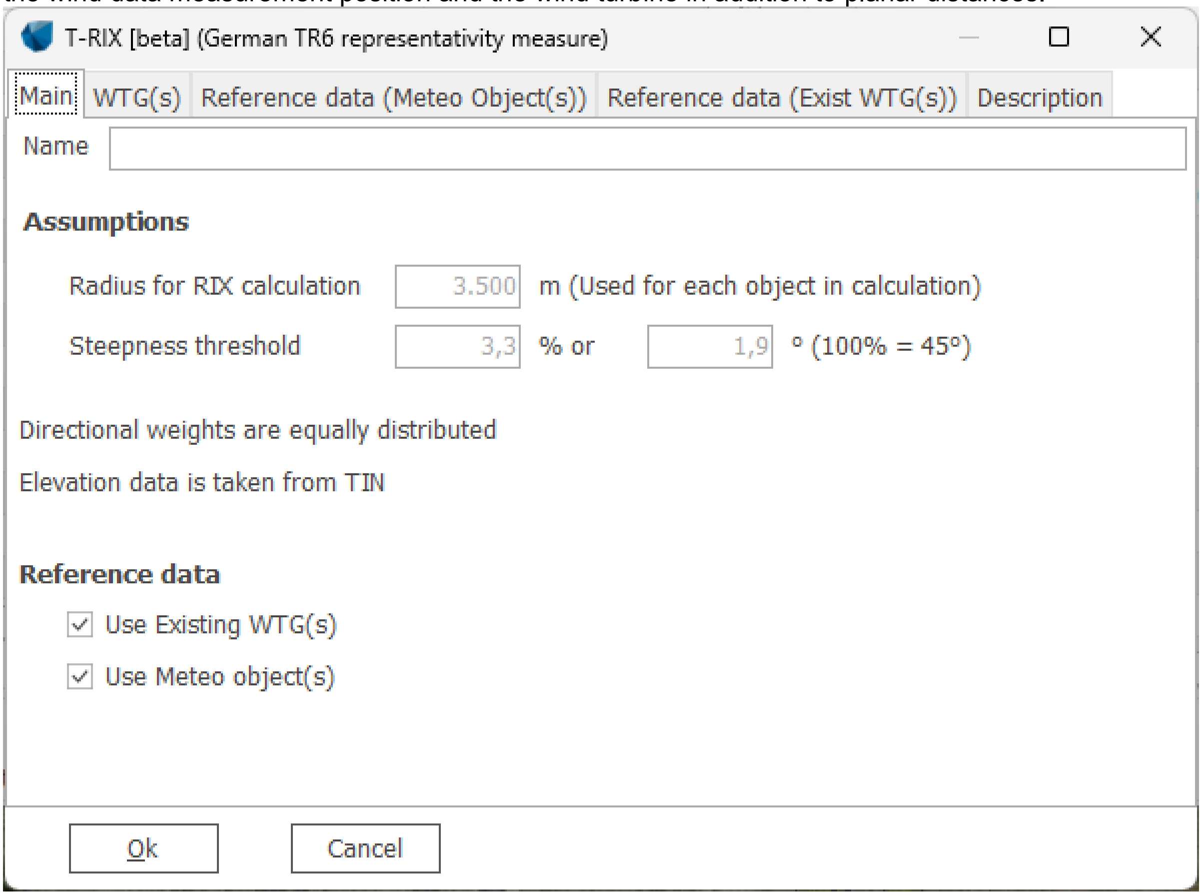
The Performance Check module is described in a separate chapter (11), where the interaction with the PARK calculation also is described (11.9).

3.4.8 T-RIX tool

From windPRO 4.0 it is possible to run a terrain complexity check according to the German Technishe Rechtlinie 6 (TR6) revision 12. The tool can be found in the Tools tab:



T-RIX is the representativity measure for the Technische Richtlinie 6, a German guideline, that standardizes the parameter settings for the RIX calculations. For the RIX calculation it provides parameter settings for the radius, critical slope, number of radii (wind sectors), the spatial resolutions (horizontal and vertical) for the digital elevation model and the contour line interval. Since RIX values are affected by the chosen parameter values, the standardized approach allows for a better comparison and correction of RIX values. It also guides with the choice of parameters. In addition to the standard RIX calculation, T-RIX considers the height distance between the wind data measurement position and the wind turbine in addition to planar distances.



The method provides two horizontal distance specifications A and B between the wind data measurement position and the wind turbine in kilometers; A specifies the recommended distance (should-criterion) and B specifies the distance that must not be exceeded (must-criterion). Correspondingly, it also specifies a recommended (should-criterion) and maximum vertical distance (must-criterion). Moreover, uncertainty quantification is defined for AEP-predictions for horizontal and vertical distances between the should and the must criteria.

It is possible to calculate the complexity check using New WTGs and Existing WTGs and/or Meteo objects.

The T-RIX module produces a main report and a detailed report. The main report lists the input data and parameters, and it can be checked whether the input data and parameters are coherent with the TR6 guidelines. The detailed report shows the T-RIX values per WTG, distances A and B, and lastly the quantified uncertainties obtained using the T-RIX specifications. Finally, the complete report can be exported to a text file or saved to clipboard via Result to File.

3.4.9 MCP (Measure-Correlate- Predict) - Long term correction module

MCP is an advanced module that enable users to calculate long-term corrected wind data in windPRO.

The MCP module can be found in the top Ribbon under **Climate** tab:

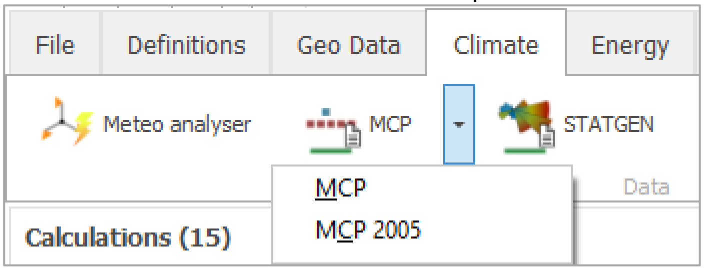


Figure 44 Start MCP calculation.

Starting with windPRO 3.2 a fully new MCP module is available. This will coexist with the former MCP module, now renamed to MCP2005, from its release year 2005.
The manual focuses on the MCP module, the previous version being described in Appendix: MCP2005.

In general wind measurements are undertaken for a limited period of time, which may represent a different wind speed level compared to the long term expectations. If these short term measurements are further used in an AEP calculation, the energy estimates may result in errors or may not be regarded as long term representative. The purpose of the MCP module is to provide the tools and methods necessary to calculate the potential long-term wind climate at the site.

The MCP module consists of the following methods:

- Simple Mean Wind Speed Scaling
- Linear Regression
- Matrix
- Neural Network
- Solver based (for Scaler)
- Scaling Local

The documentation for the different MCP methods can be found in the MCP Reference Document as well as in section: 3.4.13 Models used by MCP.

In addition, several features are available for conducting an evaluation: of the long term datasets to be used, the adequate long term period, and adjustments to be applied on the datasets involved in the MCP process. Some of these tools are briefly introduced below, while a comprehensive description is available Chapter 7 of MCP Facilities in windPRO.

- **Evaluate reference:** Alternative long term datasets can be compared to a selected long term reference. These datasets can be downloaded within MCP for a 20 years' time frame. In the download process the nearest point to the selected reference is considered. The alternative datasets can be downloaded from several sources, such as: the EMD's comprehensive database ; via METEO object, by using users own sources; or from Performance Check database, where e.g., turbine based indexes can be imported.
  The "**Compare to other references (LT Bias)"** function gives fast and precise answers on how much would the alternative datasets predict higher/lower than the selected reference, where the local data measurement period is used as part of the evaluation.
- **Auto filter time offset:** In the **Adjustments** tab long term datasets can be adjusted for time offset based on best correlation between local and reference time series wind speeds. This tool can be part of the selection process of a long term dataset.
- **Auto Veer:** A feature in the **Adjustments** tab that automatically calculates the veer between the local data and the reference time series. The user can decide to apply this veer correction on any of the two datasets, local or reference.
- **Interpolate reference:** A feature in the **Adjustments** tab. A typical reference has 1-hour resolution, while the local measurements typical has 10-min. By resampling the reference to 10-min (by simple interpolation) the amount of data for training the model increases essentially, and better prediction results can be obtained.
- **Concept Choice:** This tab provides the option to choose between:
  - a classic long-term correction, where the output is a corrected long-term time series or a wind statistic.

- a scaling approach where the output is a short term dataset (local measurements) scaled to be long term representative, but keeping the dynamics and direction distribution of local data.

- Slicing: In the **Model LT** tab a more comprehensive evaluation of the methods performance can be done by giving the user the option to split the dataset into several concurrent sets. These sets will be used for training and testing the models/ methods. Sic different alternative period slicing are available.
- **Uncertainty:** As part of the **Concept Choice** tab, an MCP uncertainty method is available. The uncertainty calculation is based on the Klintø model (Klintø, April 2015), and considers four main parameters as uncertainty contributors: the wind index, the correlation (Pearson factor), the inter-annual variability and the number of concurrent years.
- **Session** concept: In the **Main** tab of the MCP calculation the user has the option to create sessions independent of each other, which allow to combine various long term datasets with the local measurements and various methods. This window allows the user to structure the work and decide on a specific combination of reference data and method to be used for the final evaluation.

3.4.10 MCP

3.4.10.1 Measure

On the **Measure** tab the user will select the input data to be used in the long term correction process.

Figure 45 In the Measure tab the input data is loaded and can be analysed.

In the drop-down menu of **Meteo object and height**, the user will select the local measurement and the long term timeseries to be used in the analysis. As a minimum requirement, the two loaded datasets shall be concurrent for the analysis to happen. In general, one full year of concurrency is recommended between the two datasets.
The local measurements should cover a full year of data while the long term dataset vary in length from 10 to 30 years.

The top table shows details of the two loaded datasets, such as time period used, the time resolution, the mean wind speed for the entire dataset and the mean wind speed during concurrent time between the two datasets.

The time series graph shows the two datasets, by default, as monthly averages.

The colour code seen in the graphs represent the colour coded datasets defined through the text color in the top table.
An overview of the correlation parameters for the concurrent period between the two datasets is presented underneath the time series graph. The correlation figures are calculated on the averaged datasets, as indicated in the averaging cell underneath the time series graph.

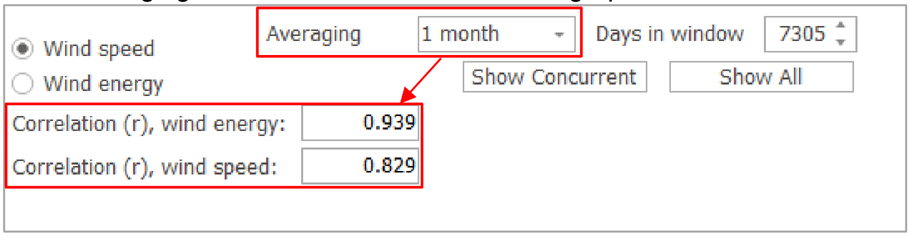


Figure 46 Correlation of the two datasets averaged to monthly level.

Note that the correlation will typically be poorer, the higher time resolution. Still, a more realistic correlation is achieved on raw data, the scatter and dynamics of the timeseries being preserved.
The wind energy correlation is calculated using the power curve defined under **Session Setup** tab. If no power curve is defined a standard power curve based on u^2 truncated at 13 m/s is used.

On the right side are shown the wind rose and diurnal profile between the two datasets. These can optionally be set to show e.g., only concurrent data or all data.

The rose view shows parameters such as: Wind direction frequency, Mean wind speed or the Wind energy distribution.
The number of sectors can be adjusted in steps up to 36 sectors or to a maximum of 360 sectors. By default, 12 sectors are shown.

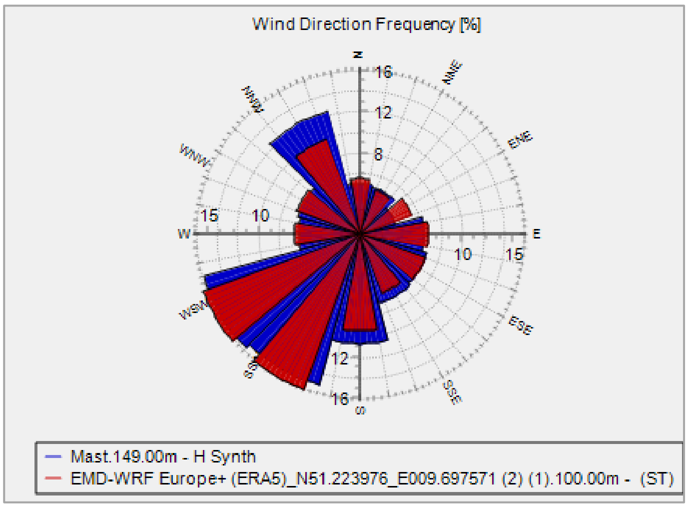


Figure 47 Wind direction frequency distribution on concurrent data between local measurements (blue) and concurrent long term reference (red).

Figure 47 gives a good overview of the concurrency between the two datasets during concurrent period. It is also a visual indication for possible directional bias. Any bias can be corrected in the **Adjustments** tab.

Reference ST/LT shows the rose between the long term reference dataset and the short term reference dataset (concurrent with local measurements).

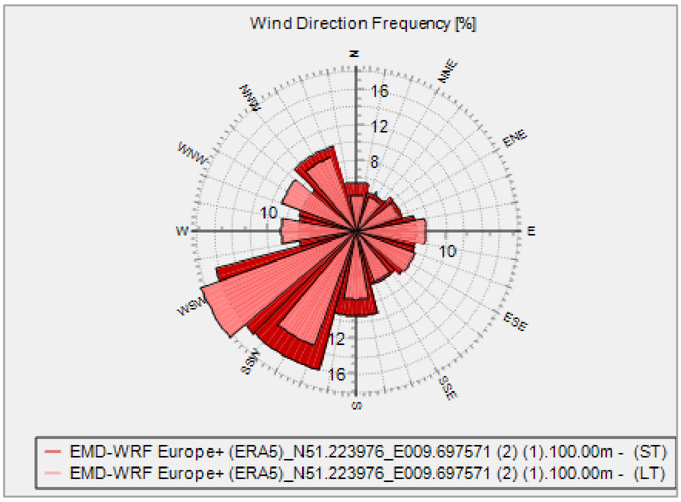


Figure 48 Frequency distribution between the long term dataset (pink) and the long term dataset during concurrent time with local data (red).

Figure above indicates if the wind direction observed during the measurement year is the same as the long term observed wind direction. The data from the same time series is compared during different time periods, the measurement period, and long term one. If the distributions match it can be concluded that the wind direction during measurement period is long term representative. This analysis indicates whether the wind direction should be corrected and is relevant in the selection of the long term method.

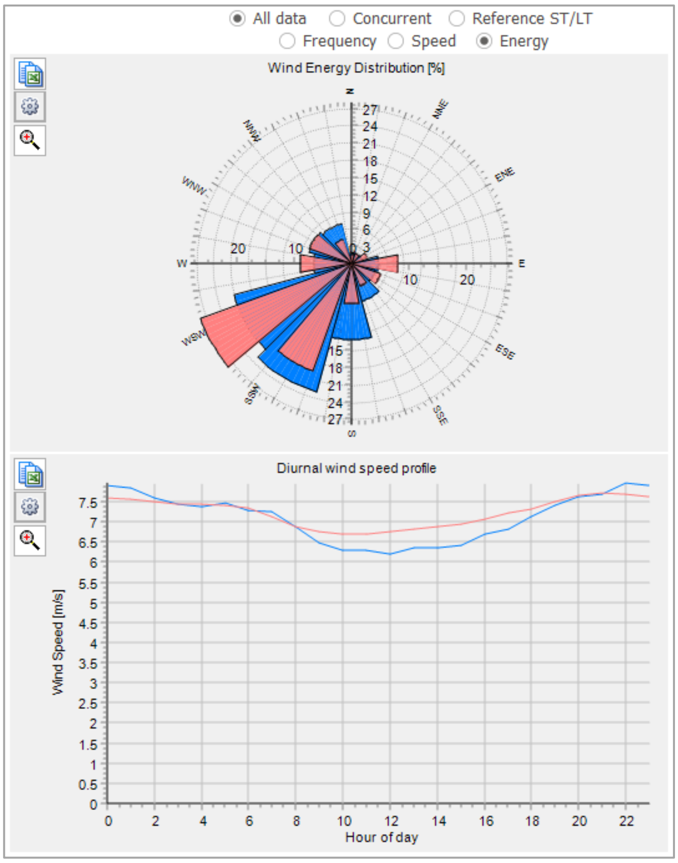


Figure 49 Wind energy distribution between local measurement and long term reference data (top) and the diurnal wind speed profile between the local measurements and long term reference data (bottom).

Showing the short term vs. long term wind energy distribution can tell if the period with local measurements is long term representative. In the diurnal graph example, the short term mean wind speed (blue) shows a stronger variation day/night compared to the long term data.
These comparisons are relevant in the process of selecting a long term correction method.

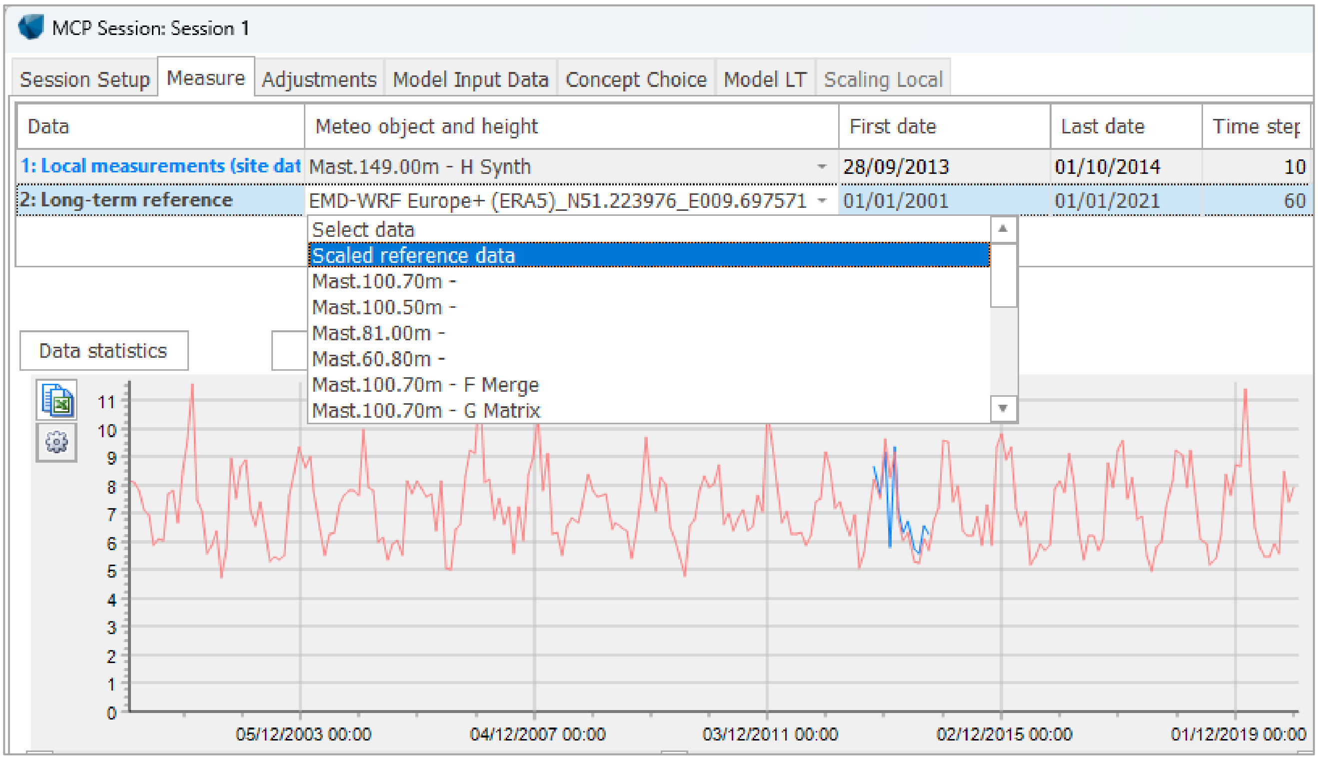
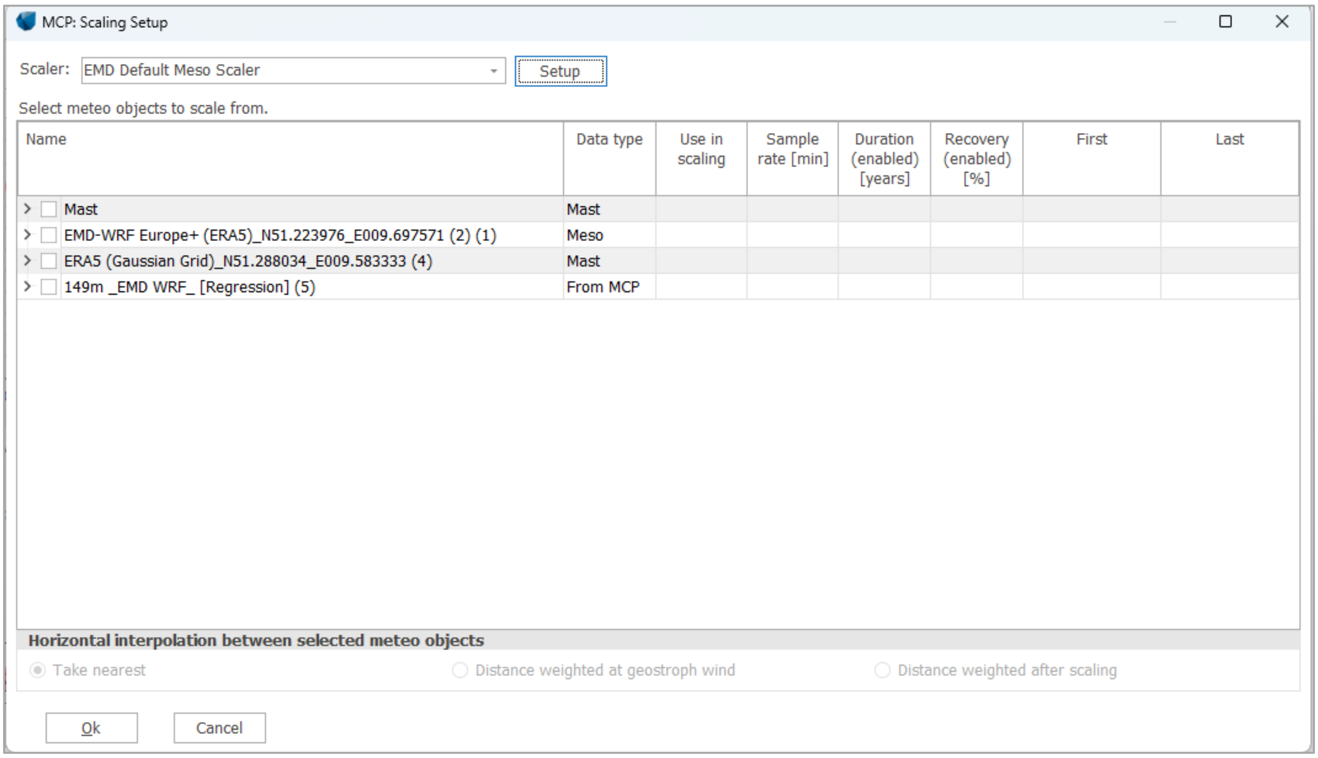


Figure 50 Scaled reference data available for creating reference data from more model points.

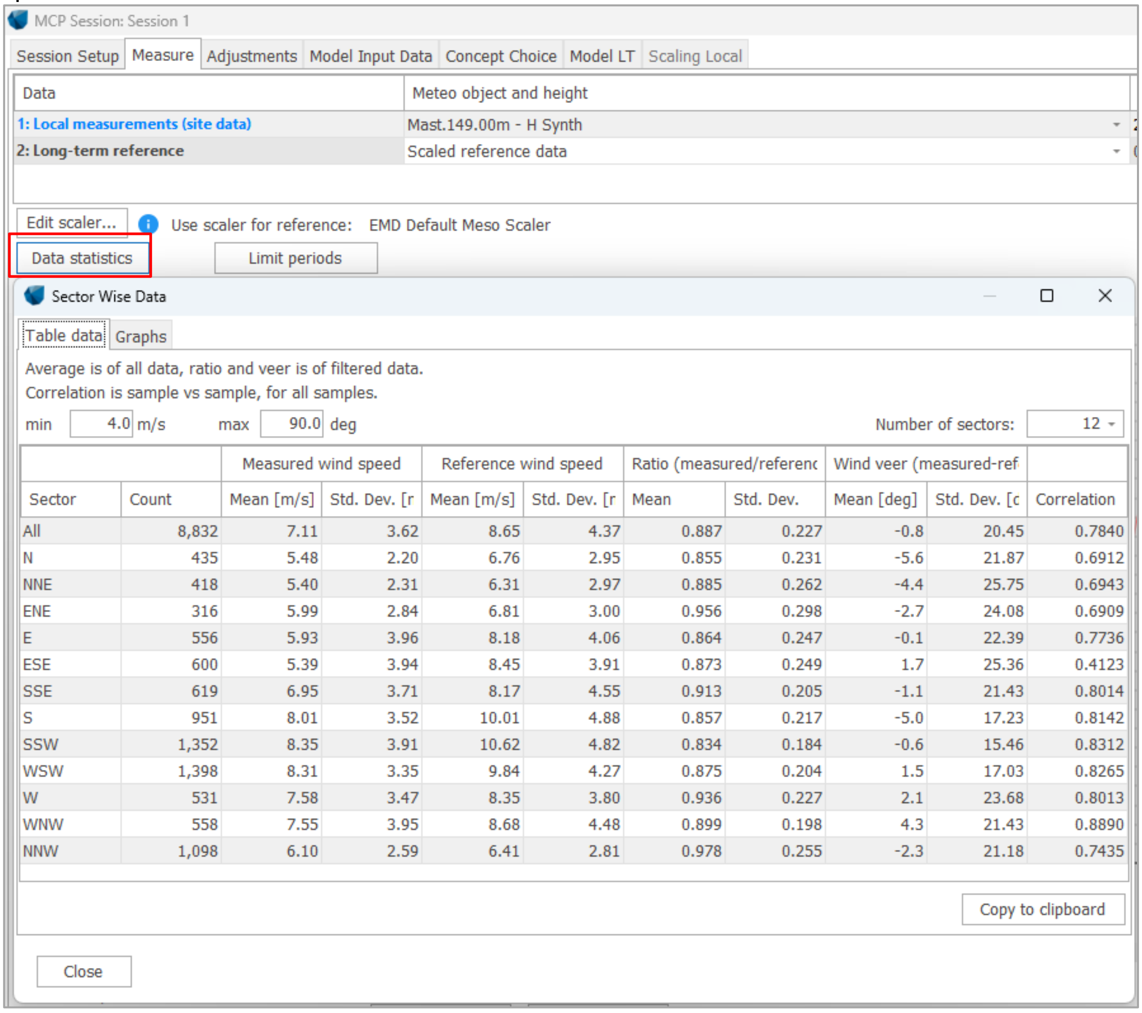
In the **Long term reference** dropdown menu the user has the option to scale a reference dataset, by selecting **Scaled reference data**.



Scaling the reference data is an option, meaning that more reference datasets can be merged within MCP. This can as well be used for downscaling more mesoscale points to the local mast position, as to average more model data points. Or, if having more long-term reference masts near the site these can be scaled to local mast position and averaged by distance weight. **Note:** If several reanalysis datapoints selected at some distance to the site, are to be used as distance averaged points by the Scaler, then the scaler should be setup without terrain scaling. To preform terrain scaling a terrain model should be available in the dataset, and this is available only for the mesoscale data.

By downscaling the mesoscale dataset to micro terrain level, it is expected to get closer to the level of the local mast data as both are represented by the micro terrain effects. Thereby there will be better conditions for the MCP models to give a more accurate prediction. More details on the Scaler are available in section: 3.4.2 SCALER - downscaling/post scaling/interpolation.

Data statistics button shows statistical information, sectors wise, for each of the two datasets, local measurements and long-term reference. On the first tab, **Table data,** the sector wise correlation is presented together with information on the sector wise mean and standard deviation of the wind speed, the ratio of wind speeds and the wind veer for the selected datasets.



		Measured wind speed		Reference wind speed		Ratio (measured/referenc		Wind veer (measured-ref		
Sector	Count	Mean [m/s]	Std. Dev. [r	Mean [m/s]	Std. Dev. [r	Mean	Std. Dev.	Mean [deg]	Std. Dev. [c	Correlation
All	8,832	7.11	3.62	8.65	4.37	0.887	0.227	-0.8	20.45	0.7840
N	435	5.48	2.20	6.76	2.95	0.855	0.231	-5.6	21.87	0.6912
NNE	418	5.40	2.31	6.31	2.97	0.885	0.262	-4.4	25.75	0.6943
ENE	316	5.99	2.84	6.81	3.00	0.956	0.298	-2.7	24.08	0.6909
E	556	5.93	3.96	8.18	4.06	0.864	0.247	-0.1	22.39	0.7736
ESE	600	5.39	3.94	8.45	3.91	0.873	0.249	1.7	25.36	0.4123
SSE	619	6.95	3.71	8.17	4.55	0.913	0.205	-1.1	21.43	0.8014
S	951	8.01	3.52	10.01	4.88	0.857	0.217	-5.0	17.23	0.8142
SSW	1,352	8.35	3.91	10.62	4.82	0.834	0.184	-0.6	15.46	0.8312
WSW	1,398	8.31	3.35	9.84	4.27	0.875	0.204	1.5	17.03	0.8265
W	531	7.58	3.47	8.35	3.80	0.936	0.227	2.1	23.68	0.8013
WNW	558	7.55	3.95	8.68	4.48	0.899	0.198	4.3	21.43	0.8890
NNW	1,098	6.10	2.59	6.41	2.81	0.978	0.255	-2.3	21.18	0.7435

Figure 51 Data statistics window.

In the **Graphics** tab all concurrent data are extracted with optional outlier filtering. By default, samples with wind speeds below 4 m/s and wind direction differences above 90 degrees are excluded both in the local and reference dataset.
Sectors are defined by the local direction measurements.
The table is based on concurrent time stamps for the ratios between short and long term, and on all data for the averages of individual datasets.

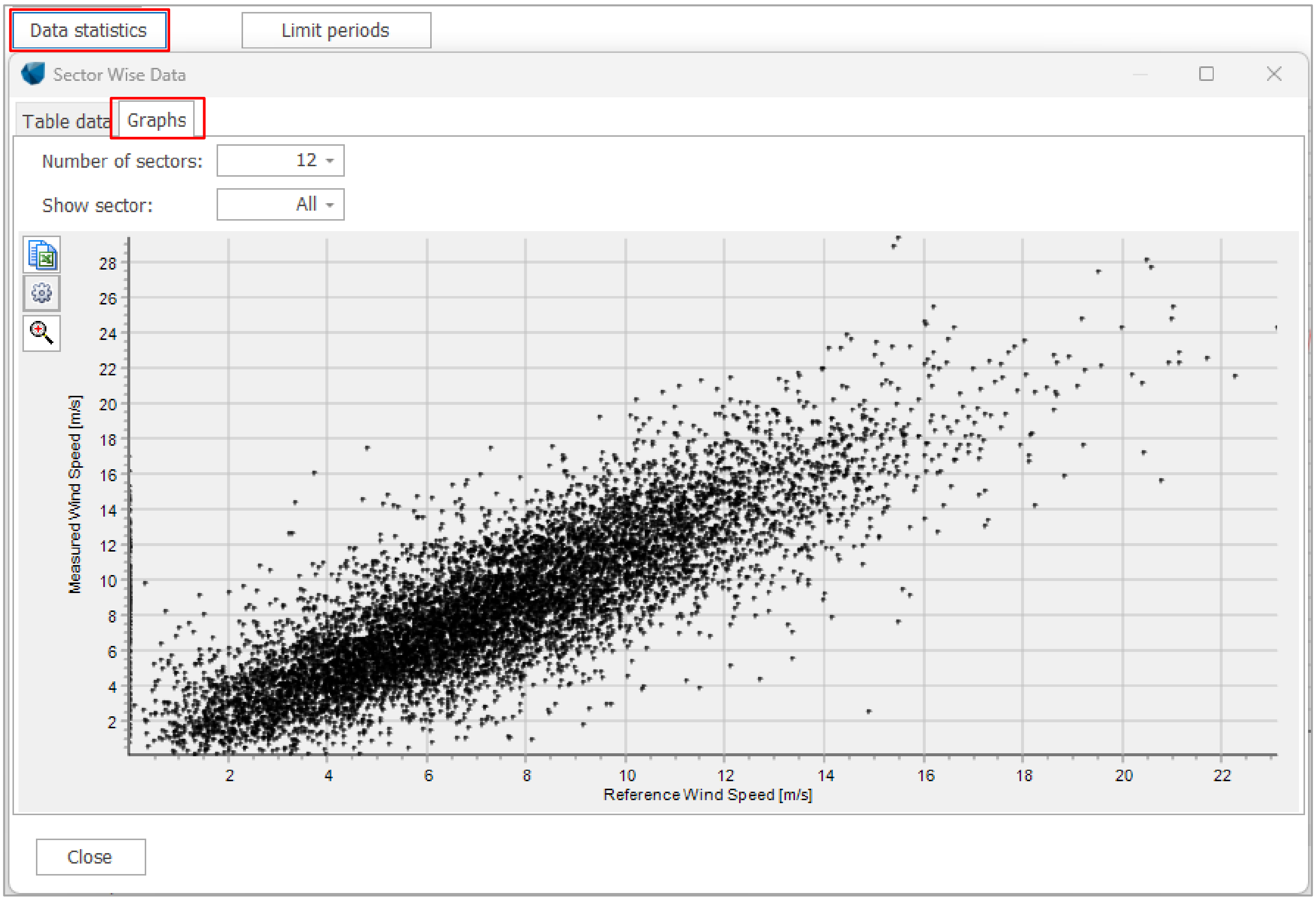


Figure 52 Data statistic graph

The Graph tab provides a visual representation of the mean wind speed relation between short and long term datasets.

Limit periods button allows the user to limit the period used in the analysis on any of the two datasets selected.

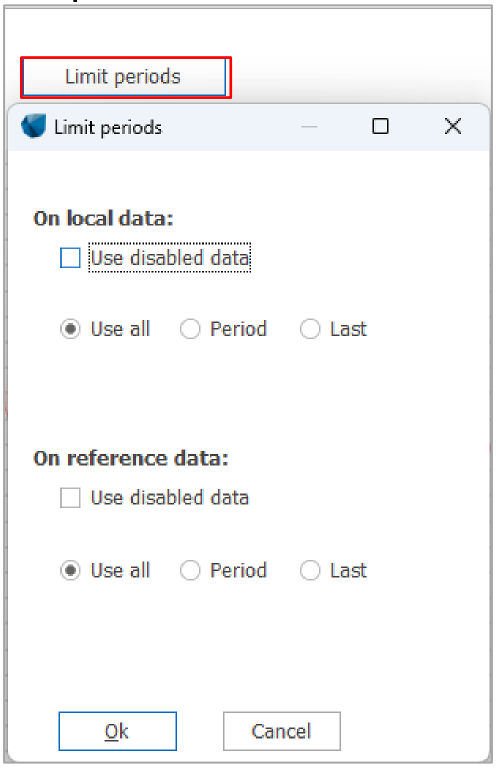
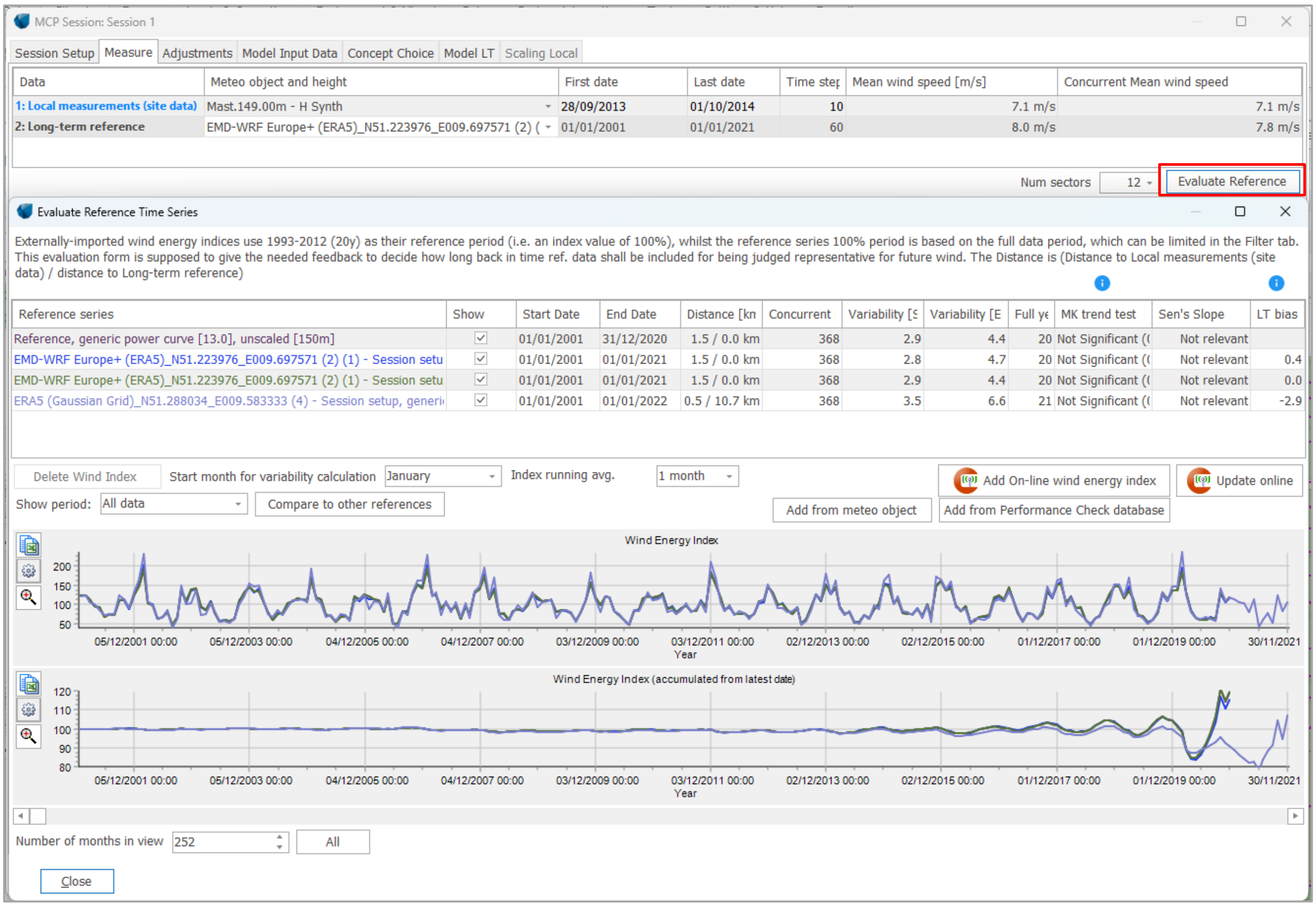


Figure 53 Limit period for local and/or reference data.

Limit period tool is typically used in cases where one of the datasets needs to be limited to a shorter period or for sensitivity analysis situations.
For instance, if the reference dataset seem less trustworthy in the older part of the data, then it might be a better choice just to use the recent 10 years than a longer period of time. In the **Evaluate reference** paragraph is explained how to evaluate such a choice.
Another example could be related to testing using one year of local measurements of the full two years period.

The option “**Use disabled data**” is convenient, if disabling’s performed in the Meteo object were done with other purposes than removing bad data.

Evaluate Reference is a comprehensive part of the MCP process, which can be opened from the **Evaluate reference** button in the **Measure** tab.



Data	Meteo object and height	First date	Last date	Time step	Mean wind speed [m/s]	Concurrent Mean wind speed
1: Local measurements (site data)	Mast.149.00m - H Synth	28/09/2013	01/10/2014	10	7.1 m/s	7.1 m/s
2: Long-term reference	EMD-WRF Europe+ (ERA5)_N51.223976_E009.697571 (2) (	01/01/2001	01/01/2021	60	8.0 m/s	7.8 m/s

Reference series	Show	Start Date	End Date	Distance [km]	Concurrent	Variability [S	Variability [E	Full ye	MK trend test	Sen's Slope	LT bias
Reference, generic power curve [13.0], unscaled [150m]	☑	01/01/2001	31/12/2020	1.5 / 0.0 km	368	2.9	4.4	20	Not Significant (	Not relevant	
EMD-WRF Europe+ (ERA5)_N51.223976_E009.697571 (2) (1) - Session setu	☑	01/01/2001	01/01/2021	1.5 / 0.0 km	368	2.8	4.7	20	Not Significant (	Not relevant	0.4
EMD-WRF Europe+ (ERA5)_N51.223976_E009.697571 (2) (1) - Session setu	☑	01/01/2001	01/01/2021	1.5 / 0.0 km	368	2.9	4.4	20	Not Significant (	Not relevant	0.0
ERA5 (Gaussian Grid)_N51.288034_E009.583333 (4) - Session setup, generi	☑	01/01/2001	01/01/2022	0.5 / 10.7 km	368	3.5	6.6	21	Not Significant (	Not relevant	-2.9

Figure 54 Evaluate reference times series window.

In the Reference series table, the following series are available by default:
Reference, user power curve – session setup. A wind index calculated with the entire reference data series having 100% index in average. Is based on the index calculation setup chosen in **Session setup** tab (see 3.4.10.2 Session setup). Note that this series is visible only after a user power curve is selected in the Session setup window.
Reference, generic power curve – Simple index. As above, but based on the default session setup, with a power curve based on U^2 truncated at 13 m/s. This is the method for the index’s downloaded with the only difference that the downloaded always has 1993-2012 as reference period (100% index).

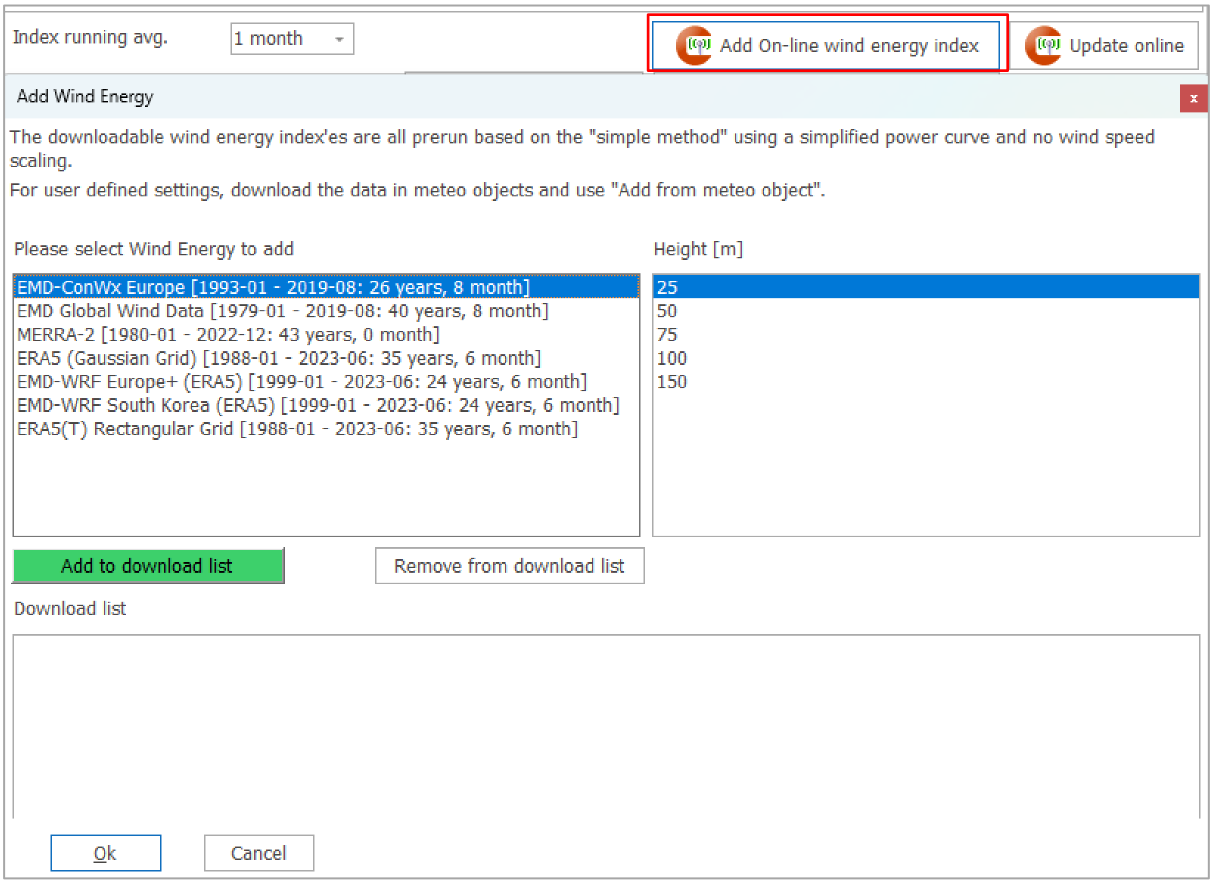


Figure 55 Add on-line wind energy index -downloading alternative reference wind energy indices.

Add On-line wind energy index button, gives the option to download different predefined indices. Depending on the location of your project on the globe, different indices are available, such as EMD Global Wind Data (based on ERA Interim), ERA5 or Merra-2.
A number of mesoscale datasets are available in regions where EMD has pre-run the WRF mesoscale model for a predefined domain.
More information on the pre-run mesoscale datasets and reanalysis data is available here.

NOTE: All indexes have a 1993-2012 (20years) timeline, as long term reference period, giving 100% in average for this period. The timeline was selected in order to have a fixed reference, evaluated by EMD to be long term representative for Northern Europe. It is based on around 40 years' experience with turbine operation data and also validated against very long-term sources like NAO index. However, this period might not be the best reference for other places on earth. For other places in the world, issues like poor data quality or insufficient sources for historical data, could limit the time line to the recent 10 or 15 years as long-term reference.

It is also possible to create own wind energy index based on own settings, like reference period, dataset and power curve. This can be done in the Performance Check module.

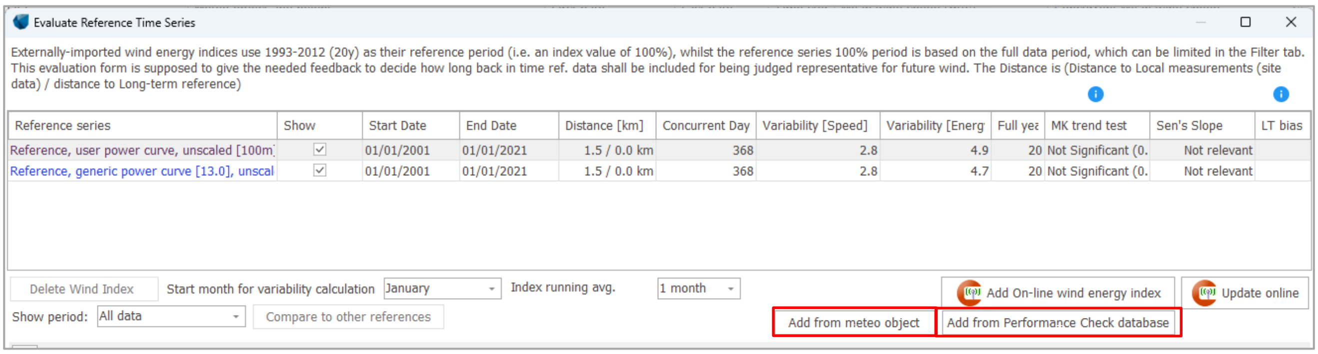


Figure 56 Wind energy indices can be browsed and loaded using different source. Detailed information is provided for each series loaded.

Having created an index database in Performance Check it is possible to browse the database and import the indices.

Add from Meteo object (Figure 56) makes it possible to load a reference dataset which has previously been downloaded in a meteo object. The energy index will use the settings established in the **Session setup** window, namely the power curve choice and wind speed scaling, and will by default treat all data in the meteo object as the reference period (100% index). To reduce the reference period, the data in the meteo object must be disabled.

The **Reference series** (Figure 56) table provides information on the start-end date, the distance to local data point/ and distance to long-term reference, the concurrent number of days between the reference and the local measurements. Several parameters are calculated as follows:

- *Variability* on wind speed and energy is calculated as standard deviation on complete 12 months average. As a curiosity it can be mentioned that this value is sensitive to the start month (which can be user defined), probably related to a certain coupling on high/low wind months around new year.

- *MK trend test (Mann Keldall)* is a quantitative figure that identifies if there is a significant trend in the reference data. The result will approach 1 if perfectly un-trended and 0 if perfectly trended. A trend in the dataset can indicate a climatic event or could appear due to a data artefact. The trend should not necessarily disqualify the data, but rather raise awareness on the suitability of the dataset. A classic example in the ground stations, are the trees growing near a measuring mast used as reference. The impact of the trees during the years would results in a trend making the data unusable.

- *Sen's slope*: It is only calculated if there is a trend. The slope, or linear rate of change and the intercept are calculated.

- LT bias: Show how much an alternative reference will adjust the measurements relative to the selected reference based on wind energy index ratios.

In the bottom of the **Evaluate Reference Time Series** window the wind energy index and the cumulated wind energy index are presented. The wind energy index graph can be shown as running average based on different period lengths. By default, 1 year is used.

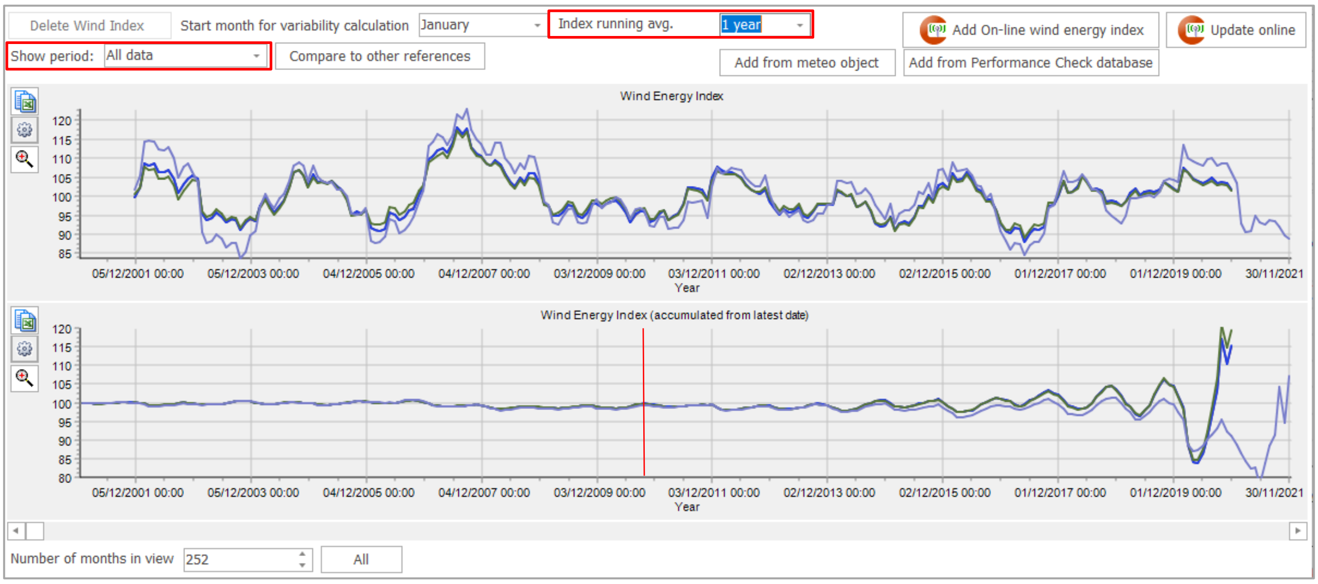


Figure 57 Wind energy index graph (top) and the cumulated wind energy index (bottom).

By increasing the running average to e.g., 5 years the relative drift between different data sources will be easier to spot.

Looking at the accumulated wind energy index graph, for recent 120 months/10y (marked with red line), it shows a rather constant offset between the different sources, all being very close to index 100 accumulating 10y back. This would help conclude that recent 10 y seem a good choice, while these sums up to ~100% and the further back in history discrepancies will be taken out.

One could also consider the e.g. 6 years period as a good long term selection, being the point where all lines cross first at the 100% index, however it should also be considered if the wind direction is long term representative during these recent 6 years. The shorter the period, the higher the risk of not having long term representative direction distribution.
There will later, when predicting, be an adjustment option for the "very long-term wind", in case it is decided to use a period, which do not reach 100%.
The **Show period** dropdown menu (Figure 57) gives the option to show the concurrent datasets. This has an impact on the datasets which have additional months at the end period, as the accumulated analysis starts from the latest date.

Compare to other references function gives an overview on how much would the alternative datasets predict higher/lower than the selected reference, where the local data measurement period is used as part of the evaluation.

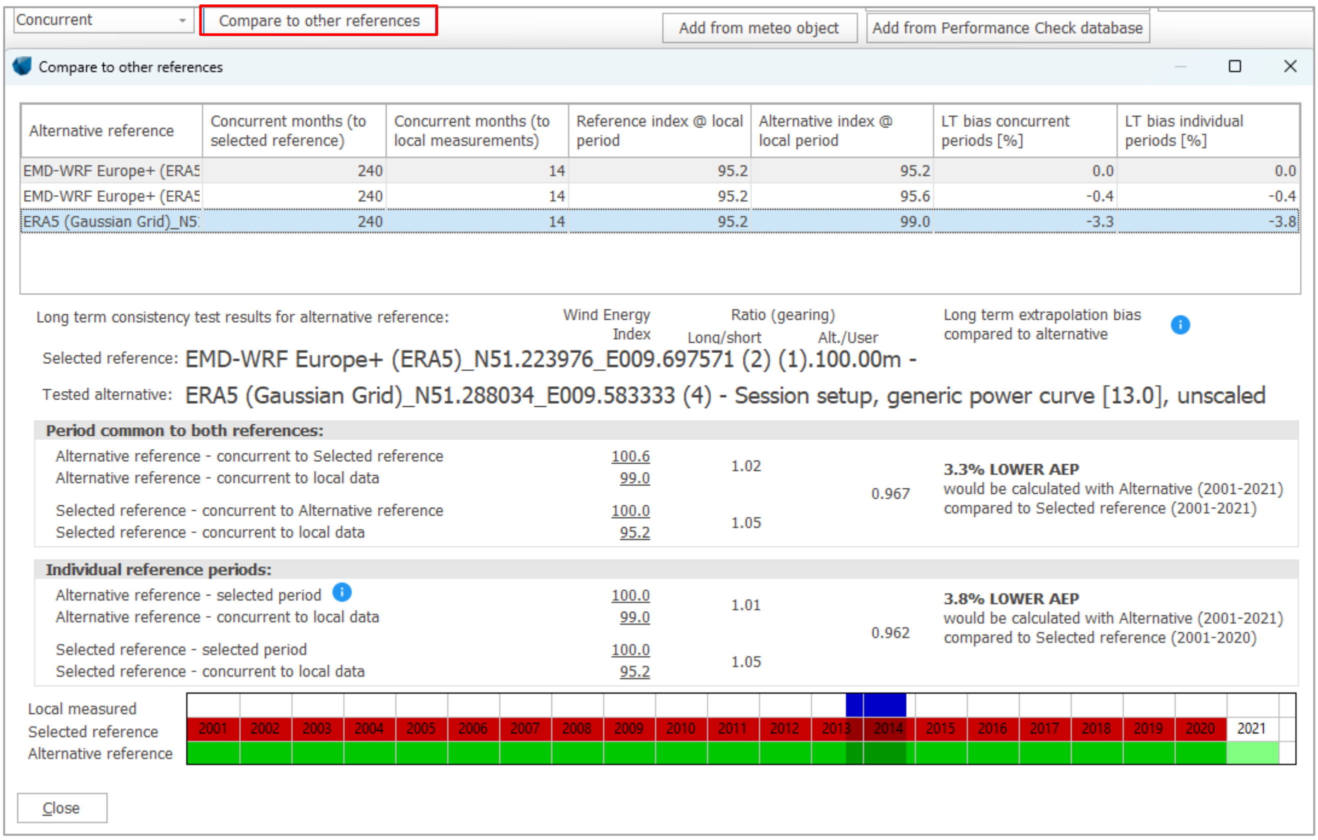


Figure 58 Comparison to other references (LT Bias)

This tool establishes wind energy indexes for the alternative reference and the selected reference.
Then by comparing the index for the local measurement period to long term, it tells how much each reference will gear up/down the local data. The ratios between the gearings tell how different the prediction with alternative datasets is compared to the selected reference.

For each tested alternative reference there are:

1. Common reference periods (upper)

The alternative uses the same reference period in this evaluation as the user selected reference. If the alternative has a shorter period than the selected reference, the evaluation is based on the concurrent reference period.

2. Individual reference periods (lower)

The alternative dataset uses the period it was defined during the selection process, either defined by the user (the reference was added from external sources Figure 56), or a predefined period for the wind energy indices available within windPRO (Figure 55). Note the user can shorten the reference period by using the Limit period feature (Figure 53). This can make sense in countries with poor data quality back in history, that also affects the model data like Merra and ERA. In such regions it thereby often will be recommended to use a shorter reference period.

By mousing over the underlined figures, the periods behind the data used are graphically marked in the coloured table.

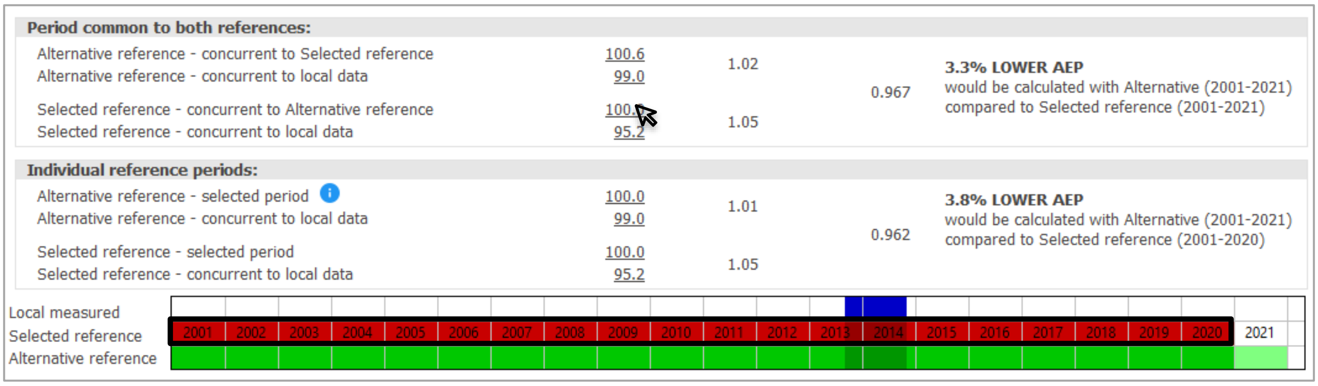


Figure 59 Period used for different alternative and reference datasets.

The text explains what would be calculated by the alternative reference compared to the selected reference.

The decision on the reference source and period to be used is probably the most important choice in an MCP session. The tool will provide the answer, but it offers the above-mentioned tools to support the choice.

3.4.10.2 Session setup

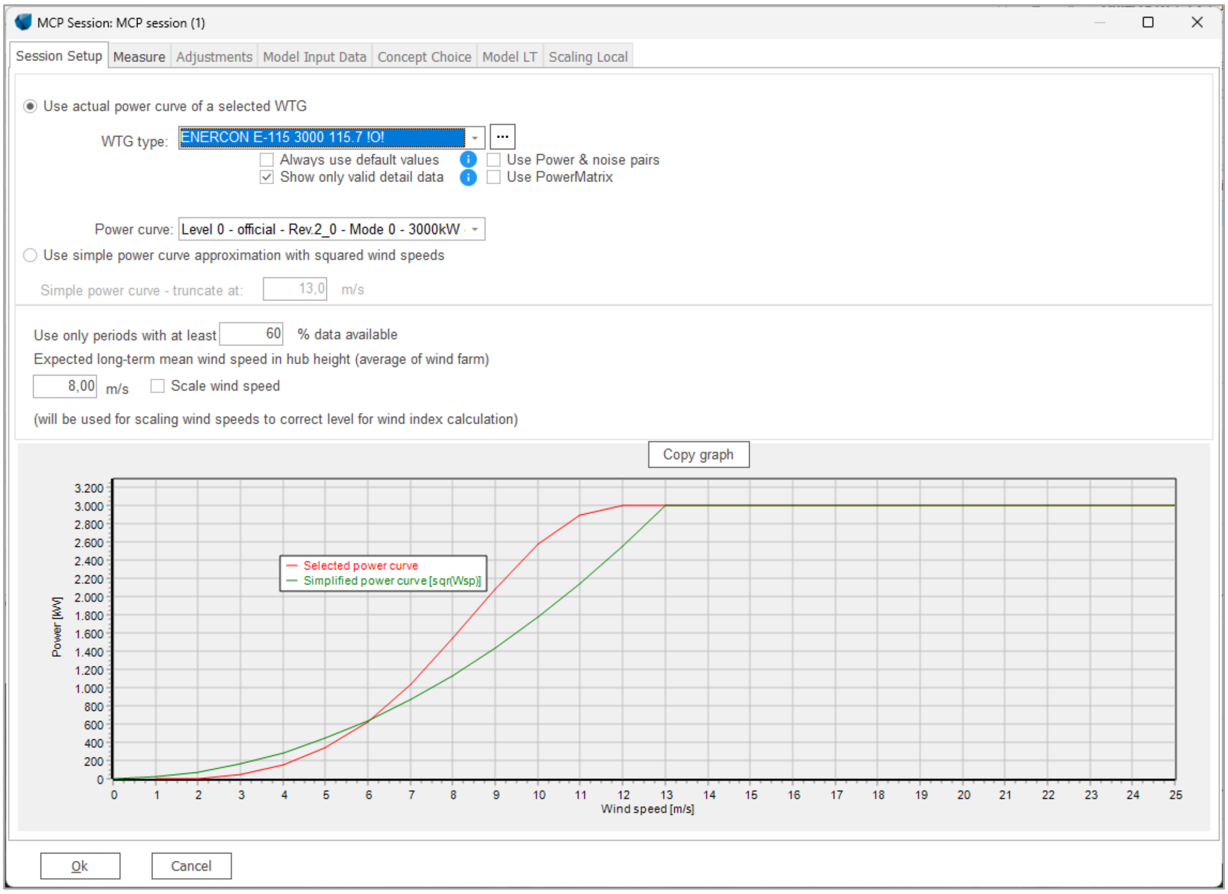


Figure 60 Session setup window. Default setup changed.

In session setup it is decided how wind speeds are converted to energy, in all places in MCP where wind energy is used as measure.

There are two options available:

- *Use actual power curve of a selected WTG*- this option allows you to select a power curve from the turbine catalogue.
- *Use simple power curve approximation with squared wind speeds*. This is also the default setup and uses a simple power curve, established as squared wind speeds, truncated at 13m/s and cut out at 25m/s, to convert the wind speed time series to energy.

In terms of data availability, the default selection uses periods with at least 60% data available to avoid calculating e.g., weekly or monthly wind energy index with too few data.

The *Scale wind speed* option can be used if the local and reference wind speeds differ too much. The reference might be at a level around 5 m/s while the local is around 7 m/s. This will when by looking up in the power curve, create a relative bias between the local and reference, that will make the energy correlation very poor. Scaling both series to same level makes the energy indexes comparable.

Going back to "Measure" will right away update the Energy based evaluations.

3.4.10.3 Adjustments

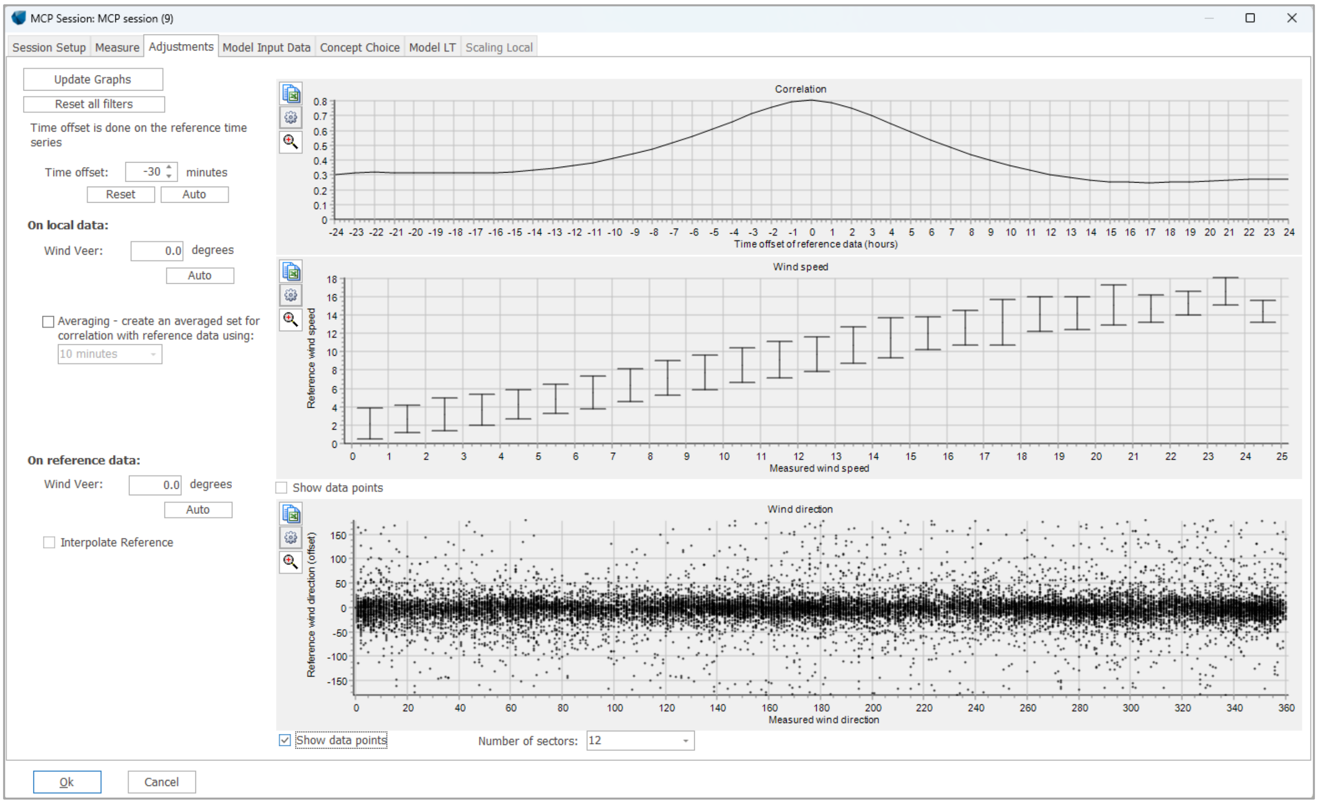


Figure 61 Adjustments available on the loaded time series.

Following adjustments can be set:

- **Time offset** - calculates which time offset gives the best correlation between local time series and long-term data on the wind speeds level. This is tested by running a number of correlation calculations (up to +/- 24 hours). Often the local data has a 10-minute time domain while the reference data comes with an hourly time resolution. An auto detection method solves the challenge of matching the time stamps between the two datasets with different time resolution. This also solves the issue of datasets being in different time zones.

- **Wind Veer:** Calculates the veer between local and reference data for concurrent samples at wind speeds above threshold (min 4 m/s) set in Data statistics (Figure 51). The output is the veer correction which results from the average of all included samples.
  Show data points check box will show the entire amount of data points used to create the whisker plot graph.

There can be several reasons for seeing a veer between the two datasets, such as:

1. poor calibrated wind vane at the local mast. Here the local data should be veered.
2. local turns in wind direction affected by micro terrain effects (steep slopes) not captured by meso/model data. in this case the reference data should be veer corrected. For other reasons it must be judged which to veer. **Note**: Veering will affect the final output!

- **Averaging** - it averages the local data, and it is possible, for instance, to create hourly averaged values based on 10-minute data series. The averaging is a moving average, and it is made on the preceding period up to the time stamp indicated.

- **Interpolate reference** - A typical reference dataset has a minimum time resolution of 1-hour, while the local measurements typical have 10-min time resolution. By resampling the reference timeseries to 10-min (by simple interpolation) the amount of data for training the model increases, and better prediction results can be obtained.

3.4.10.4 **Model input data**

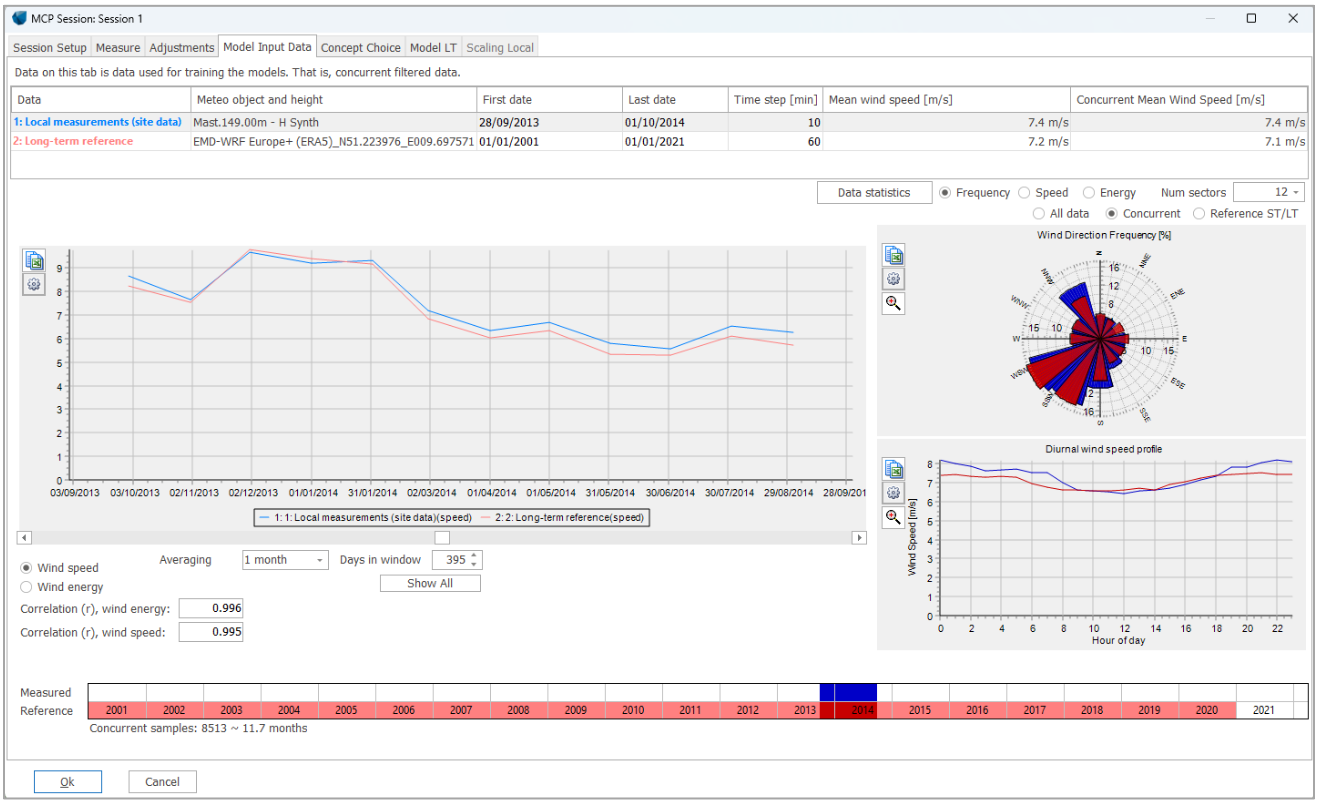


Figure 62 Input data after all applied adjustments.

In the **Model Input data**, the two datasets, local and reference, are presented, this time, considering all adjustments applied by the user in the **Adjustments** tab.
The data to be used by the model(s) can now be inspected. The relations between the two datasets and the features available in this window are similar to the ones in **Measure** tab.
It is recommended to conduct a final inspection on the datasets in this window, before proceeding to the selection of methods for long term correction. Any suspicion or erroneous data, e.g., a week with large deviation between reference and local should be addressed by going back to the Meteo object for a second review in the data screening, or by reconsidering the adjustments applied in previous tabs.

3.4.10.5 Concept choice and uncertainty

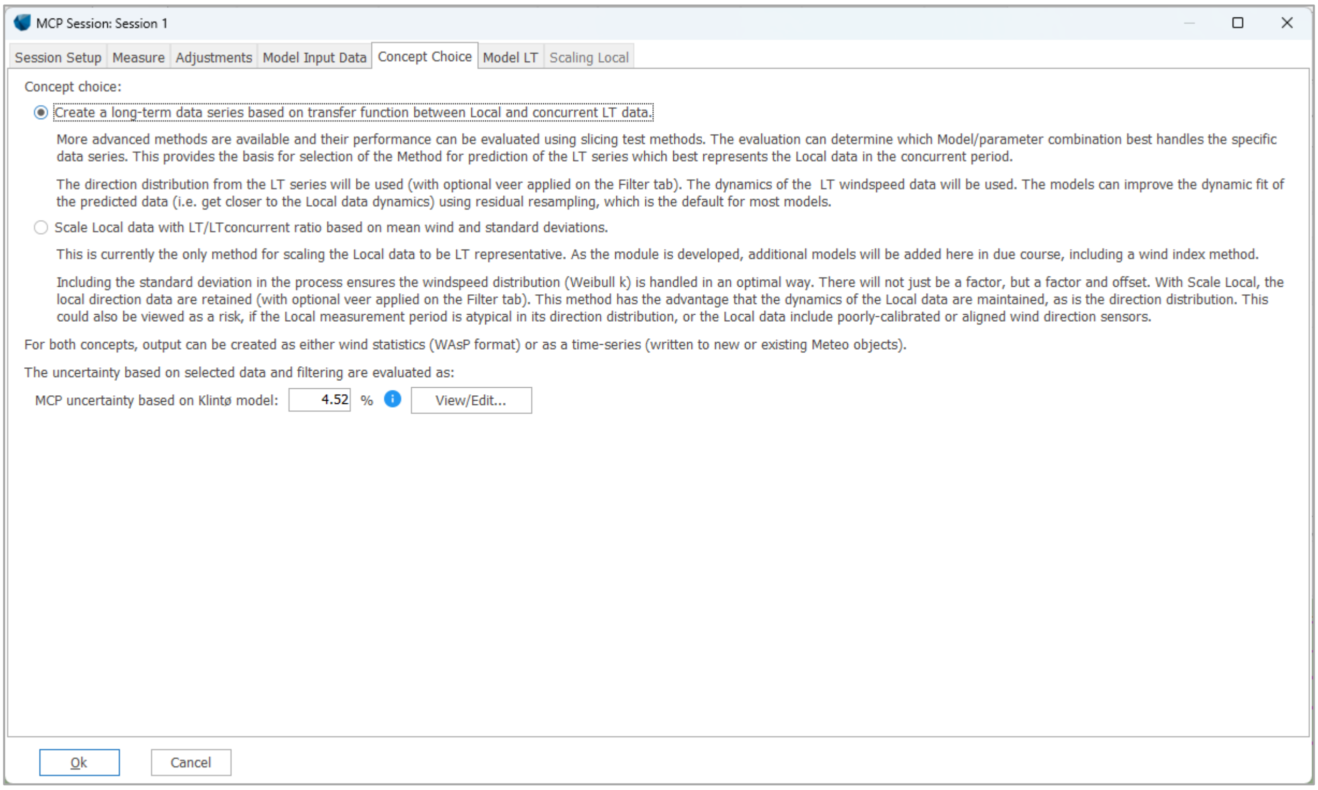


Figure 63 Choice of two different concepts for MCP

As the texts explain, there are two different concepts to choose between:

- Create a long term data series – several methods are available and their performance can be evaluated by using a slicing method. The user will determine which method best handles the specific data series by evaluating the performance of this various methods. The resulted long term time series will have the same length as the reference dataset selected in the **Measure** tab.

- Scale local data to be long term representative – a single method is available which does a scaling based on the ratio of wind speed and standard deviation between the local and reference data. The resulted time series has the length of the local measurements.

More details on each method are provided in 3.4.13 Models used by MCP.

The uncertainty based on selected data and filtering is shown. This is based on the Klintø model (Klintø, April 2015). The model is based on analyses of many datasets, where it is identified which parameters drive the prediction errors, and in which size order. The results of the analyses are then converted to a formula setup, that takes the most important parameters into account and creates an uncertainty figure that match the analyses results.
The parameters considered in the uncertainty evaluation are the wind energy index, the Pearson coefficient (correlation), the inter annual variability and concurrent period. The formula used is presented in Figure 64.

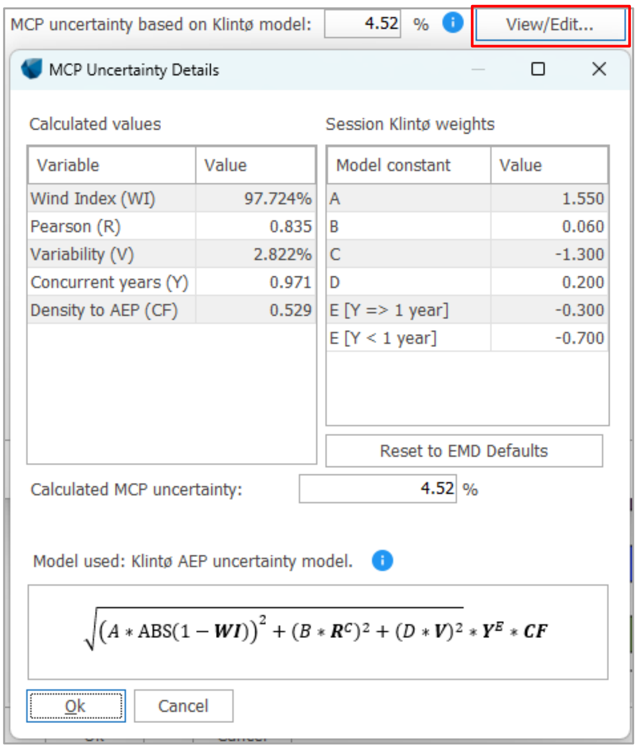


Figure 64 Uncertainty calculation in MCP

It has so far been decided not to bring uncertainty results based on less than 1 year of concurrent data to the reporting. The value is however calculated. But having much less than 1 year of data, it is not considered reliable to give a qualified uncertainty.

The most comprehensive part of the MCP module is the modelling of a long term data series which is being processed in the Model LT and/or Scaling Local tab, presented below:

3.4.10.6 Model LT data – Model Choice

Here the transfer functions between the two concurrent datasets, local and reference, are generated using five main methods, as shown below.

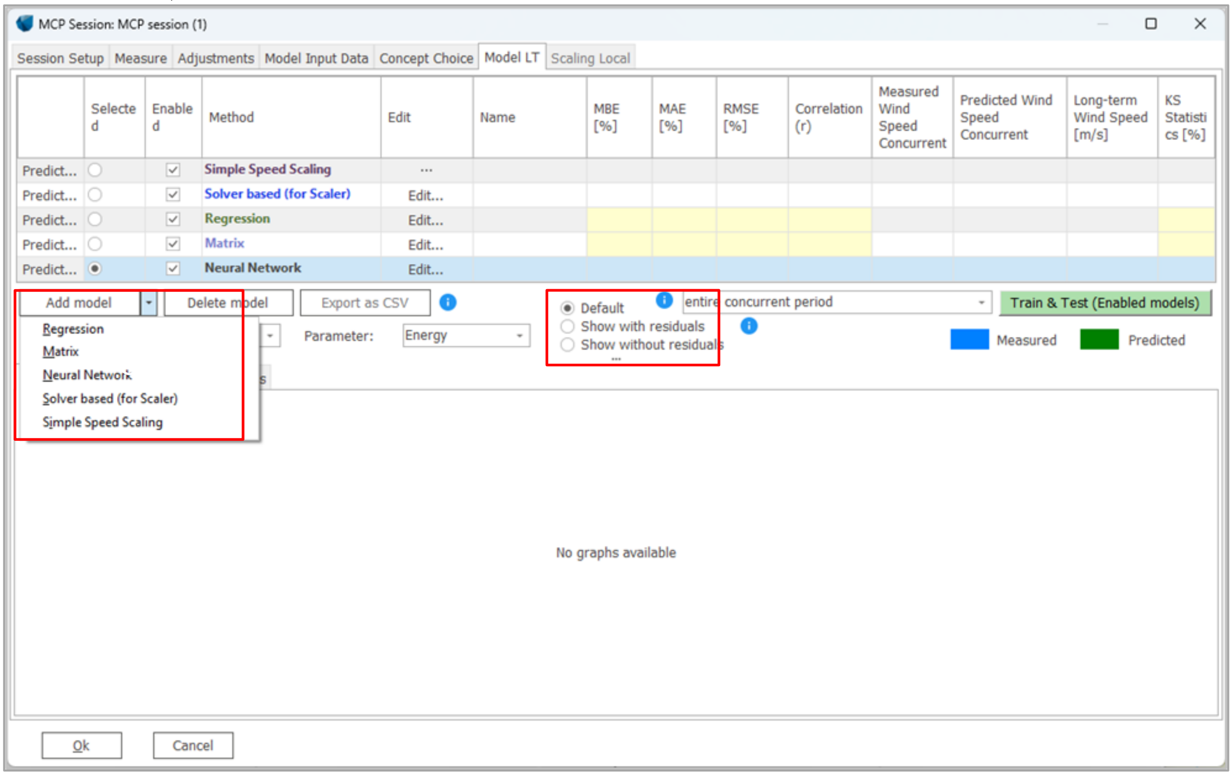


Figure 65 Model LT tab

Five different methods are available:

Simple Speed scaling – it is set as a default method. This simple method calculates the ratio between local measurements and reference mean wind speed during concurrent time. The ratio is further applied on each reference wind speed time step. Only the wind speed is being scaled in the process.

Regression – It is the most common used model through decades. It makes a regression analysis on the concurrent datasets and establishes the regression lines per direction sector. Adjustments are available for this method. Detailed explanations are provided in the model paragraph 3.4.13.2. Both the wind speed and wind direction can be long term corrected in this process.

Matrix – This method models the changes in the wind speed and wind direction through a joint distribution fitted on the wind speed and wind direction bins. Both the wind speed and wind direction can be long term corrected in this process.

Neural network – This model is a machine learning algorithm which trains a neural network to detect a pattern between the local measured and reference wind conditions during concurrent time.

Solver based – This method finds the best scale and offset parameters for each sector, season and diurnal index to be applied on the reference wind speed. The method uses the linear regression to determine these factors. Additionally, the found factors can be further exported to the Scaler and used directly in a Post calibration process.

Features available in the Model LT data:

Train & test model– provides a basis for the user to assess the performance of the four methods, by alternating slicing the time series into several intervals, and checking how well the predicted data matches the observations (measured).
Datasets are divided in concurrent time periods used for training the model and testing it.
For example, if the 5-hr alternating slices is used, the first 5 hours are used for training, next 5 hours for testing, following 5 hours for training and so on. Further it is possible to evaluate how well the model works based on having only half of the data, by looking at the other half. Thereby different models can be intercompared on a fair basis.

The alternating slicing option is selected from the drop-down menu next to the **Train & Test** button.

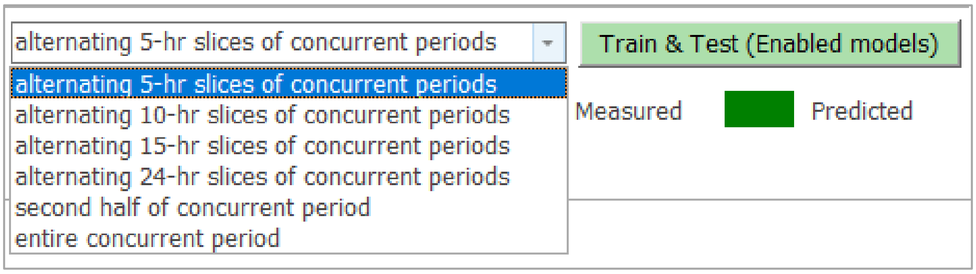


Figure 66 Drop down menu with the alternating slicing options and the Tran & Test button.

Note, in the final prediction, after a method is selected and the long term dataset is saved, the entire period is used in training, no matter the alternating slicing selected. The purpose is to give the method the option to train on as much data as possible and ideally result in the best possible trained model.

Residual resampling - is optional for all models, except simple scaling. It can be selected from the radio button marked in Figure 65 Model LT tab.
Residuals add 'noise'to the predicted time series, which gets the wind speed distribution closer to real measurements. But it also reduces the correlation and increases the errors shown in the prediction table. Therefore, a more fair measure for errors and correlations is seen without residuals. *Default* means that residuals are only included in evaluations where these normally improve the results. In section 8.3.1 of the MCP Reference Manual more details are given.

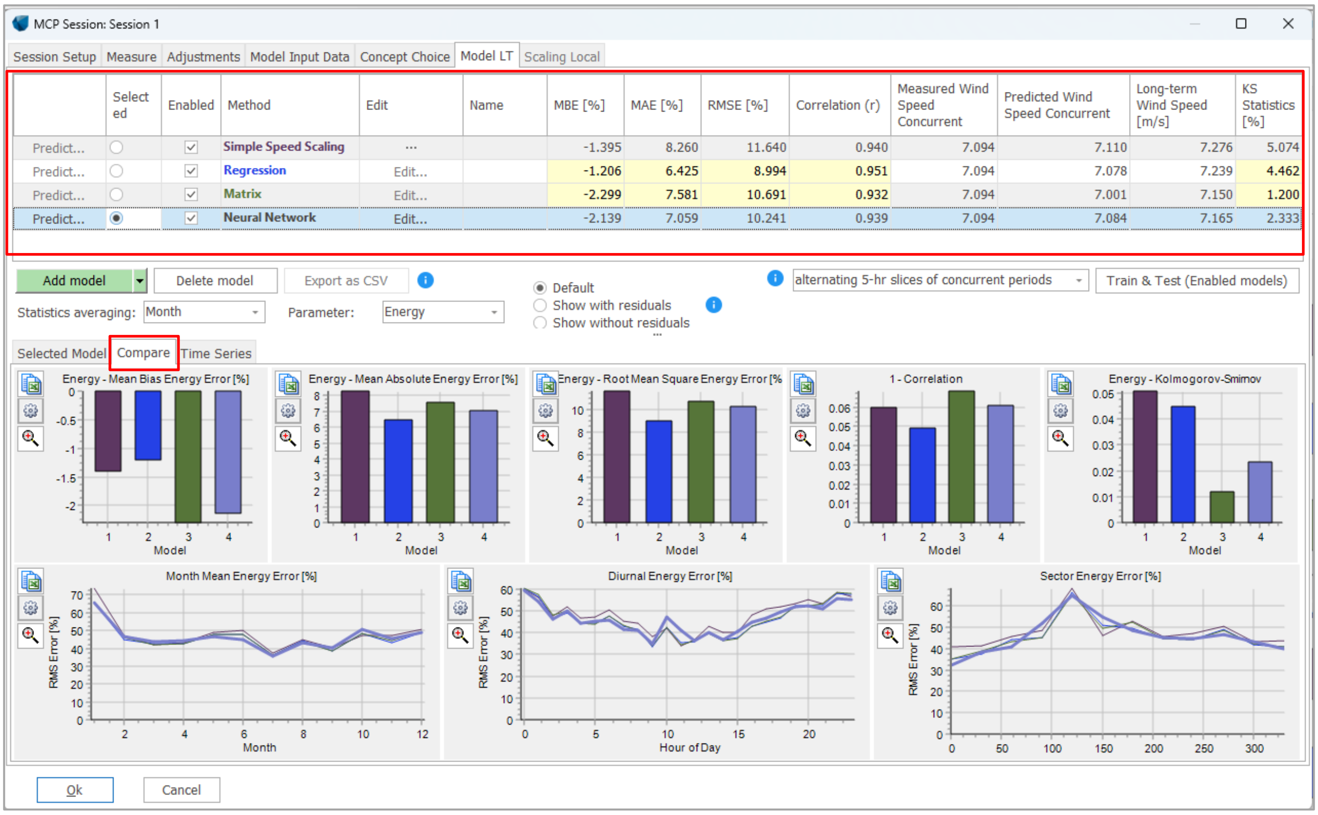


Figure 67 The Compare view in Model LT

Upon running all prediction models with the **Train & Test** button, results are displayed in a table next to the selected model, as well as graphically under the Compare tab. The values in the table can be copied to clipboard from the right-click menu.
The table values and graphs can be shown based on aggregation on different time resolution (hour-day-week-month), and as well on wind speeds or energy. These selections are made from the drop down menu next to **Statistics averaging** and **Parameter.**

The table offers an overview of the performance of different selected methods. The first four parameters: **MBE** (mean bias error), **MAE** (mean absolute error), **RMSE** (root mean square error) and **Correlation**, provide information on how well the wind speed is predicted by the model across the time series and the correlation between the measured and predicted datasets is given.

Measured and **Predicted concurrent wind speed** – These two parameters are not entirely comparable, depending on the slicing method selected. If the slicing test 'Entire concurrent period' is used, than the two are comparable. **Measured Wind Speed Concurrent** represents the mean wind speed of the part of the local measurements concurrent with the long term reference. **The Predicted concurrent wind speed** represents the mean wind speed of the predicted timeseries using a certain method. If any other slicing method is used, the predicted wind speed will only cover half of the dataset, the test period.

Long term wind speed – is the predicted mean wind speed for the entire reference period, corresponding to the trained model applied on the full reference dataset.

KS (Kolmogorov- Smirnov) Statistics – This tests if the two datasets, both measured and predicted, follow the same distribution, and calculates the size of the difference between the two. In MCP it is worth to notice that it is not just the KS-test hypothesis, which finds if the largest error is below a given threshold, but the statistics, where we test the modelled vs measured accumulated distributions and find the largest error. This is reported as the deviation in number of accumulated samples where the deviation is largest, divided with the total number of samples. Thereby it is not just a yes or no, but a value that tell how well the two distributions match.

All parameters mentioned above are further described in section 8 of the MCP Reference Manual.
Compare graphs – it provides a graphical representation of the parameters shown in the table. The color code is defined in the text of each method.
The Correlation graph is shown as (1 – result) to get a better resolution and still have 0 y-value at x-axis. Note that all models are shown with "Default residuals" in figure above. This means all without residuals, except for KS statistics. For all bar graphs: The smaller numerical value the better!

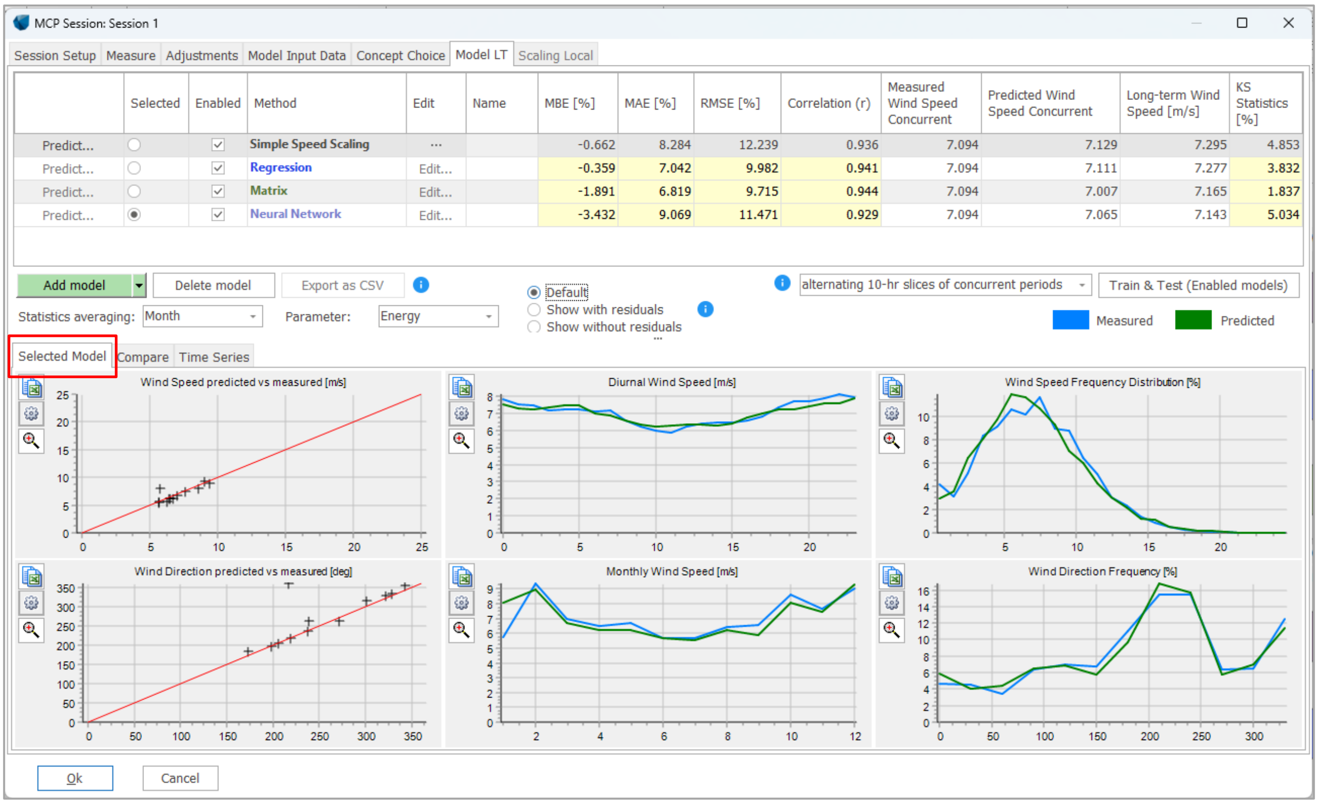


Figure 68 Evaluation of Selected model with residuals

Selected model tab shows a series of graphs with information on the correlation between measured and predicted wind speed and wind directions, as well as the frequency, diurnal and seasonal distributions.

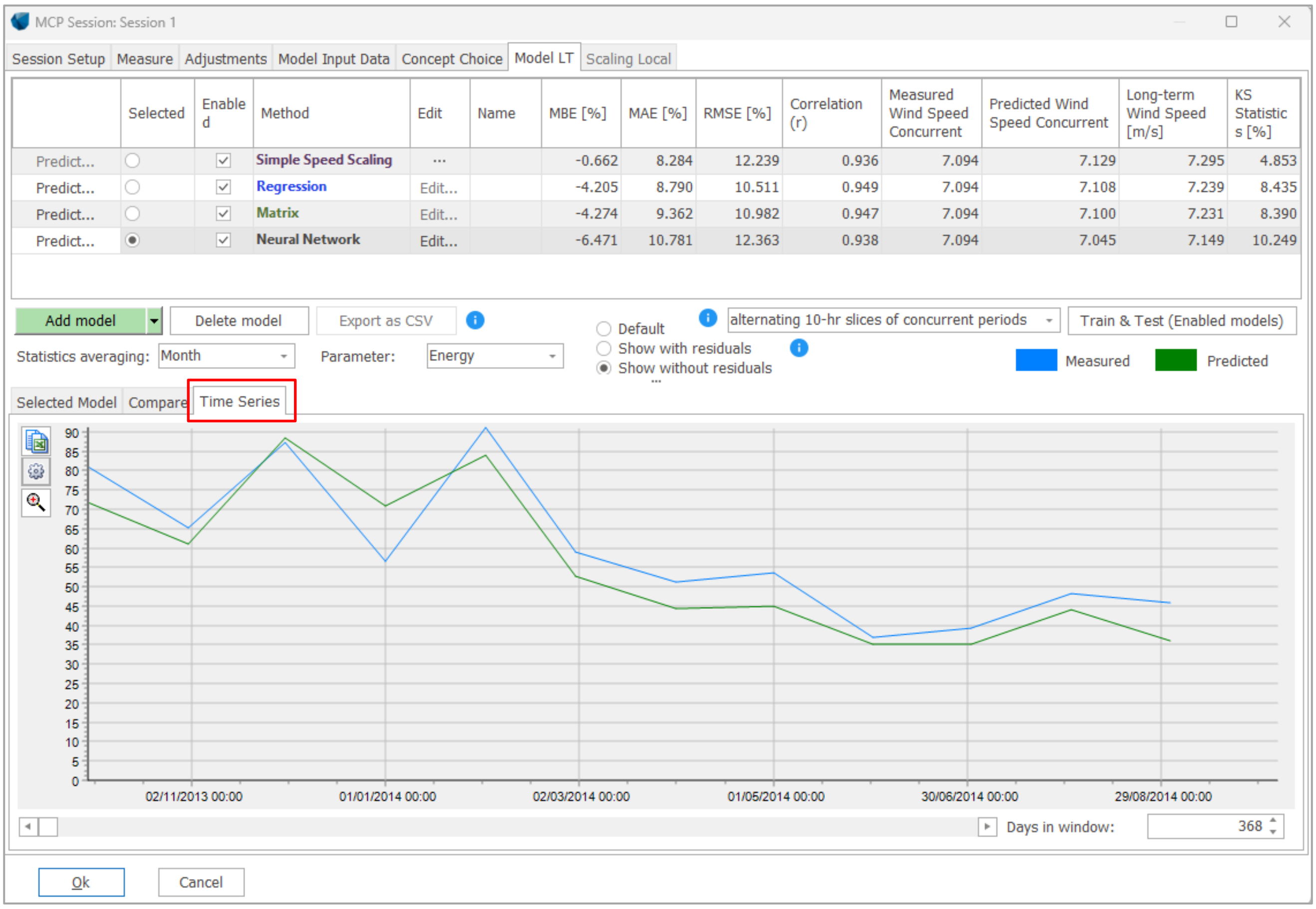


Figure 69 The predicted data shown along with the local measurements.

Time series tab – shows the predicted and measured datasets with different time resolutions, selected from the **Statistics averaging** drop down menu. At this evaluation it is possible to see performance between the two datasets, predicted and measured. If the performance is poor a double check of the measured data and reference data is recommended. In the Meteo object additional cleaning or adjustments can be done.

Predict

Each method has a predict button. The method that performs best should be used for prediction. Click the predict button next to the model.

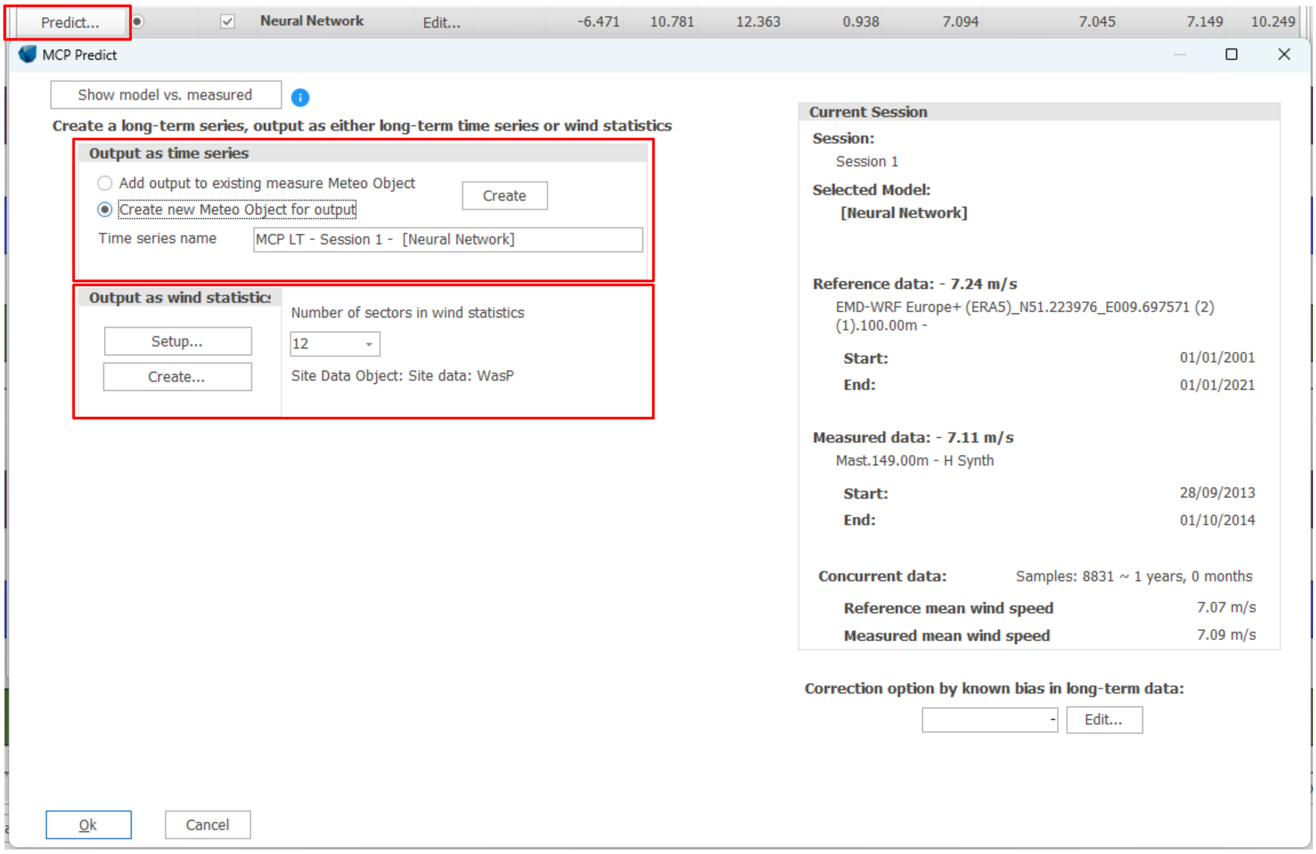


Figure 70 Prediction of long term dataset

On the right part of the form, the used model and data, local measured and long term reference, is shown. In bottom part, it is possible to correct the long-term series if there is a known bias which doesn't make it long term representative.

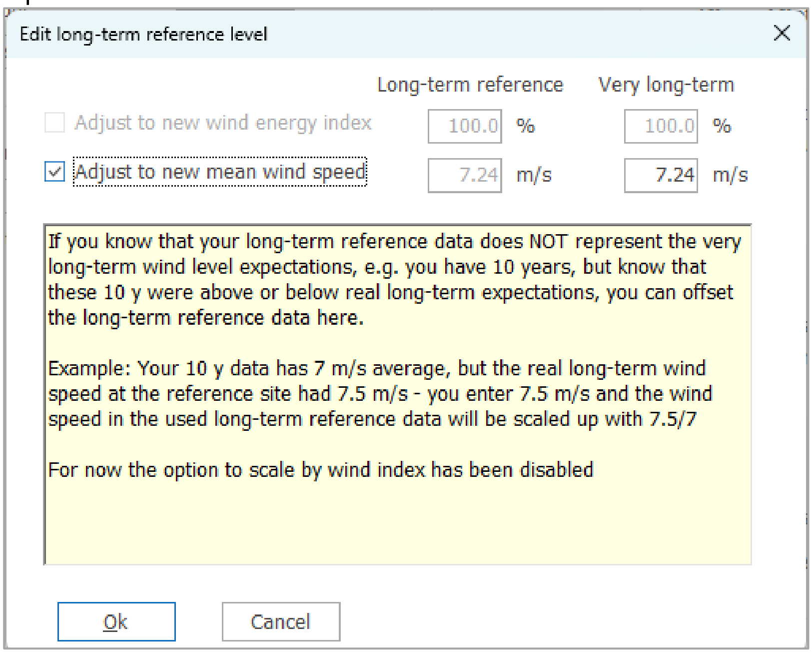


Figure 71 Correction for non long term representative reference

The bias correction can be made on wind speed or wind index by adjusting the mean wind speed.

In the left part of the Predict form, there are two output options:

- Output as time series- The long term corrected data is saves as a time series in a new meteo object or added to an existing meteo object depending on the user selection.

- Output as wind statistic – The long-term corrected data is saved as a wind statistic. To generate a wind statistic, a Site Data Object must be chosen in the Setup button. This holds the information on the terrain (roughness and orography) as well as the handling of eventual obstacles. On the setup page handling of displacement height can also be chosen.

3.4.10.7 Model Choice: Scale Local

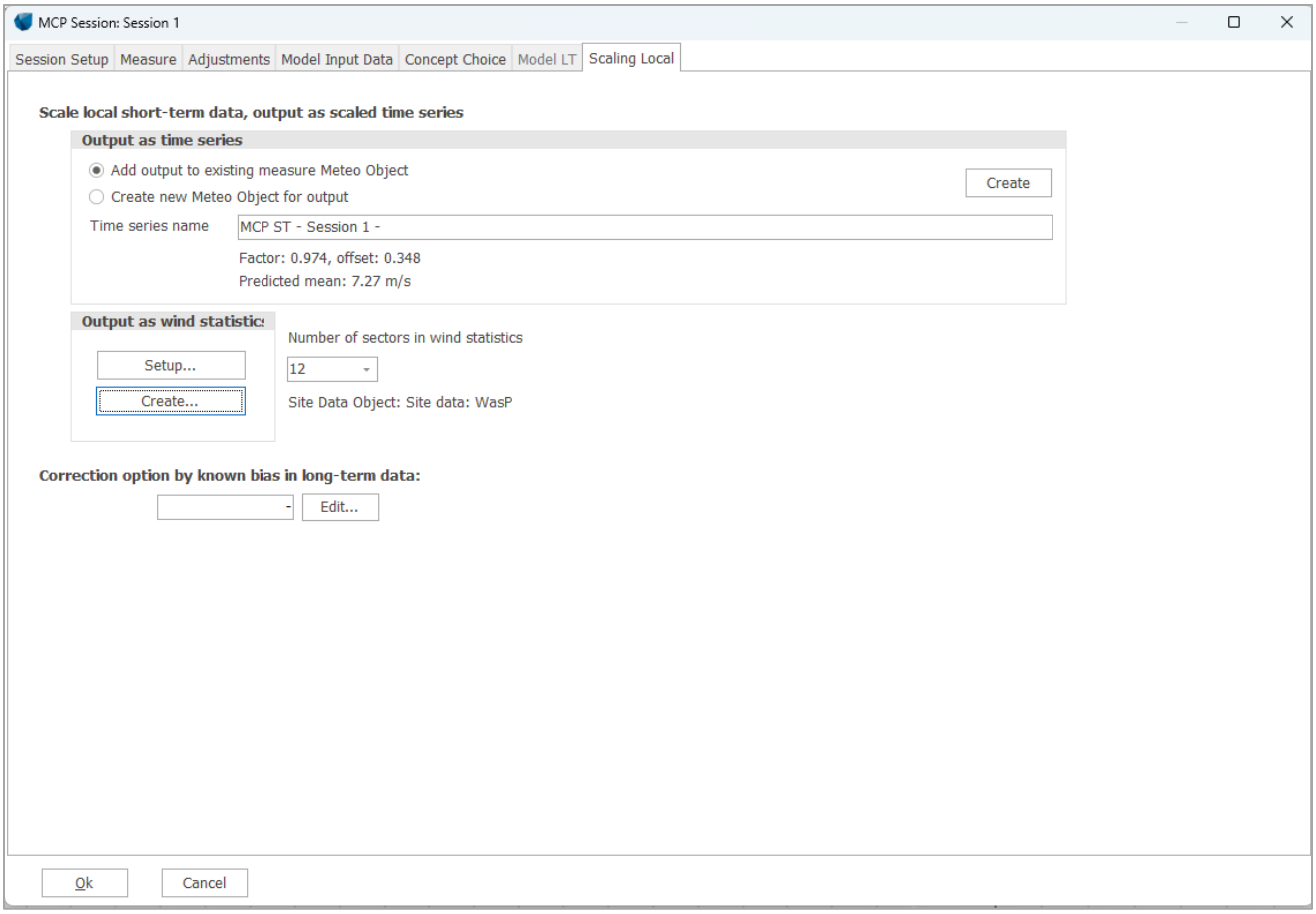


Figure 72 Scaling Local data to LT level

This is often a preferred method, if longer local measurements are available, if the site is in a wind climate that is very much the same year by year, e.g., where temperature is the main driver, or if the correlation between local and reference data is very poor and a traditional long term correction with transfer function is not recommended.
The advantage is as previously mentioned that the local measured direction distribution is used, which on locations with much turn e.g., near mountains often will be a better approach while the reference data might not reflect this. Also preserving the dynamics of the local measured wind speeds can improve accuracy, especially when calculating by time step.

The implemented method is the variance ratio method, 3.4.13.6.Scaling Local, where a Factor and Offset parameters are used to long term correct the local data.

Based on the Factor and Offset, the scaled calculated time series can be written to a Meteo object or a wind statistic can be generated based on the scaled time series and the terrain from the Site Data Object.

If the local data includes a period non concurrent to reference, this is included and an extra “post factor” is used to make the entire local period long term representative.

3.4.11 Sessions in MCP

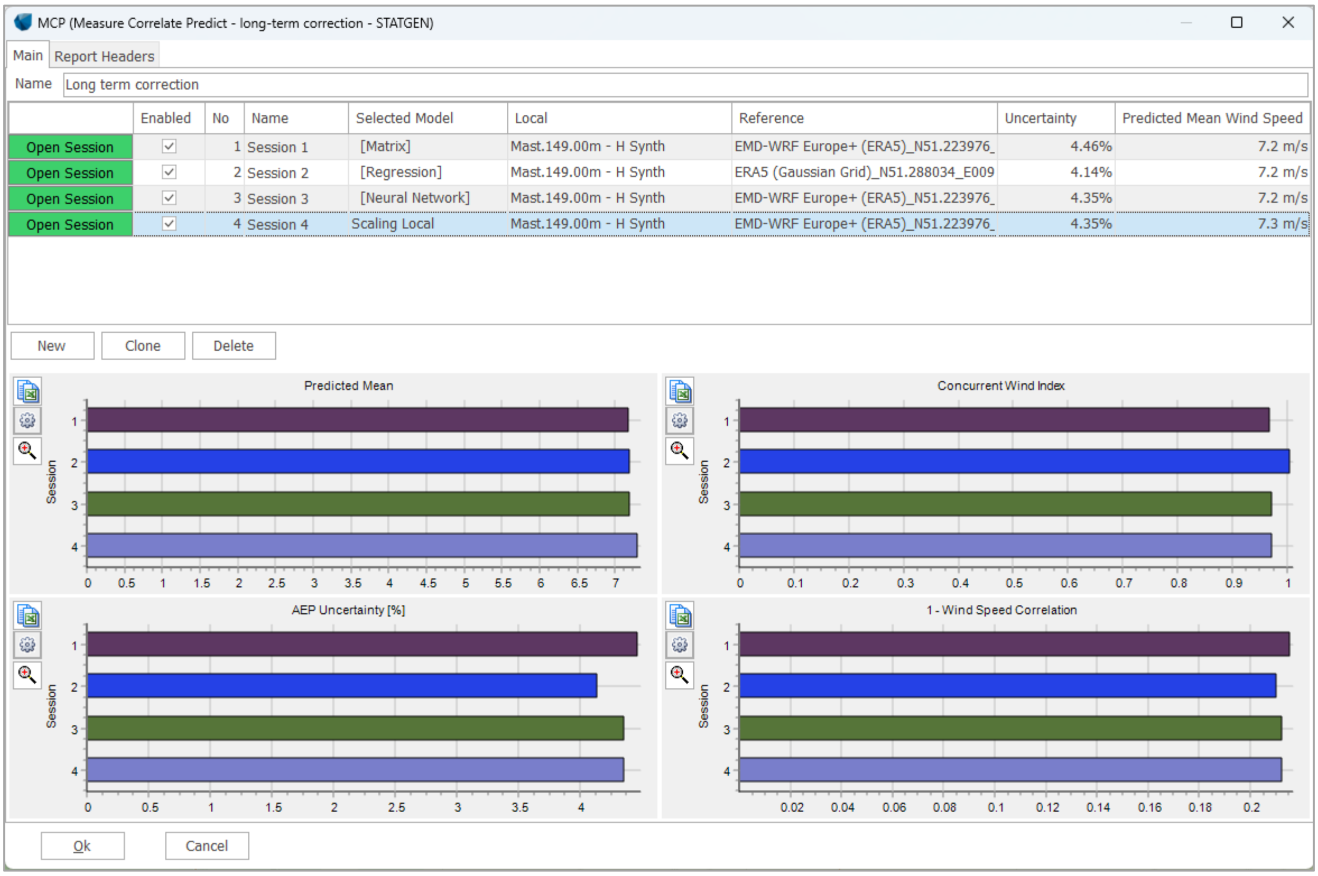


Figure 73 Example of several sessions compared.

Multiple sessions can be created in MCP. Each session can differ by:

- Choice of reference data
- Choice of local data
- Model selection and parameters
- Different periods for as well reference as local
- Different adjustments (time offset and veer)

Thereby the changes in results based on different choices can be seen fast and easy and confidence can be gained, or outliers detected. Key parameters as predicted long term mean wind speed and uncertainty within each session is seen. The figures will be available in the reporting part.

3.4.12 Reports from MCP

Reporting consists of two parts:
Session overview - The different session results are compared based on selected model within each session. The uncertainties based on selected data for each session is a part of the report, where each parameter included in the uncertainty calculation is shown.
Session details – For each session, the tested models are reported for comparison.

MCP - Session Overview

Calculation: Long term correction

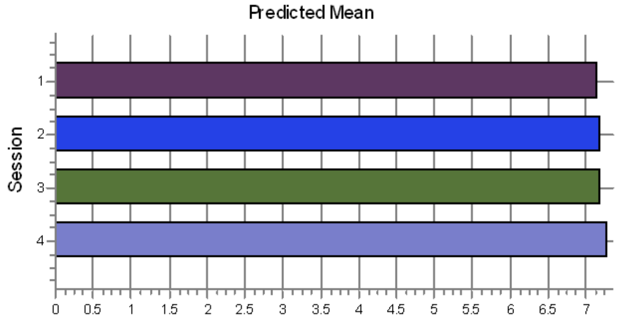
The Session Overview shows the input for each session. The results for each of the tested models in a particular session are shown in the Session Detail report. Please note that for all results in the report, the models have been trained and tested using all concurrent data. Predicted wind speeds are always in local measurement height.

Session Overview

No	Concept	Session	Local	Reference	Local Mean [m/s]	Local Mean [concurrent] [m/s]	Reference Mean [m/s]	Reference Mean [concurrent] [m/s]	Predicted Mean [m/s]	Concurrent Wind Index	Concurrent Months [months]	Correlation, r	AEP Uncertainty [%]
1	A	Session 1	Mast.149.00m - H Synth	EMD-WRF Europe+ (ERA5)_N51.223976_E009.697571 (2) (1).100.00m	7.11	7.09	7.24	7.07	7.15	96.8	12.09	0.785	4.5
2	A	Session 2	Mast.149.00m - H Synth	ERA5 (Gaussian Grid)_N51.288034_E009.583333 (4).100.00m -	7.11	7.11	5.49	5.45	7.19	100.4	12.09	0.790	4.1
3	A	Session 3	Mast.149.00m - H Synth	EMD-WRF Europe+ (ERA5)_N51.223976_E009.697571 (2) (1).150.00m	7.11	7.11	7.99	7.83	7.20	97.1	12.09	0.788	4.4
4	B	Session 4	Mast.149.00m - H Synth	EMD-WRF Europe+ (ERA5)_N51.223976_E009.697571 (2) (1).150.00m	7.11	7.11	7.99	7.83	7.29	97.1	12.09	0.788	4.4

A) Concept: Long term data series, based on a transfer function applied to the reference data.
B) Concept: Scaled local data to be long term representable.
Correlations in table is the windspeed correlation in the same time resolution as a the reference data.

Different sessions may have different local data (and therefore will not be directly comparable regarding mean wind speed) and different long-term reference data sets (for the evaluation of the effect of the reference choice). Sessions may also have different filter settings, such as veering one of the series, limiting the data period, etc. Finally, sessions can use different MCP methods, which can have individual settings (linear, parabolic, etc.). With more sessions it becomes clear how much the selected choices can affect the predicted mean wind speed and provide users with a broad decision basis for making the right choice when selecting the session(s) that generates the output for the final calculation.



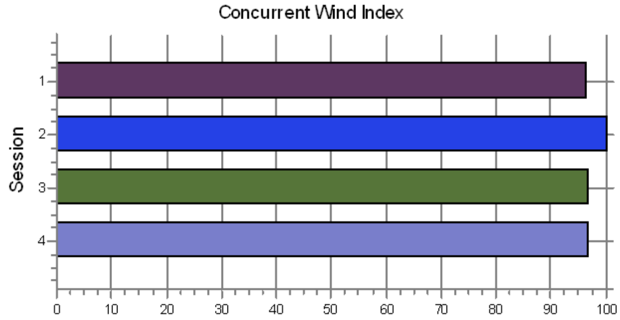
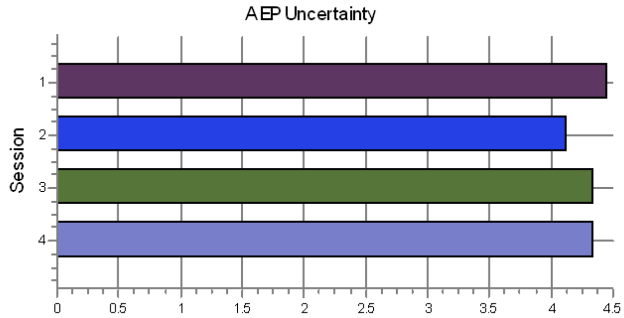
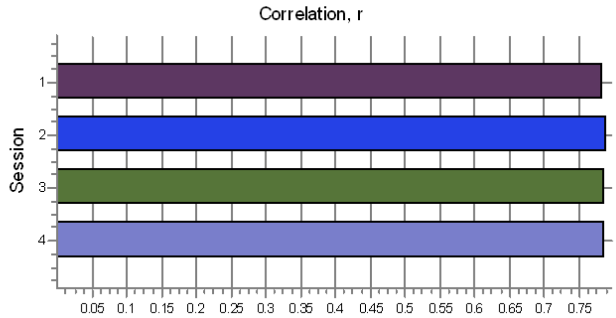


Figure 74 Part of the report for session overview





Uncertainty Calculation

No	Session	Wind Index (WI) [%]	Pearson (R)	Concurrent years (Y)	Variability (V) [%]	Density to AEP (CF)	A	B	C	D	E	AEP Uncertainty [%]
1	Session 1	97.724	0.802	1.007	2.822	0.511	1.550	0.060	-1.300	0.200	-0.300	4.5
2	Session 2	99.271	0.796	1.008	3.541	0.507	1.550	0.060	-1.300	0.200	-0.300	4.1
3	Session 3	98.014	0.805	1.008	2.883	0.510	1.550	0.060	-1.300	0.200	-0.300	4.4
4	Session 4	98.014	0.805	1.008	2.883	0.510	1.550	0.060	-1.300	0.200	-0.300	4.4

$$\sqrt{\left(A * \mathrm{ABS}(1 - \boldsymbol{WI})\right)^2 + (B * \boldsymbol{R}^C)^2 + (D * \boldsymbol{V})^2 * \boldsymbol{Y}^E * \boldsymbol{CF}}$$

Figure 75 Uncertainty calculation

In the uncertainty calculation, the input figures and the constants are shown. In this case the Wind energy index is the major difference driving the uncertainty up where the index differs most from 100%.

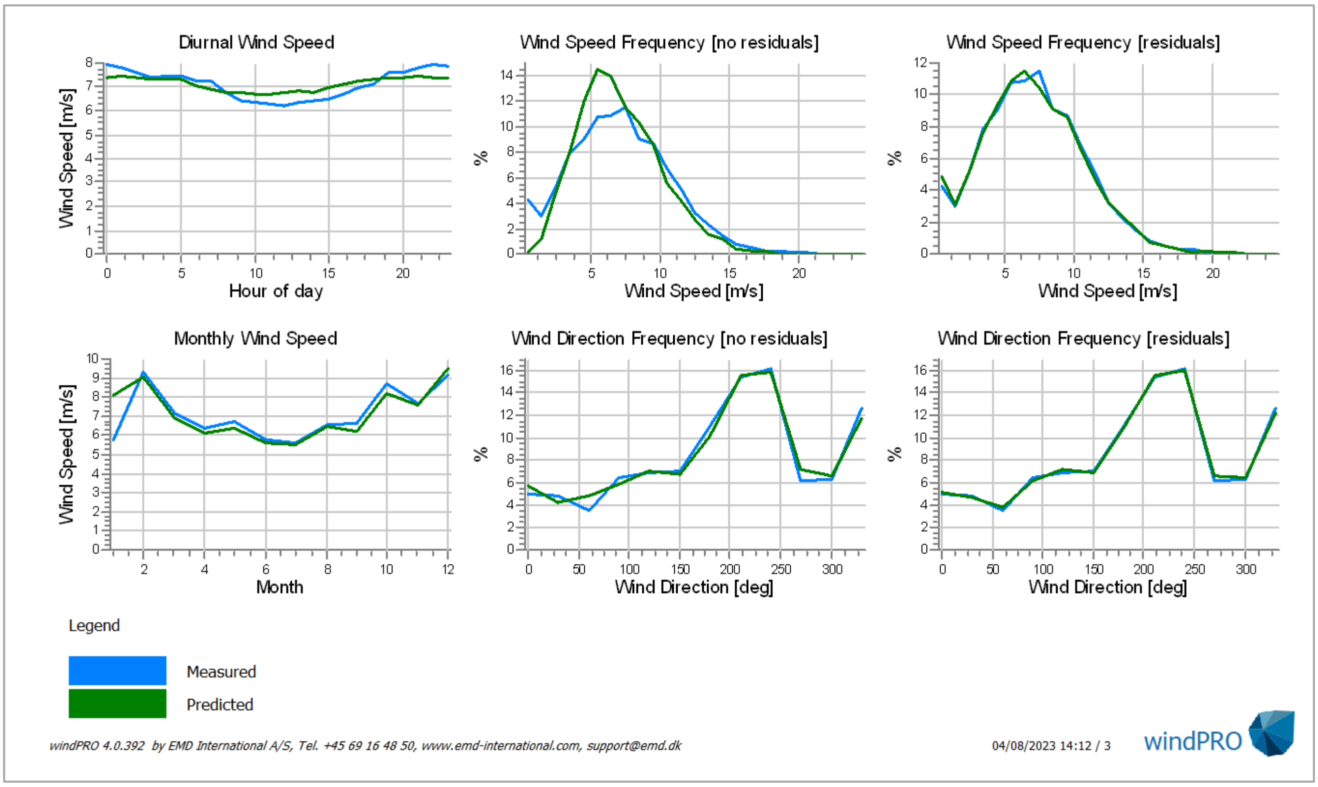


Figure 76 Example of MCP session details report

In session details, it can among many other information's be seen how the use of residual resampling improves the wind speed frequency distribution, while it is shown in direct comparison with the result without residuals.

3.4.13 Models used by MCP

In the MCP reference document more information on the math behind the methods is found. In this chapter detailed explanation is given to the different input options for each of the models.

3.4.13.1 Model LT; Simple Speed scaling

A simple method is used which consists of simply dividing local concurrent mean wind speed with reference concurrent wind speed. The resulted ratio is further multiplied with the wind speed series of the reference dataset, resulting so the long-term corrected mean wind speed.

3.4.13.2 Model LT; Regression

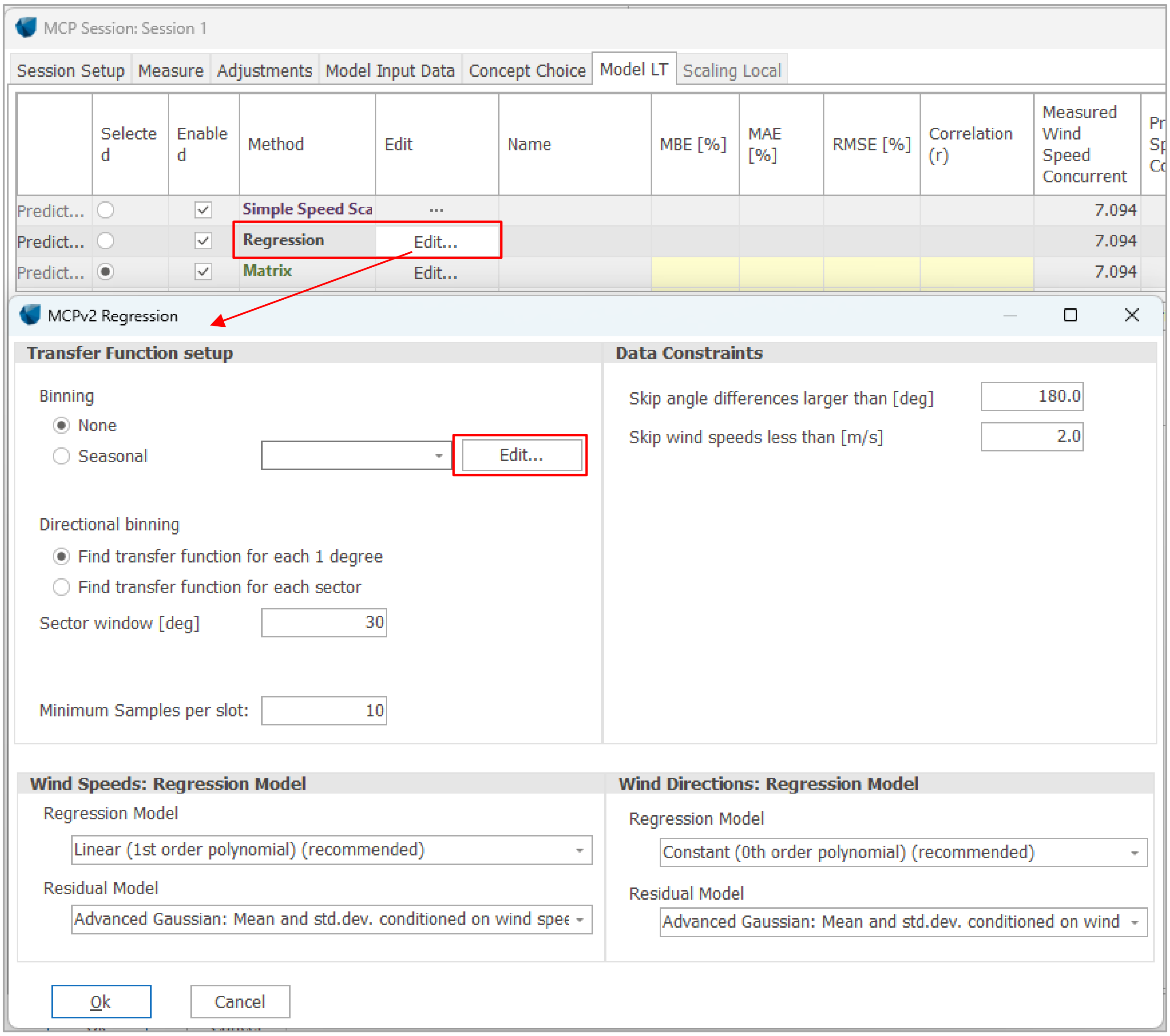


Figure 77 Settings for Regression opened by pressing the Edit button.

Binning is by default by direction sector. Optional binning can be set by season, where the EMD Season setup is used:

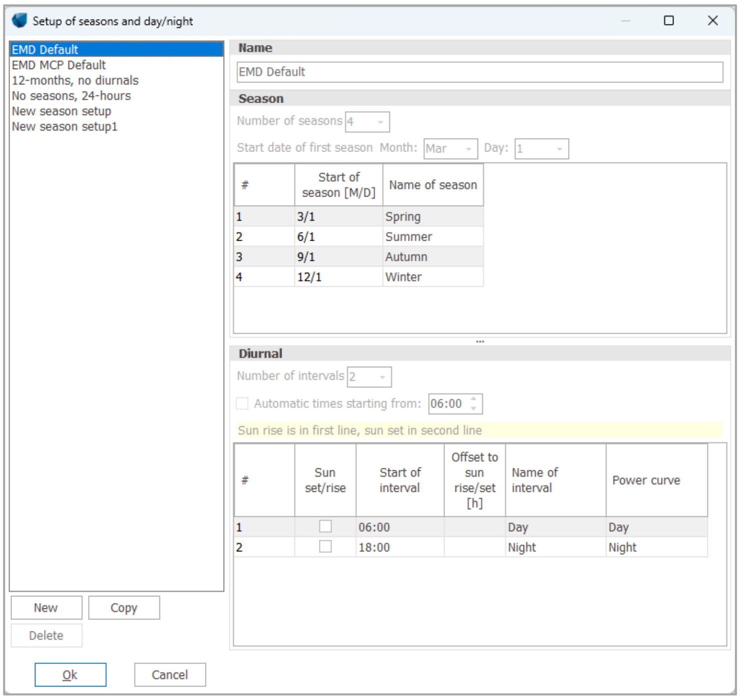


Figure 78 Season setup

Setup of seasons and day/night – This setup can divide in time of the year as well as time of the day. It is e.g., possible just to divide in day/night by reducing the number of seasons to 1. It is not recommended to divide into many seasons, this would give too few data for the analyses, only day/night and/or summer/winter would probably be the best recommended resolution.

Transfer function type - Sector handling
The transfer functions can be made for a small number of sectors (usually 12) or for 360 directions, meaning 360 transfer functions. Division in a number of sectors (typically 12) is the way for "homemade" Excel applications. This should be chosen for comparison with such calculations. But letting the software tool do the hard work, making 360 transfer functions based on a specific window size will be more accurate and is here chosen as default.

Sector window - Each transfer function will be made on the basis of data from a range of directions centred on the direction in question. The directions refer to the reference directions and 30 degrees is default. If 360 are chosen only one transfer function is made based on all data.

Skip angle difference larger than - Particularly at low wind speeds the angle between matching reference and local data may deviate significantly and cause a lot of noise. By rejecting point with large difference in direction this noise can be reduced. However, this means discarding information that could be important. By default, all data are included.

Skip wind speeds less than - As very low wind speed contributes with a lot of noise and often deviate from the linear relation seen at higher wind speeds it is useful to simply discard them from the transformation function. This does not mean that they are discarded from the full reference dataset being transformed to. Depending on the amount of noise and actual wind speeds at the reference this limit can be set freely but 2 m/s is default.

Regression model (Wind Speeds)

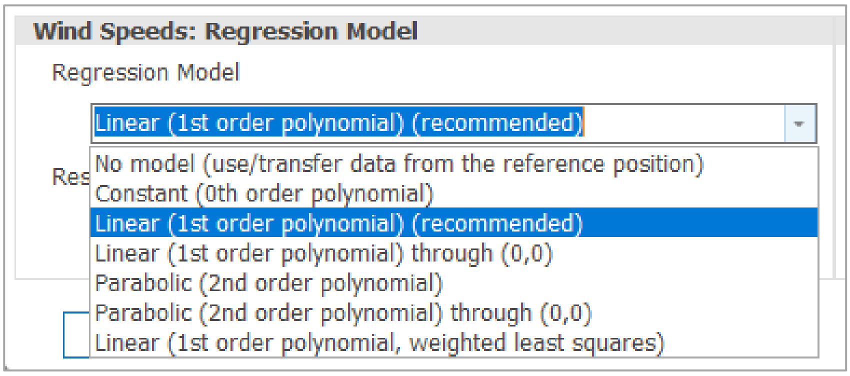


Figure 79 Wind Speeds- Regression Model.

Here the type of regression on the wind speed is selected. Linear regression means first order and a two-component linear regression will usually be preferable to a regression through origin (0,0) as this provides a better fit in the wind speed range relevant to production. This is also default. An alternative is a 2nd order regression, which will fit a parabolic curve to data. This may create a better fit but allow deviating extreme wind speeds to influence the fit at high wind speeds.

Regression model (Wind Directions);

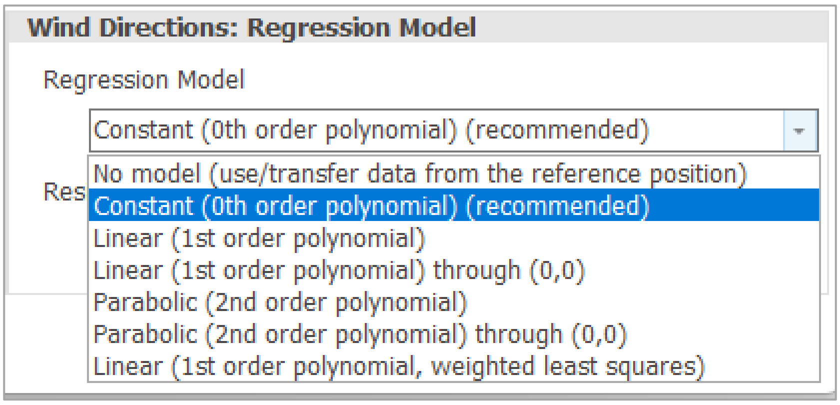


Figure 80 Wind directions - Regression Model.

Usually, the direction change is independent from wind speed and so a 0th order regression should be used.

Residual Model (for wind speed and/or direction):

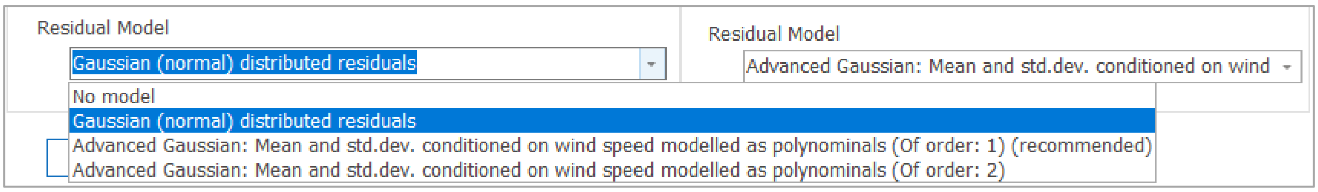


Figure 81 Residual Model selection for wind speed or wind direction

Gaussian (normal) distributed residuals are mainly included for backward compatibility. It proved to be a too simplified approach.

The "Advanced Gaussian" of order: 1 is the recommended model. This method is a function of the reference wind speed so that the regression formula is $y = ax+b+e(x)$.

The reference wind speed range is divided into a number of intervals. Within each interval the observed scatter is found as a standard deviation of the scatter together with the bias on the observations. Both are then applied when transferring the reference data to the site.
The observed standard deviation is modelled as either a first or a second order polynomial. The result is a much more dynamic fit than a standard linear regression. On well correlating data, internal tests have shown a significant improvement on the precision of the long-term prediction. The second order residual resampling do have the problem that few very scattered points at high wind speeds can exaggerate the resampled scatter

unreasonably. It is therefore recommended to use it carefully and if in doubt stay with the default first order advanced Gaussian residual resampling.

3.4.13.3 Model LT; Matrix

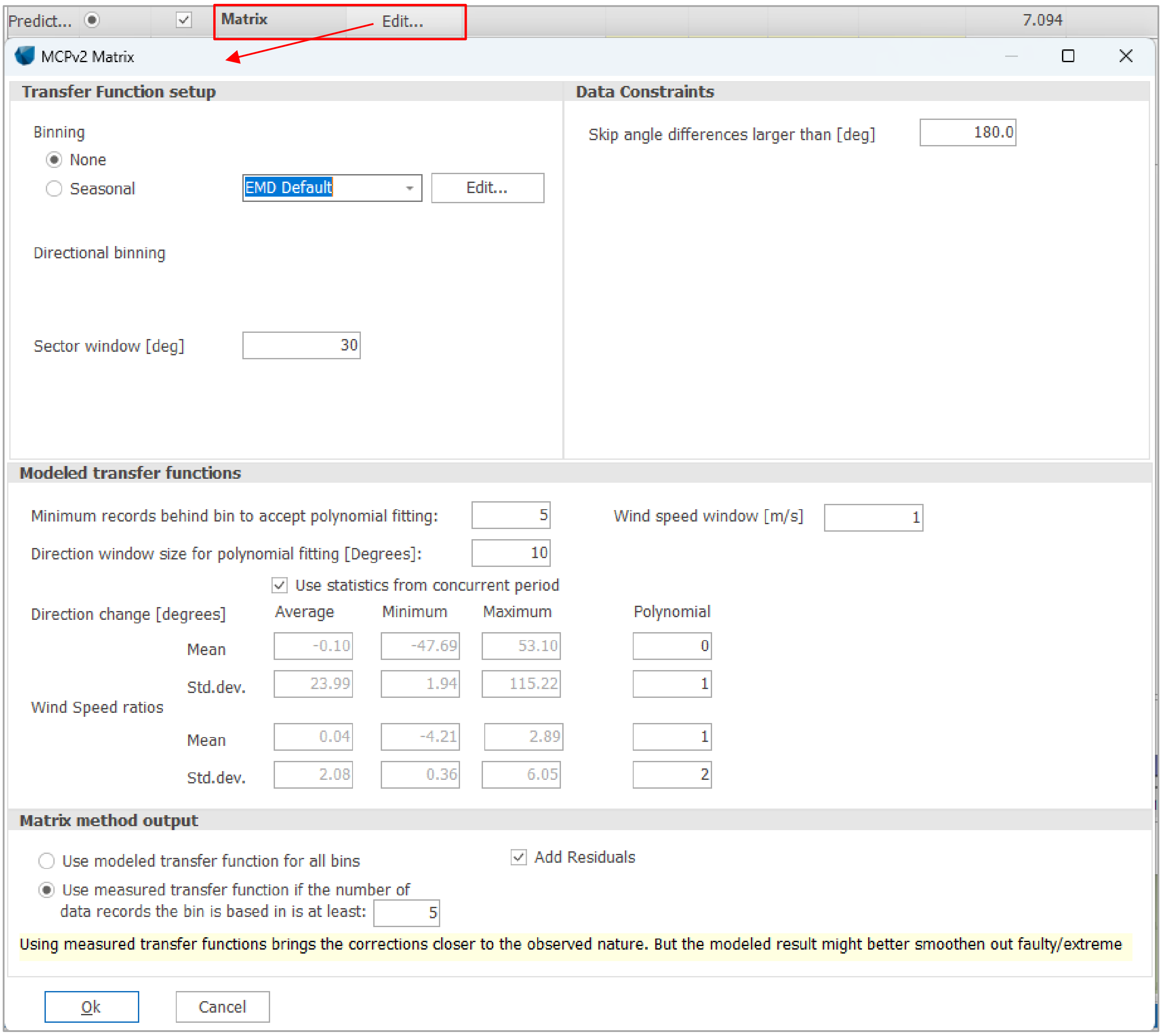


Figure 82 Settings for Matrix method.

The binning is done the same as described in the regression model, by default by direction sector, alternatively a seasonal binning can be defined.

Sector window - Each transfer function will be made on the basis of data from a range of directions centred on the direction in question. The directions refer to the reference directions and 30 degrees is default. If 360 are chosen only one transfer function is made based on all data.

Skip angle difference larger than - Particularly at low wind speeds the angle between matching reference and local data may deviate significantly and cause a lot of noise. By rejecting points with large difference in direction, this noise can be reduced. However, this means discarding information that could be important. By default, all data is included.

Wind speed window - Since the Matrix builds a list of possible outcomes for the transformation for each degree and each 1 m/s wind speed bin, the user can decide to include also neighbour wind speed bins for each bin in calculation. Default only the wind speeds within the bin in question is used.

Minimum records behind to accept polynomial fitting - To avoid bins based on very few data records to influence the model, these can be filtered by choosing a minimum number of records. By default, the minimum is set to 5 records.

Direction window size for polynomial fitting -Transfer function regression will be based on all transfer function within a specific window width. By default, the window is set to 10 degrees.

The observed extreme minimum and maximum values of mean and standard deviation on direction and wind speed change are listed. Extreme values indicate highly uncertain transformations. If this shall be changed, you must go back to the setup of the parameters for calculating the transfer functions.

Polynomial order - For each of the parameters a polynomial regression can be fitted to describe the transformation function. The order can be freely chosen and can even be different from parameter to parameter. The default choice for mean wind speeds is a 1st order fit as this is less sensitive to deviating extreme values. For mean change of wind direction, a 0th order polynomial is default (wind speed independent direction change). For the standard deviations, 1st order higher is recommended for wind veer and 2nd order for wind speed.

3.4.13.4 Model LT; Neural Network

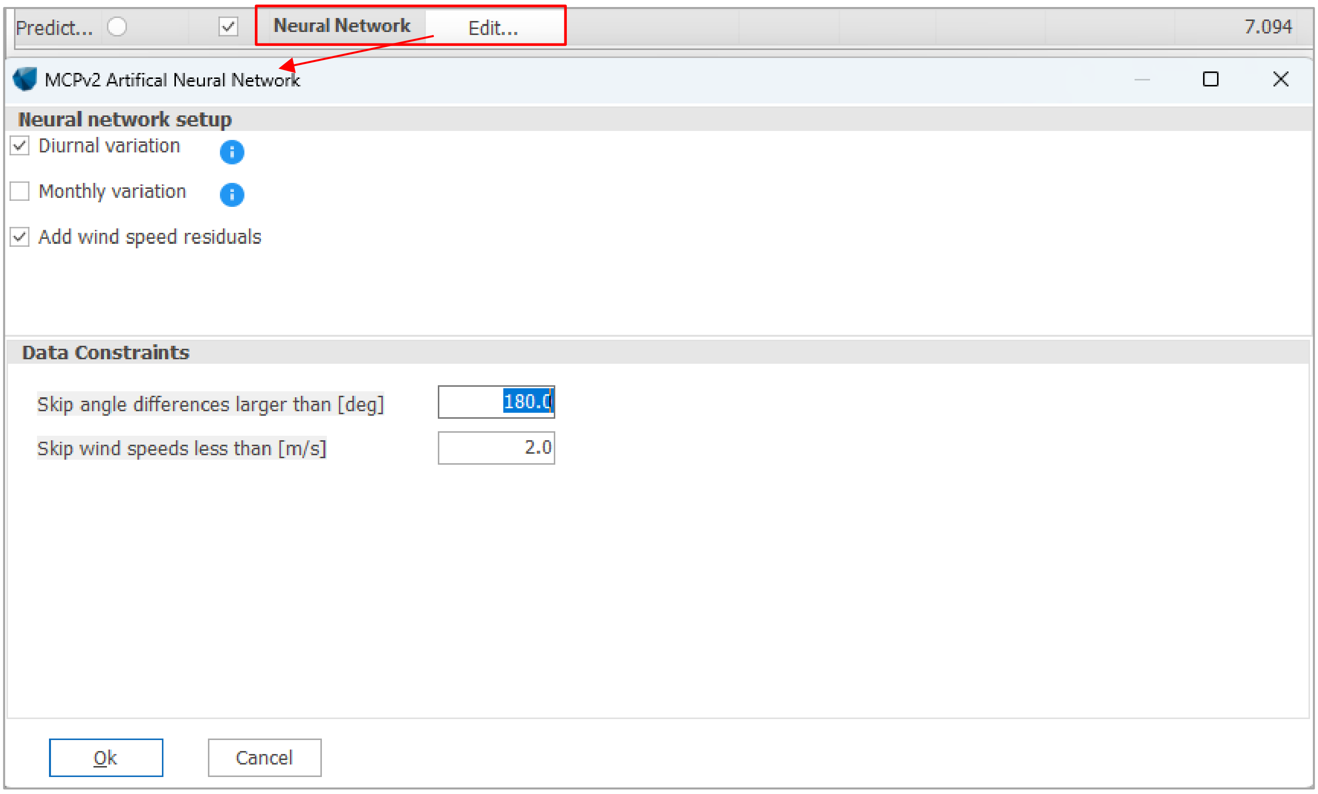


Figure 83 Settings for Neural Network - MCP model

The Artificial Neural Network (ANN) - establishes transfer functions from reference data to measurement data by using ANN networks trained with reference data as input and measurement data as output. Once the networks are trained (with backpropagation algorithm) they can be used to predict wind speed and direction based on the reference data.

From a user perspective the ANN method only has three settings:

Diurnal variation - The hour of the day is used for each sample as input to the network. It will often give a better diurnal match when this is enabled.

Monthly variation - Similar to diurnal variation this will add the month of the year as input to the network. In cases where the difference between reference- and measured data seems to have a monthly variation this option can be enabled to possibly get better results. This option should be used with caution if the measured data doesn't include a full year since the network would then eventually be used with input data that it hasn't been trained with.

Add wind speed residuals - Like regression methods an ANN approach tends to “remove” some of the variability in the predicted data. Therefore, residuals can be added as a post-processing to re-establish the variability seen in the measured data. The ANN method uses the 1st order Advanced Gaussian method that is also used in the Regression MCP method. The residual model is calculated based on the predicted data vs. the measured data, and then used to add a residual on each predicted sample.

3.4.13.5 Solver based (For Scaler)

The goal of the Solver based MCP method is to establish a method that has training parameters identical to the ones found in the Scaler Post Scaling options, so that the parameters can be exported from MCP to a Scaler and used in e.g RESOURCE and PARK.

These parameters are:
1. Overall offset that is added to all samples (g_{offset})
2. Overall scale that is multiplied to all samples (g_{scale})
3. Scale factor based on wind direction sector ($sector[sec_{ndx}]$)
4. Scale factor based on season of year, also called month factors ($month(month_{ndx})$
5. Scale factor based on diurnal index, which can be seasonal dependent $diurnal[season_{ndx}, diurnal_{ndx})$

Since all these parameters will correlate it is not possible to establish a deterministic method that will set the parameters, so an iterative solver must be used.
The solver works best if the overall offset and scale is determined first. Those factors are determined by linear regression on all concurrent samples. So, the basic expression of determining a sample would be:

$$predicted_{ws} = reference_{ws} * g_{scale} + g_{offset}$$

Once the overall offset and scale parameters are determined each sample in the concurrent time series is marked with an index of how they belong to each of the other post-scaling parameters (points 3 to 5 above). This means that the combined expression for a predicted wind speed would be:

$$predicted_{ws} = \left(reference_{ws} * g_{scale} + g_{offset}\right) * sector[sec_{ndx}] * month[month_{ndx}] * diurnal[season_{ndx}, diurnal_{ndx}]$$

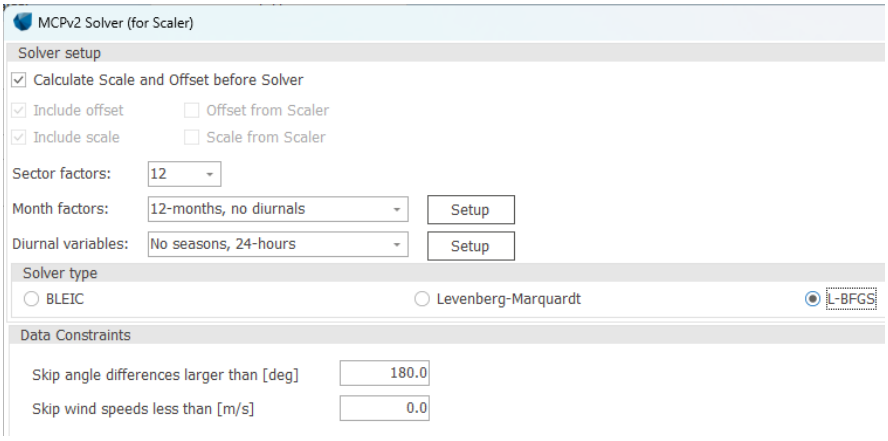
The goal of the Solver MCP method is then to minimize the objective:

$$\sum_{0}^{N}(predicted_{ws} - measured_{ws})^2$$

In the current implementation we offer three different solver algorithms, namely:
- L-BFGS (default)
- BLEIC
- Levenberg-Marquardt

Tests have so far shown that L-BFGS gives the best results and most users would not need to change that.
Currently the sector, month and diurnal variables are initialized to 1.0 before starting the solver. It could later be investigated whether results could be improved by finding better start guesses before starting the solver.
The solver uses steps of 0.01 and has a default stop-criteria of 50.000.000 iterations or when the goal function is below 0.1 m/s.

The setup window for the Solver model looks like this with default settings:

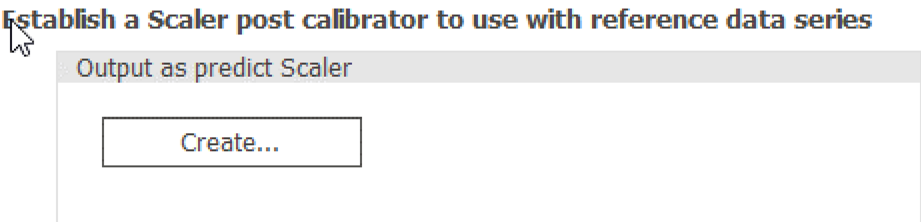


In this setup the overall Scale and Offset are calculated before the solver runs for the other parameters. The sector factors are set to 12 sectors by default.

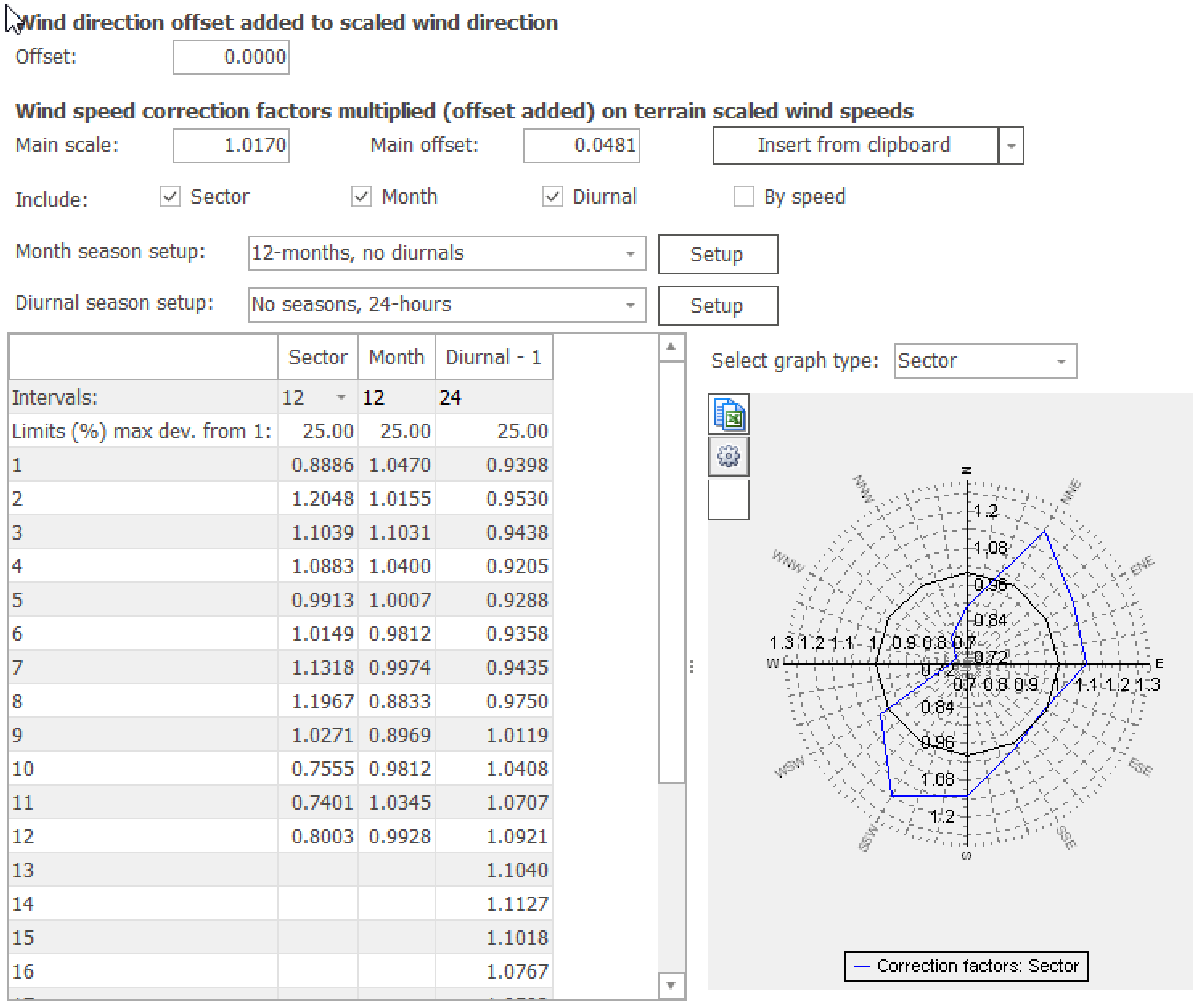
For both Month and Diurnal factors, the user chooses a windPRO season setup (see Figure 78 Season setup). This season setup defines how many seasons a year should be divided into for the Month factors and for the Diurnal factors it defines how a day should be split into periods and whether different diurnal factors should be used for different seasons of the year.

If the MCP session is set up to use a Scaler the user can also choose to use the Sector, Month and Diurnal factors from the original Scaler. So, if the user has already found e.g. the Sector factors, then these can be used directly and will not be part of the Solver algorithm.

If a Scaler is used in the MCP session there is a new option in the Predict window to output the predicted scaler:



This button creates a copy of the Scaler used in the MCP session and then adds the trained parameters to the Post Calibration of the copied Scaler. Here is an example of a Post Calibration from a MCP Solver model:



	Sector	Month	Diurnal - 1
Intervals:	12	12	24
Limits (%) max dev. from 1:	25.00	25.00	25.00
1	0.8886	1.0470	0.9398
2	1.2048	1.0155	0.9530
3	1.1039	1.1031	0.9438
4	1.0883	1.0400	0.9205
5	0.9913	1.0007	0.9288
6	1.0149	0.9812	0.9358
7	1.1318	0.9974	0.9435
8	1.1967	0.8833	0.9750
9	1.0271	0.8969	1.0119
10	0.7555	0.9812	1.0408
11	0.7401	1.0345	1.0707
12	0.8003	0.9928	1.0921
13			1.1040
14			1.1127
15			1.1018
16			1.0767

3.4.13.6 Scaling Local

The purpose is to adjust the short-term site time series of wind speed using the long-term reference to ensure that the wind speeds of the local series match the long-term level.
This requires the local data and reference series to fully overlap in the concurrent period.
With the concept of index correction, we do not establish a direct site-to-reference relationship as in standard MCP methods. Instead, we base the correction solely on the reference series. As a result, the correction reflects the relationship between concurrent and full concurrent-to-full for the reference series.

Figure 84 Graphical representation of dataset used and their lengths.

In the Scaling local method, the transfer function is allowed to have both a slope and an offset, so it is possible to correct both the wind speed mean and stdev from concurrent-to-long term conditions.

$$\text{Model:}\, u_{site,corr} = \alpha\, u_{site} + \beta$$

Two equations are needed to constrain both parameters, α and β, one for the mean and one for the stdev, which both follow directly from the definitions of mean and stdev. and the assumed linear relationship/transfer-function.

$$\text{Constraints:}\langle u_{ref,full}\rangle = \alpha\,\langle u_{ref,conc.}\rangle + \beta$$

$$\sigma_{ref,full} = \alpha\ \sigma_{ref,conc.}$$

Which together yield the following expressions for α and β.

$$\alpha = {\sigma_{ref,full}}/{\sigma_{ref,conc.}}$$

$$\beta = \langle u_{ref,full} \rangle - \langle u_{ref,conc.} \rangle \frac{\sigma_{ref,full}}{\sigma_{ref,conc.}}$$

A minor problem is that the correction model may lead to negative wind speeds for some of the corrected wind speed samples. This is pragmatically handled by truncating these samples to zero.
Thus, the full correction equation for u_{site} is.

$$u_{site,corr} = \max\left\{0, \frac{\sigma_{ref,full}}{\sigma_{ref,conc.}}\ u_{site} + \langle u_{ref,full} \rangle - \langle u_{ref,conc.} \rangle \frac{\sigma_{ref,full}}{\sigma_{ref,conc.}}\right\}$$

The found scale and offset is shown on the form:

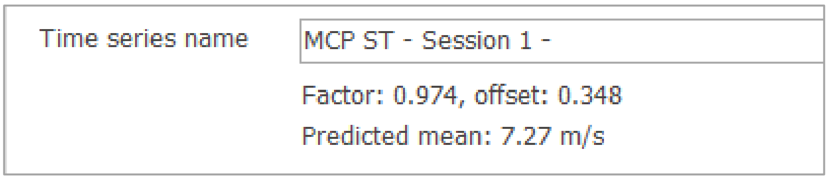


Figure 85 Found scale and offset together with predicted long-term mean wind speed.

If the local data include a period non concurrent to reference, this is included and an extra “post factor” is used to make the entire local period long term representative. The post factor is simply the average wind speed for concurrent local data divided with the average wind speed for all local data. This is multiplied on all wind speeds in the scaled local series. Example including post factor is shown below:

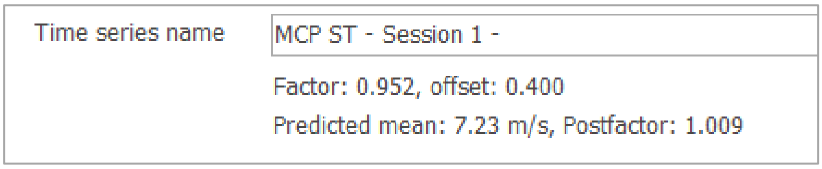


Figure 86 Found scale, offset and post-factor together with predicted long-term mean wind speed.

Note the post factor here change the mean wind speed 2.6%. This is unusual high, and the reason is we have found a period with an extreme high month and excluded this just to test the model.

3.5 Models/modules for initial calculations

Most AEP calculations will be performed with the PARK module. But, for providing data to the PARK module or for doing initial tests calculations or for calculating single turbines, there is a number of auxiliary modules. As an example of a possible use is the comparison of AEP for many different turbine types at a specific site.

In the following descriptions, selected features are documented within each paragraph, but not repeated for all modules since the input screens are the same for several other modules.

3.5.1 METEO

The METEO module performs a calculation of the wind distribution and the AEP on a single spot, where the measurement mast is located. The calculation assumes the wind data are long-term representative. Having, e.g., ½ year or 1½ year of data, thereby, will give a biased AEP result as all seasons are not equally represented. AEP results will always be “scaled” to a full year, no matter the length of data period or data recovery.

Input:

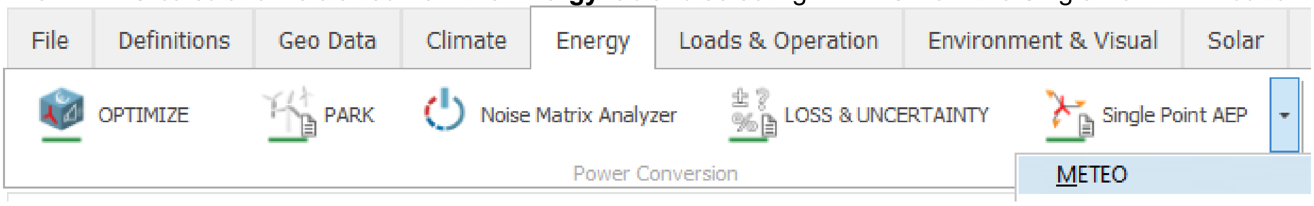
- METEO object with wind data.
- Turbine types (from turbine catalogue or user defined wtg file) and hub heights
- Air density correction (world climate database, available within software)

Output:

- Calculated AEP (Annual Energy Production) for each turbine and hub height at the position of the METEO object (calculation point) as the main report.
- Production analyses, Power curve analyses, Wind data analyses, Wind profile (optional) and Map as detailed report pages.
- Data files for spreadsheet analyses with turbine specifications, calculation results etc. If time series is used in the calculation, a 24-12 (hours-months) distribution will be available.

The input data must come from a METEO object, where the measured data is imported, or data from EMD On-line data services is downloaded. No horizontal model extrapolations are available, but, optionally, vertical extrapolations based on shear input are available.

The METEO calculation is started from the **Energy** tab and selecting METEO from the Single Point AEP button:



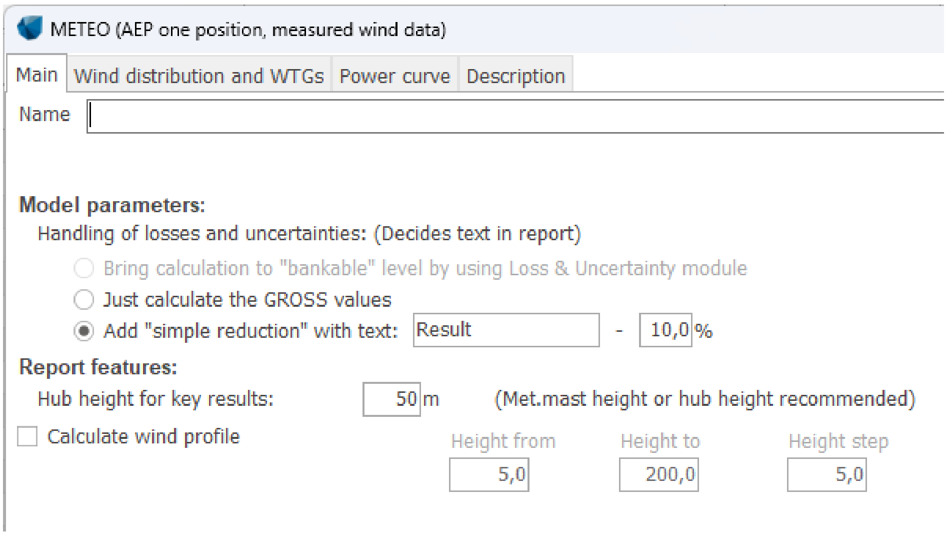


Figure 87 Main page input for METEO calculation

At the main page, it can be decided to include a “simple reduction” to compensate for expected losses and, eventually, uncertainty deduction. This “primitive” approach can be overruled by different choices, as seen in the form above. The hub height for key results can be set. This is in order to have comparable results for different calculations, where the hub heights might differ. It is optional to calculate wind profiles that will be reported as an average for the site and by direction sector also.

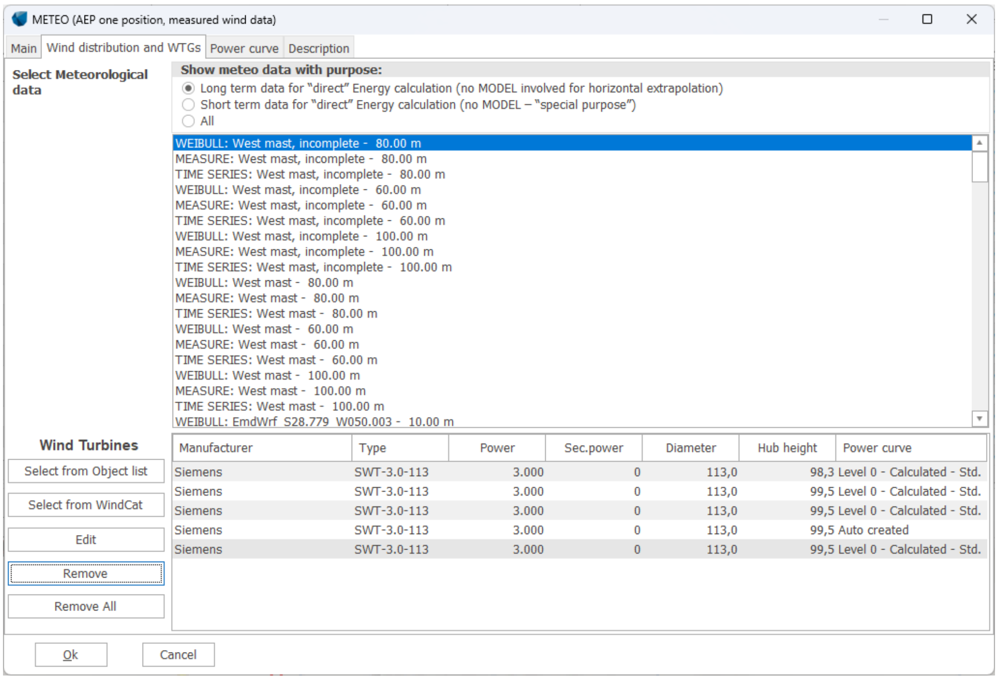


Figure 88 Wind distribution and WTGs input

The wind data selection offers data from all METEO objects in the project (filtering based on "purpose" is possible), where, as well as the time series, the "MEASURE" (the table or histogram data) or the Weibull fitted distribution can be chosen. Thereby, it is easy to compare the difference in results using, e.g., the measurements direct with the Weibull fitted data. In the input form, more turbines and hub heights can be selected. Finally, the power curve handling, especially the air density correction, can be setup. See Section 3.7.4 Common settings for Wind statistics based (standard) PARK calculation.

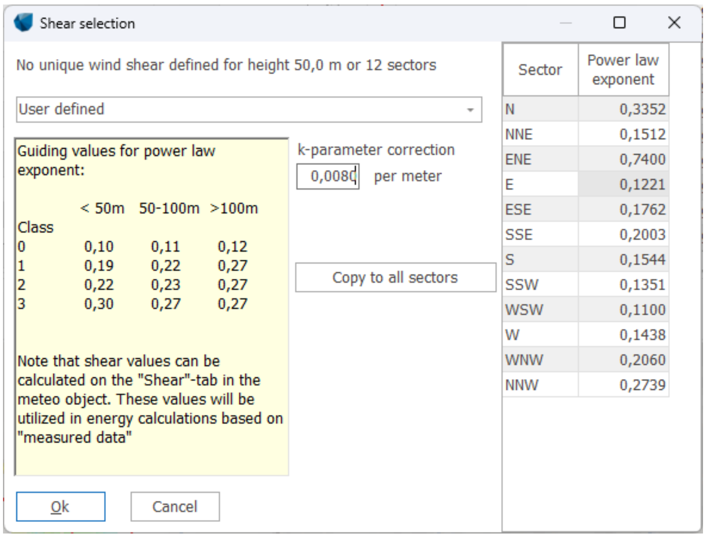


Figure 89 Input of shear in METEO calculation

When the METEO calculation starts, an input screen for shear appears. These are the options:

- Use data from METEO objects shear tab, where more sets of shear values can be established.
- User define shear by typing shear values as power law exponents by each direction sector.

NOTE: Shear values in non-flat terrain can, when established from more measurement heights, partly include hill speedup. This is also similar near forests. It can, thereby, give a highly uncertain calculation result.

The **k-parameter correction** is a little complicated as it highly depends on the height scaled from and to. Until windPRO 3.5 the default was 0.008 increase per meter, based on rather old empirical values. From windPRO 3.6 no value is recommended. Taller measurement and hub heights has turned the old default irrelevant. If needed, the below information might support making a good choice. A better choice would although be to create a synthesized time series in meteo object in for calculation height. Then no extrapolation of k is needed.

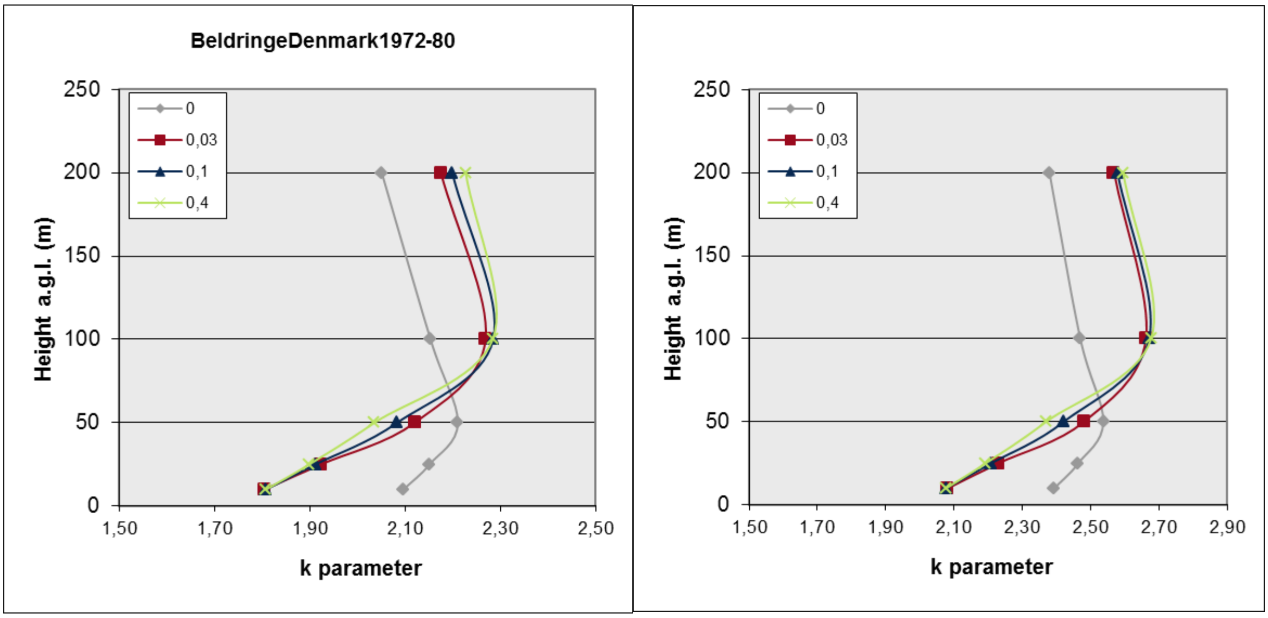


Figure 90 k Weibull parameter change with height, left onshore, right offshore wind statistic for DK.

The figures above show how WAsP assumes the k-parameter to change for the 4 roughness classes, 0 – 3, for a given wind statistics. On the left is the Danish "basis" wind statistics, Beldringe. On the right is a Danish offshore based wind statistics. The general picture is the same, only the offshore based values are higher, which is partly due to higher mean wind speeds. It can be seen that onshore, from 50m to 100m, the increase is around 0.2 for 50m, meaning that the increase is 0.004 per m. Going higher than 100m or offshore, the increase becomes negative. -0.001 seems to be a reasonable value if your measurements are from 100m and you want to scale to larger heights, or if you go up from 50m offshore.

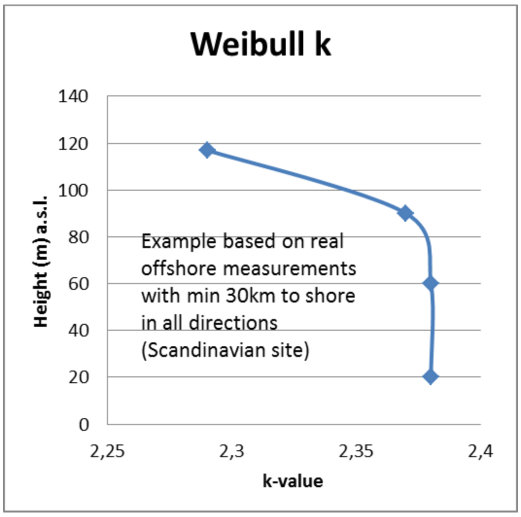


Figure 91 Measured Weibull k change by height – offshore example

Above is an example of real, measured k-values on a tall offshore mast in Scandinavian waters with long distance (>30km) to shore in all directions.

Weibull data 30 m above ground level

Sector	A- parameter [m/s]	Wind speed [m/s]	k- parameter	Frequency [%]	Wind gradient exponent
0 N	8,23	7,30	2,343	5,3	0,335
1 NNE	8,45	7,48	2,270	6,0	0,151
2 ENE	9,22	8,17	2,416	5,2	0,074
3 E	10,34	9,16	2,168	5,5	0,122
4 ESE	10,99	9,76	1,852	11,3	0,173
5 SSE	10,88	9,64	2,043	8,2	0,200
6 S	11,91	10,55	2,310	8,9	0,154
7 SSW	10,69	9,49	2,490	12,3	0,135
8 WSW	12,15	10,78	2,512	12,2	0,110
9 W	11,18	9,92	2,552	10,0	0,144
10 WNW	10,37	9,18	2,167	9,4	0,206
11 NNW	9,15	8,10	2,113	5,6	0,274
All	10,61	9,40	2,175	100,0	

Calculation Results

Key results for height 50,0 m above ground level
Wind energy: 9.179 kWh/m²; Mean wind speed: 10,2 m/s;

Calculated Annual Energy

WTG type						**Power curve**		**Annual Energy**			
Valid	Manufact.	Type-generator	Power, rated [kW]	Rotor diameter [m]	Hub height [m]	Creator	Name	Result [MWh]	Result-10,0% [MWh]	Mean wind speed [m/s]	Capacity factor [%]
No	VESTAS	V39-600	600	39,0	39,0	USER	Rough estimate	2.578,0	2.320	9,81	49,0
No	VESTAS	V47-660	660	47,0	40,0	EMD	Level 0 - calculated - - 07-2001	3.204,8	2.884	9,85	55,4
Yes	VESTAS	V112-3.0 MW 50/60 Hz-3.075	3.075	112,0	94,0	USER	Mode 0 1.225	19.718,4	17.747	11,39	73,2
Yes	VESTAS	V112-3.0 MW 50/60 Hz-3.075	3.075	112,0	84,0	USER	Mode 0 1.225	19.263,4	17.337	11,17	71,5

Figure 92 Output example from a METEO calculation

Above is an example of the main output from a METEO calculation. The results can be taken out and put into a spreadsheet for further processing by using the “result to file” output, shown here:

Table 5 Result to file output from a METEO calculation

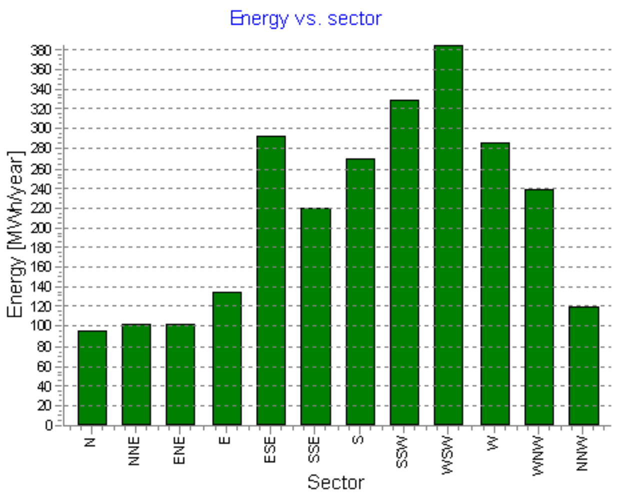
Valid	Manufact.	Type-generator	Power, rated	Rotor diameter	Hub height	Total	Regional Correction Factor	Equivalent roughness	Mean wind speed	HP-value	Air density
			[kW]	[m]	[m]	[MWh]			[m/s]	[%]	[kg/m³]
No	VESTAS	V39-600	600	39	39	2.376,80	1		9,31	99	1,224
No	VESTAS	V47-660	660	47	40	2.968,70	1		9,31	100	1,223
Yes	VESTAS	V112-3.0 MV	3.075	112	94	15.367,80	1		9,31	100	1,217
Yes	VESTAS	V112-3.0 MV	3.075	112	84	15.374,60	1		9,31	100	1,218

METEO - Production Analysis

Calculation: Test meteo**WTG:** VESTAS V39 600 39.0 !O!, Hub height: 39,0 m, Air density: 1,224 kg/m³

Directional Analysis

Sector		0 N	1 NNE	2 ENE	3 E	4 ESE	5 SSE	6 S	7 SSW	8 WSW	9 W	10 WNW	11 NNW	Total
Roughness based energy	[MWh]	95,1	103,3	103,4	134,2	292,5	219,0	269,4	329,5	385,1	286,9	238,9	120,7	2.578,0
Resulting energy	**[MWh]**	**95,1**	**103,3**	**103,4**	**134,2**	**292,5**	**219,0**	**269,4**	**329,5**	**385,1**	**286,9**	**238,9**	**120,7**	**2.578,0**
Specific energy	[kWh/m²]													2.158
Specific energy	[kWh/kW]													4.297
Directional Distribution	[%]	3,7	4,0	4,0	5,2	11,3	8,5	10,5	12,8	14,9	11,1	9,3	4,7	100,0
Utilization	[%]	34,2	34,1	33,6	26,4	19,7	22,1	21,9	28,3	23,3	26,9	25,4	28,8	24,9
Operational	[Hours/year]	398	453	394	410	848	616	666	926	916	749	705	424	7.505
Full Load Equivalent	[Hours/year]	158	172	172	224	487	365	449	549	642	478	398	201	4.297
A- parameter	[m/s]	9,0	8,8	9,4	10,7	11,5	11,5	12,4	11,1	12,5	11,6	10,9	9,8	11,1
Mean wind speed	[m/s]	8,0	7,8	8,3	9,5	10,2	10,2	11,0	9,8	11,1	10,3	9,7	8,7	9,8
k- parameter		2,41	2,34	2,49	2,24	1,92	2,12	2,38	2,56	2,58	2,62	2,24	2,19	2,25
Frequency	[%]	5,3	6,0	5,2	5,5	11,3	8,2	8,9	12,3	12,2	10,0	9,4	5,6	100,0
Power density	[W/m²]													958



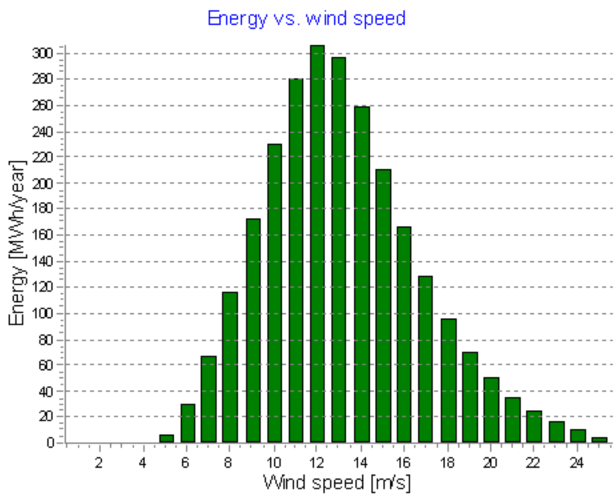


Figure 93 Production analyse output

For each turbine (power curve) and hub height, detailed presentations are available.

METEO - Wind Data Analysis

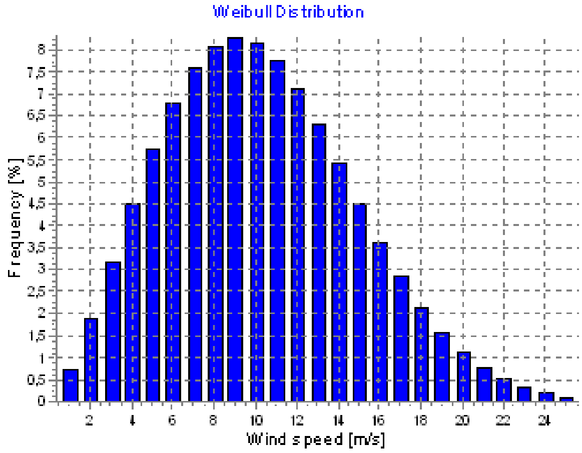
Calculation: Test meteo**Wind data:** A - Old met mast,Gillespie; Hub height: 50,0

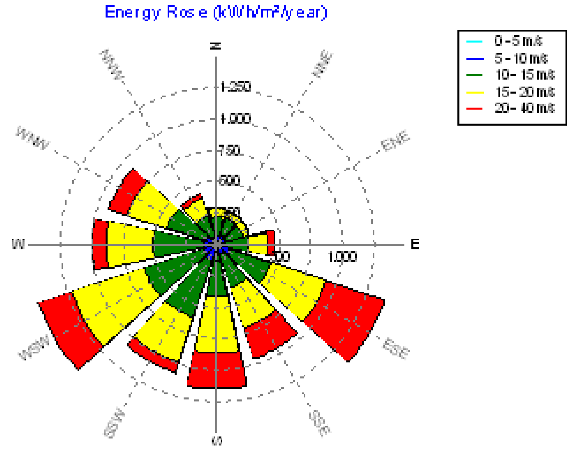
Site coordinates
ITM
East: 584.089 North: 923.911

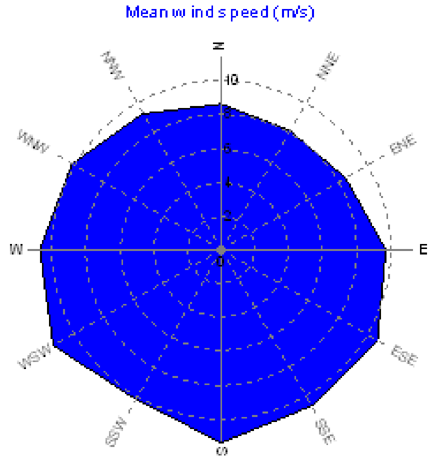
Meteo data
Old met mast,Gillespie

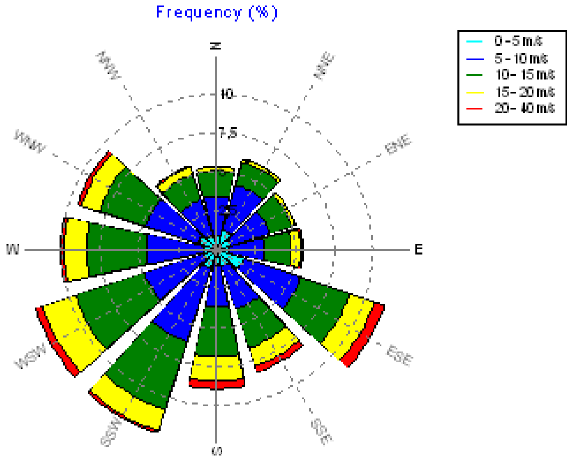
Weibull Data

Sector	A- parameter [m/s]	Wind speed [m/s]	k- parameter	Frequency [%]	Wind gradient exponent
0 N	9,77	8,67	2,503	5,3	0,335
1 NNE	9,13	8,09	2,430	6,0	0,151
2 ENE	9,57	8,50	2,576	5,2	0,074
3 E	11,01	9,75	2,328	5,5	0,122
4 ESE	12,00	10,64	2,012	11,3	0,173
5 SSE	12,06	10,68	2,203	8,2	0,200
6 S	12,88	11,43	2,470	8,9	0,154
7 SSW	11,46	10,18	2,650	12,3	0,135
8 WSW	12,86	11,43	2,672	12,2	0,110
9 W	12,03	10,70	2,712	10,0	0,144
10 WNW	11,52	10,20	2,327	9,4	0,206
11 NNW	10,52	9,32	2,273	5,6	0,274
All	11,54	10,22	2,336	100,0	









windPRO 3.0.619 by EMD International A/S, Tel. +45 96 35 44 44, www.emd.dk, windpro@emd.dk 27-05-2015 19:38 / 1 windPRO

Figure 94 Wind data analyse output

More result pages give a detailed presentation of the results.

3.5.2 ATLAS

Atlas is a simple model based on the “windatlas for Denmark” from 1979 by Risø. The model has been refined by EMD during the 80’ties, but not further developed since. The model is, although, still an affordable, simple to use and reasonably accurate model. It requires a wind statistics, describing the regional wind climate. These are available for several countries but of varying quality. Upcoming in 2015 is a world wind atlas from Risø/DTU. To establish a wind statistics from measurements the WAsP model will be needed.

Input:

- Site Data Object with wind statistics, roughness rose, hill length and height by sector and obstacles by distance, height and porosity by sector.
- Turbine types (from turbine catalogue or a user defined wtg file) and hub heights
- Air density correction (world climate database available within software)

Output:

- Calculated AEP (Annual Energy Production) for each turbine and hub height at position for Site Data Object (calculation point) as main report.
- Production analyses, Power curve analyses, Terrain, Wind data analyses, Wind profile (optional), Wind statistics info, Map as detailed report pages.
- Data files for spreadsheet analyses with turbine specifications, calc. results etc.

First, a Site Data Object is inserted in the position on the map where the calculation shall be performed.

The purpose is set to “ATLAS” calculation.

A wind statistic is chosen:

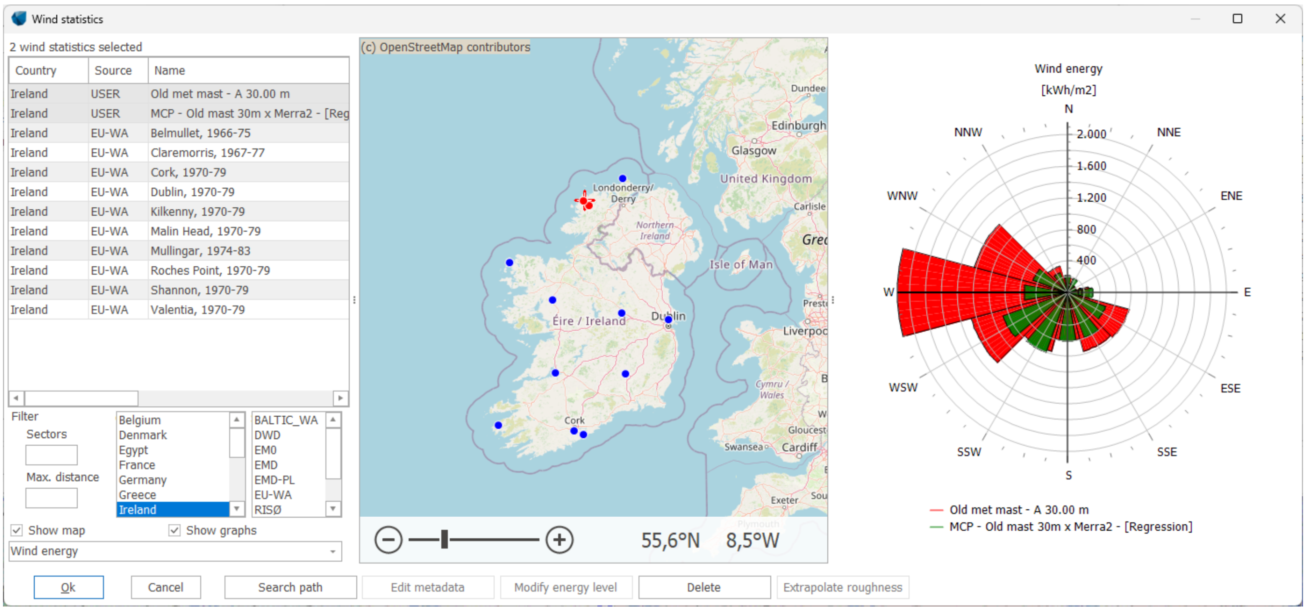


Figure 95 Wind statistics selection form. More statistics can be selected by <Ctrl>.

The wind statistics can be selected in the Site Data Object, and there will be graphical features for evaluation of the wind statistics. An important feature is that the “energy levels” can be compared, which can give an idea of how realistic a given wind statistics is by comparing to other wind statistics in the region.

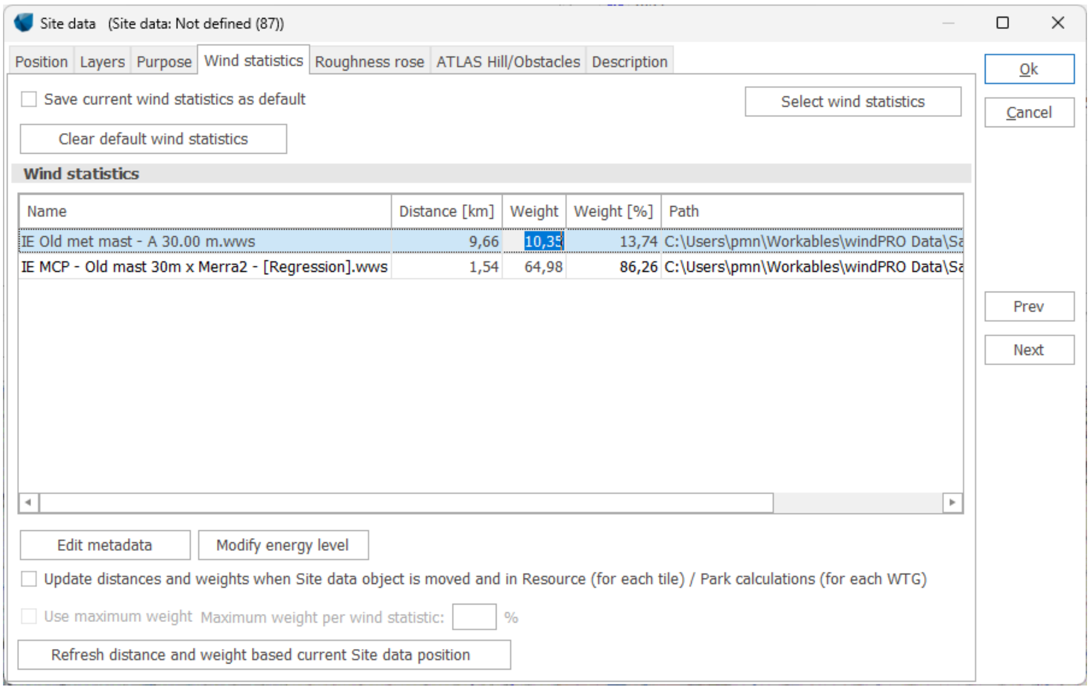
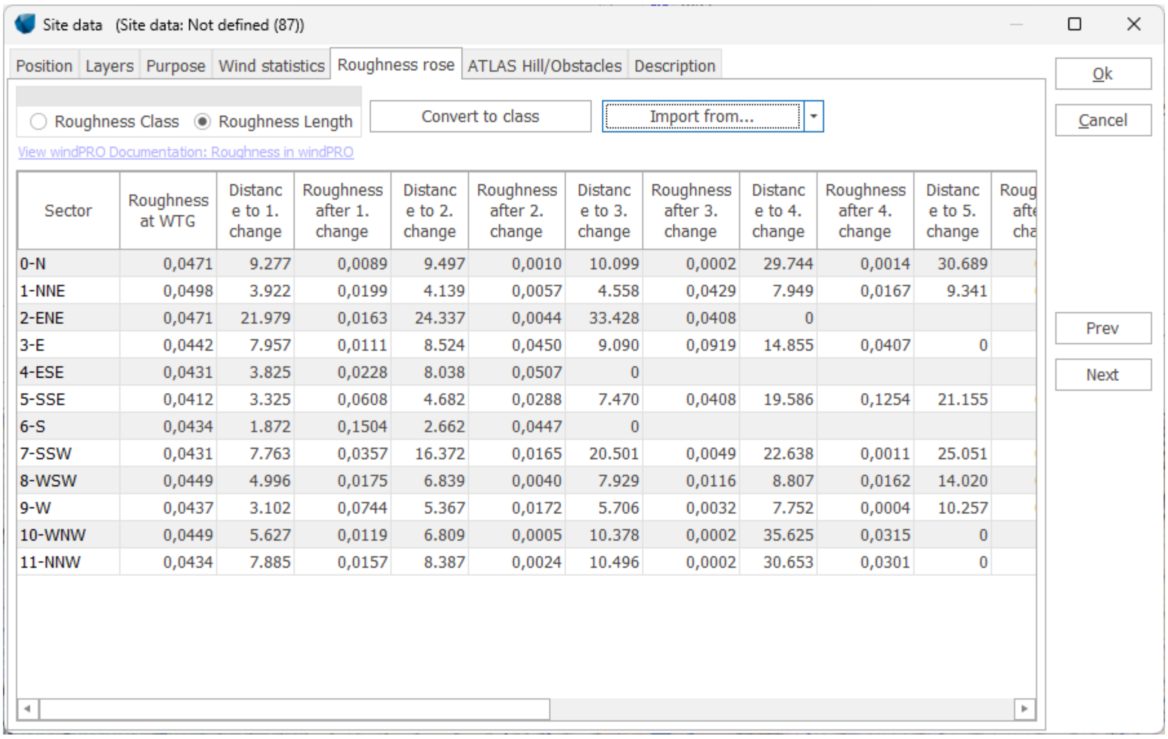


Figure 96 When more statistics are selected, individual weight can be given.

The weights given to each of more wind statistics can be decided manually. It can also be decided given by reciprocal distance weight, which can be auto updated when moving the Site Data Object on map. For resource map calculation, the auto update can be performed for each calculation point.



Sector	Roughness at WTG	Distance to 1. change	Roughness after 1. change	Distance to 2. change	Roughness after 2. change	Distance to 3. change	Roughness after 3. change	Distance to 4. change	Roughness after 4. change	Distance to 5. change	Roug afte cha
0-N	0,0471	9.277	0,0089	9.497	0,0010	10.099	0,0002	29.744	0,0014	30.689	
1-NNE	0,0498	3.922	0,0199	4.139	0,0057	4.558	0,0429	7.949	0,0167	9.341	
2-ENE	0,0471	21.979	0,0163	24.337	0,0044	33.428	0,0408	0			
3-E	0,0442	7.957	0,0111	8.524	0,0450	9.090	0,0919	14.855	0,0407	0	
4-ESE	0,0431	3.825	0,0228	8.038	0,0507	0					
5-SSE	0,0412	3.325	0,0608	4.682	0,0288	7.470	0,0408	19.586	0,1254	21.155	
6-S	0,0434	1.872	0,1504	2.662	0,0447	0					
7-SSW	0,0431	7.763	0,0357	16.372	0,0165	20.501	0,0049	22.638	0,0011	25.051	
8-WSW	0,0449	4.996	0,0175	6.839	0,0040	7.929	0,0116	8.807	0,0162	14.020	
9-W	0,0437	3.102	0,0744	5.367	0,0172	5.706	0,0032	7.752	0,0004	10.257	
10-WNW	0,0449	5.627	0,0119	6.809	0,0005	10.378	0,0002	35.625	0,0315	0	
11-NNW	0,0434	7.885	0,0157	8.387	0,0024	10.496	0,0002	30.653	0,0301	0	

Figure 97 Input form for roughness rose data

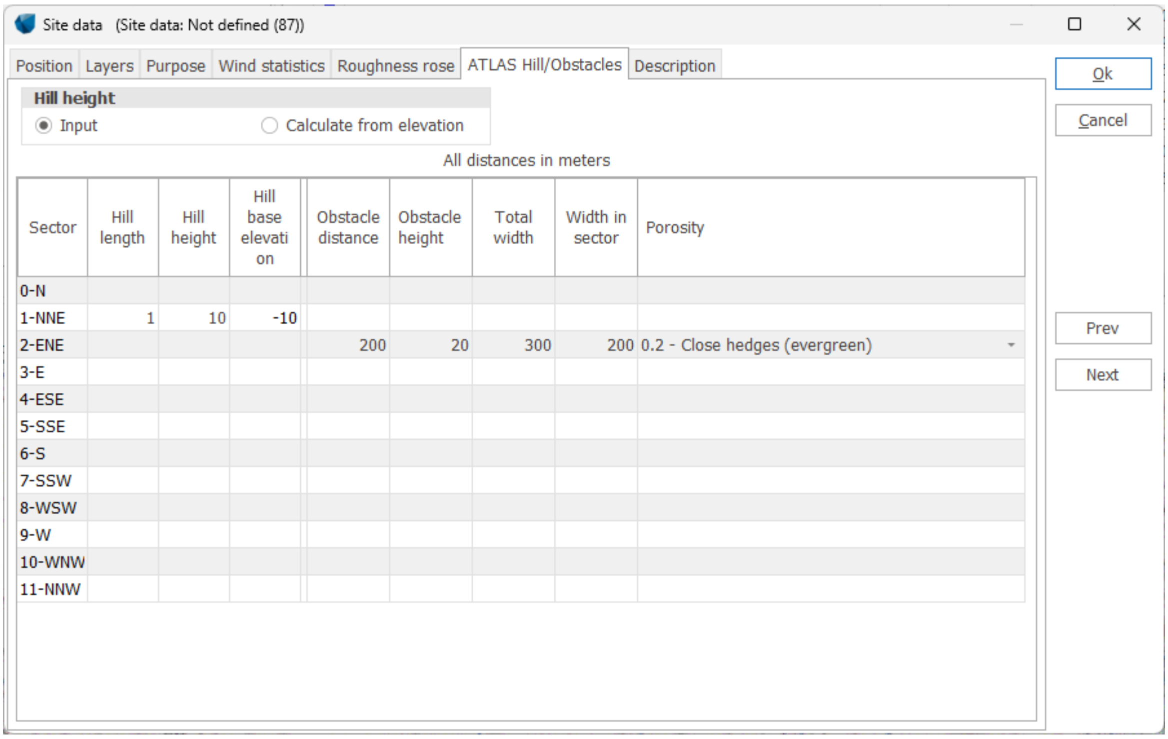


Figure 98 Input form for ATLAS Hill/Obstacles

The terrain (roughness, hills and obstacles) can be entered as values for each sector in the form, but more conveniently, choose OK to Site Data Object and make the input in graphic mode:

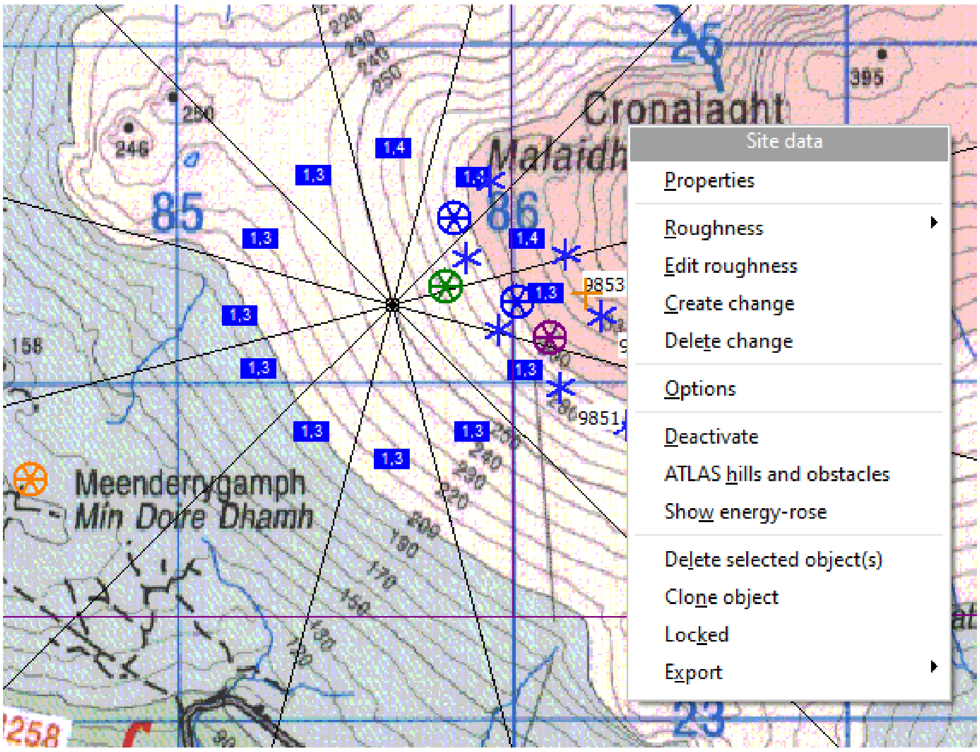


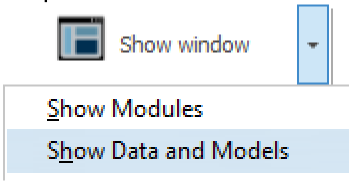
Figure 99 Graphic roughness rose establishment.

By right clicking roughness, changes can be established and the change distance can be dragged. Also, the roughness value can be set by right clicking and choosing “Roughness”. Similarly, hills and obstacles can be edited graphically by choosing the menu line “ATLAS hills and obstacles” in the right click menu as seen above.

3.5.3 WAsP interface

WAsP is the comprehensive wind atlas model calculation engine from Risø/DTU, first released in 1989, still in development and considered as the Industry standard for wind energy calculations. The WAsP model is fully controlled from windPRO and the user does not need to use the separate user interface for the WAsP model.

The installed WAsP versions can be seen by opening the Show Data and Models window from the Settings & Help tab:



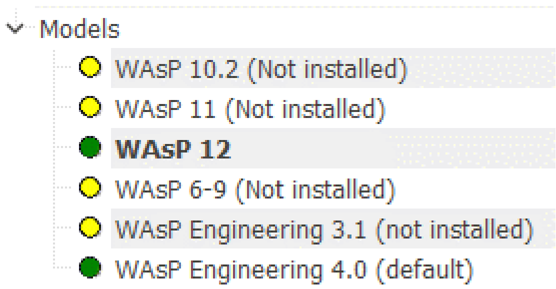


Figure 100 Models available/licensed

Green means “license activated”. It is important which WAsP version is used. In the validation Section, 8.4, an overview of the modifications in recent versions is analysed. It is of high importance to notice that, from WAsP ver. 10.2, roughness roses are no longer supported. Roughness data must be available as roughness line maps. This is the major change to WAsP 10.2, but this does not affect the traditional WAsP model. WAsP 11/12 includes CFD model handling,

Input:
- Site Data Object with wind statistics, roughness data)[2] and orography (link to files/line objects/grid objects)
- ALTERNATIVE to Site Data Object is WAsP-CFD result file(s) + wind statistics(s)
- Obstacles digitized on the map.
- Turbine types (from turbine catalogue or from a user defined wtg file) and hub heights
- Air density correction (world climate database available within software)
- Displacement height, optional calculated from sector wise displacement height calculator

Output:
- Calculated AEP (Annual Energy Production) for each turbine and hub height at position for Site Data Object (calculation point) as main report.
- Production analyses, Power curve analyses, Terrain, Wind data analyses, Wind profile (optional), Wind statistics info, Map as detailed report pages.
- Data files for spreadsheet analyses with turbine specifications, calc. results etc.

[2] Roughness data can be roughness roses (WAsP 9 or previous) or roughness line maps (all WAsP versions).

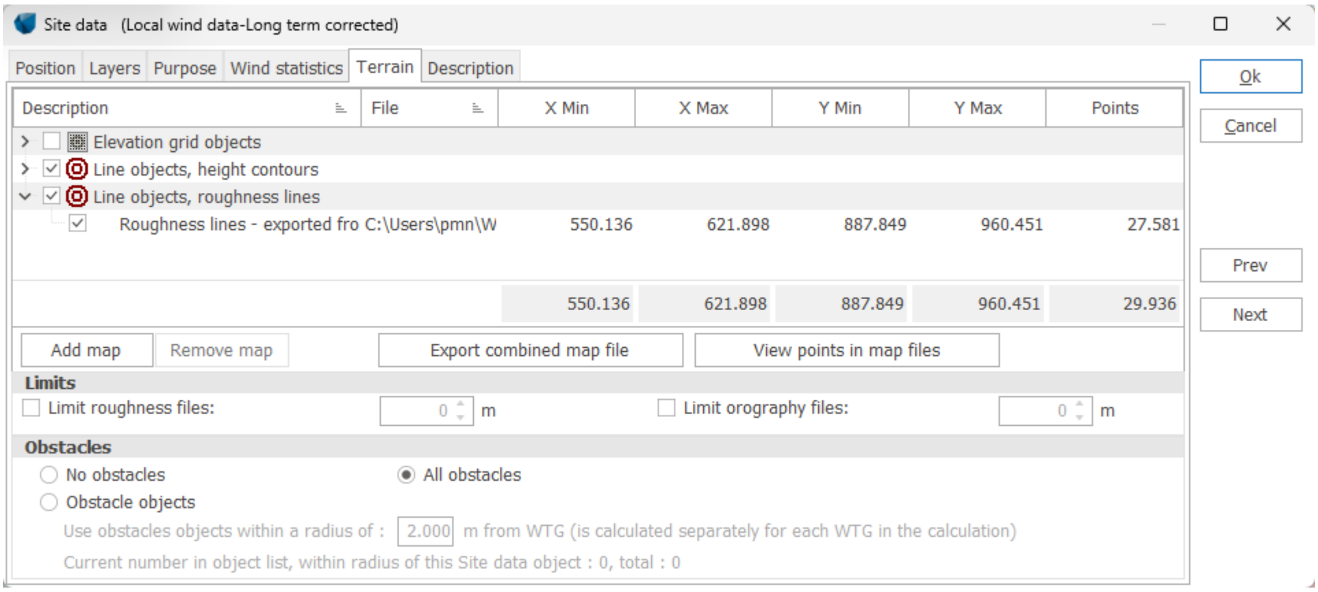


Figure 101 Selection of roughness and elevation data in Site Data Object

Above is shown the dialog box for input of elevation (orography) and roughness data. Note, more line objects, map files and elevation grid objects can be linked to the Site Data Object. All the checked ones will be used in the calculation. Be careful when using multiple datasets as this can create inconsistency, especially **having two different roughness line files overlapping can create huge calculation errors**. Thus, it is very important to be aware of which files are linked. The files linked are controlled by the settings on the line/grid objects, which have this box checked:

When checked, the data are automatically linked, when creating a Site Data Object. But NEW created line/grid objects with these setting will not be linked in a previously created Site Data Object.
When using Elevation grid objects for orography, the gridded data will, during the calculation, be converted to contour lines as specified at the WAsP tab in the elevation grid object. Elevation grid can have properties like “terrain”, “surface”, “sea depths”, which will decide it the object are relevant as input for energy calculations. By “surface” option, it can be doubtful, but it is accepted. The reason is that e.g., SRTM data are surface data, but very popular for energy calculations, although they can give misleading input in forest regions. The turbines will, if care not are taken, be handled as they are placed on the top of the forest.

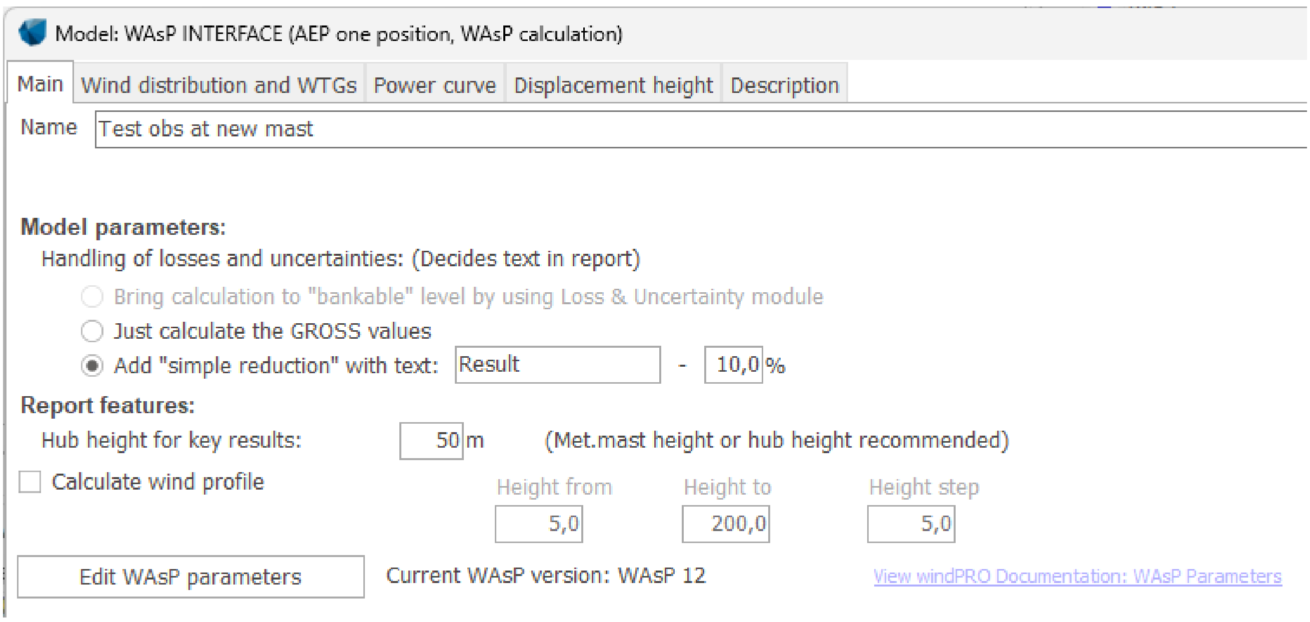


Figure 102 WAsP interface input form

The structure of input form is similar to ATLAS, but it has the extra tab for displacement height, which in combination with the wind profile calculation makes it an interesting analyse tool. The effects of as well Orography, Obstacles and Displacement height can be seen direction sector by sector vs. height in the reports.

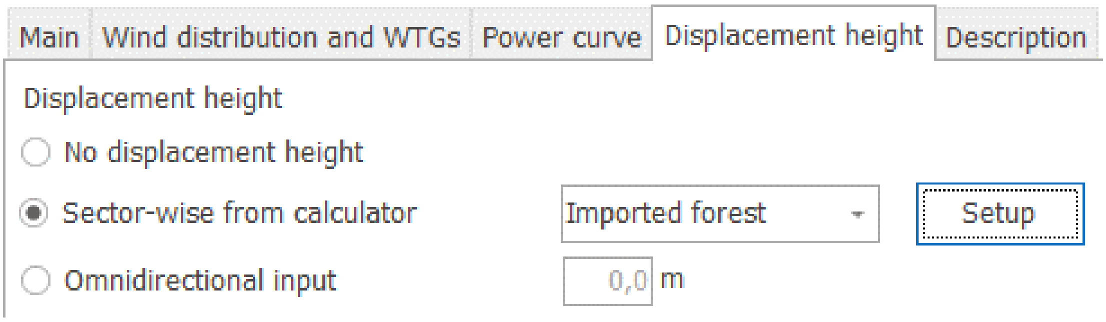


Figure 103 Set up displacement height in WAsP interface

3.5.3.1 WAsP parameters

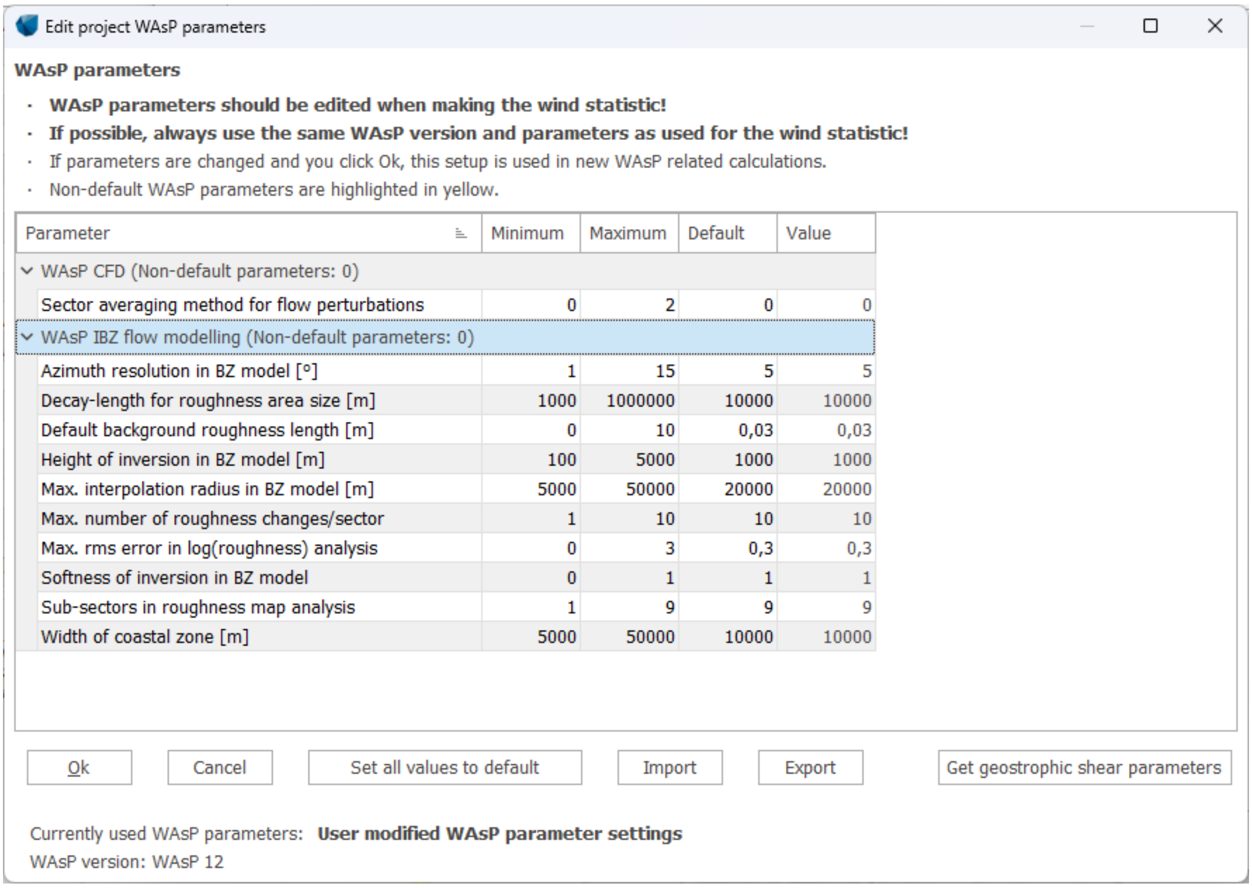


Figure 104 Edit WAsP parameters from windPRO

As an example, a few modifications are made to illustrate where changing parameters can be relevant:

Std. Height 5 is changed from 200 to 120m. If your hub height is 110 m, you might be better off using 100m and 120 m than 100m and 200m. The interpolation distance simply becomes smaller.
Std. Roughness #5 is changed from 1 m to 2 m. This could be relevant in a very high roughness region, where you expect above 1 m length (class 3.7), and thereby will avoid extrapolation, which is more uncertain than interpolation. (In the most recent, WAsP 11, extrapolation is not allowed).
Finally, the heat flux parameters could be relevant to change in very hot areas (deserts), or if you want to force water stability conditions, you can simply set the water parameters for land.

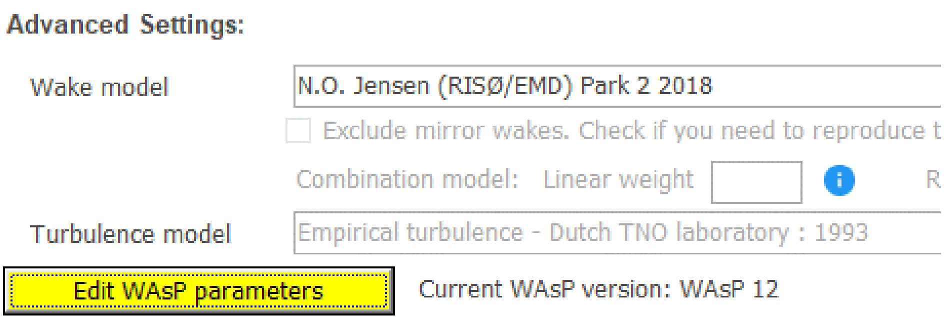


Figure 105 Edit WAsP parameters from windPRO

Remark: if WAsP parameters are changed from defaults, the button becomes yellow. When you are in other parts of the software, like in a METEO object, profile viewer, where you also have access to WAsP parameters, the button will also be yellow. This reminds you that you are working with modified WAsP parameters.
It is, of course, important that the modified WAsP parameters BOTH are used when generating the wind statisticss AND in the AEP calculation. (Going up/down with WAsP with same parameters). It will typically be in the METEO object or the Meteo Analyser experiments where "fixing" the WAsP parameters will be performed.

From WAsP 11, the WAsP parameters, when generating a wind statistics, will be saved as a part of the wind statistics and USED when calculating with this wind statistics. Thereby, it is not possible to go up/down with different parameters.

3.5.3.2 Geostrophic shear modelling

From WAsP 12 there are added two new parameters, which also are available from windPRO:

Parameter	Minimum	Maximum	Default	Value
Geostrophic shear modelling (Non-default parameters: 0)				
Baroclinic direction [°]	-180	180	0	0
Magnitude of dG/dz [m/s/ms]	0	0,012	0	0

The vertical and horizontal extrapolation models in WAsP are modified to take into account large-scale horizontal temperature gradients ('baroclinic' effects), which induce geostrophic wind shear. The method is implemented by extracting average geostrophic-scale wind shear from global CFSR reanalysis data, with values from the nearest grid points automatically used to provide more accurate AEP predictions. *(Explanation from WAsP Help)*

It must although be noted that the modifications in general are small, and only relevant when extrapolating data in height.

3.5.4 WAsP-CFD

WAsP-CFD is part of the WAsP from version version 11 and later. The base concept is the wind atlas method, but with the Ellipsys (DTU) CFD model as the flow modelling engine. The WAsP-CFD model has a very high resolution and can, so far, only run as a remote Cluster calculation, hosted by EMD. The calculation procedures are fully controlled from windPRO. Calculation credits must be purchased to run WAsP-CFD calculations. See further details in Chapter 4, where also the input data for WAsP-CFD is described as well as links to validation.

Input:

- Site Data Object with roughness data and orography (link to files/line objects/grid objects) + Defined 2 x 2 km calculation areas.

Output:

- Job to send to Cluster for calculation
- When Job is done, an email notification is sent
- When reopening the calculation, CFD result files can be downloaded
- WAsP-CFD result files can be used in PARK calculations, WAsP and Resource calculations, and also from the Meteo Analyzer and METEO objects.

3.5.4.1.1 WAsP compared to WAsP-CFD

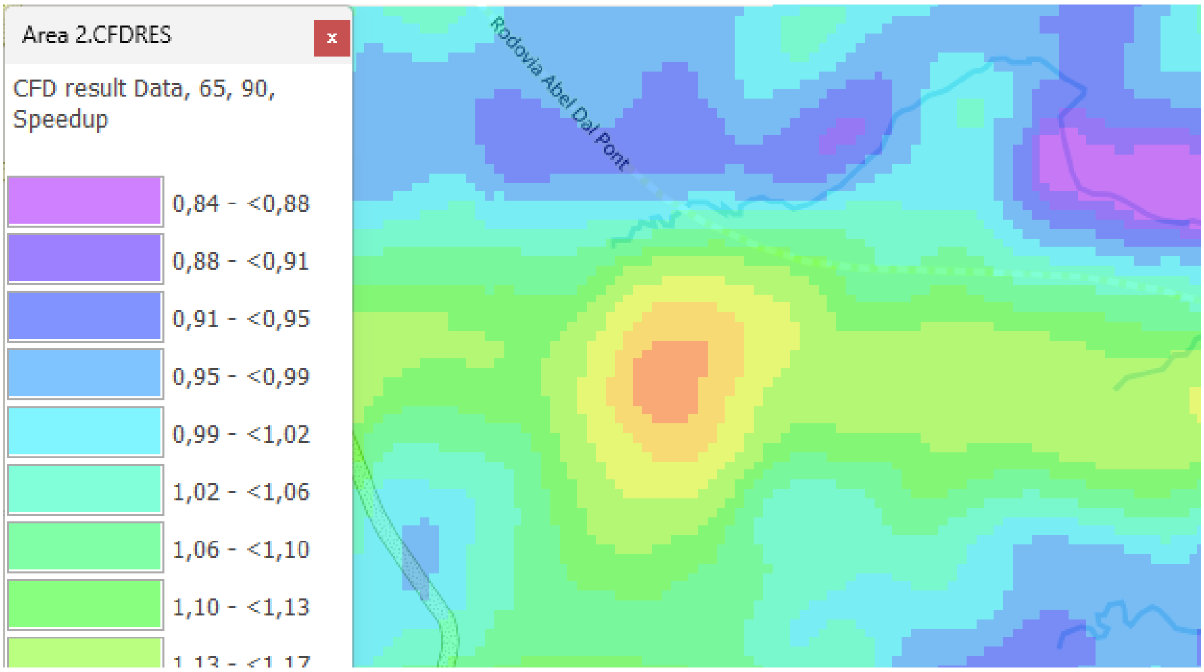


Figure 106 Example of WAsP result compared to WAsP-CFD result.

The main reason for using WAsP-CFD is to have a higher calculation accuracy in complex terrain. It is a "known issue" that WAsP tends to over predict low elevated turbines relative to higher elevated, when the terrain is relative smooth (not steep). The figure above shows the WAsP minus the WAsP CFD calculated wind speeds. In the low valleys, WAsP calculates up to 1.5 m/s higher wind speeds than WAsP-CFD. When the terrain gets complex (steepness > 30%), the differences can be even larger.

3.5.5 Resource maps

This section describes a wind resource map calculation. The tool can calculate a wind resource map based on
- WAsP model.
- WAsP-CFD result files.
- the Scaler, which can use WAsP, WAsP-CFD and .flowres files from third-party CFD flow models.

Resource maps can also be
- rescaled based on one or more measurements within the resource area.
- be downloaded from menu "Data", here .siteres files from the GASP project are available globally.

The module can also produce a resource map report based on external files, e.g., from other CFD calculation tools, delivered as .RSF or .WRG files.

3.5.5.1 Resource map calculation based on wind statistic(s)

The resource map calculation can utilize multiple cores on the PC and even get "support" from other computers connected to the network and, thereby, process large resource maps with high resolution within a reasonable time.

Input:
- Site Data Object with wind statistics, roughness data and orography (link to files/line objects/grid objects)
- ALTERNATIVE to Site Data Object is WAsP-CFD result file(s) + wind statistics(s)

Optional:
- Obstacles digitized on the map
- Displacement height calculation setup

- RIX calculation and RIX correction setup

Output:
- Resource map report
- Resource map file (can be used in PARK and OPTIMIZE module as input for AEP calculation and visualized by RESULT layer on map). The format is .RSF, the native WAsP format OR the EMD defined .siteres format.

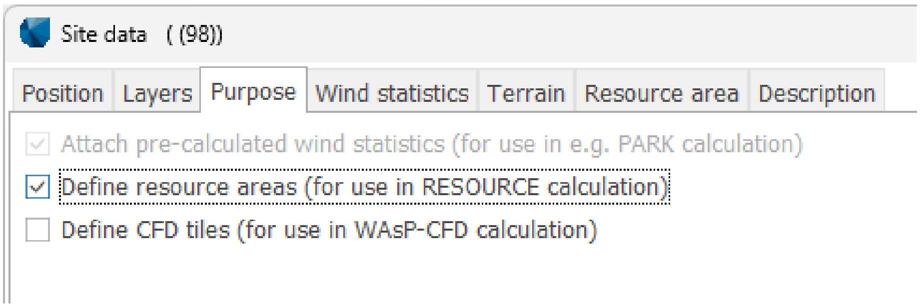


Figure 107 Purpose in Site Data Object set for Resource map calculation

Within the Site Data Object, select the option to define resource areas, where there will be a few differences from previous described input to Site Data Object:

Figure 108 Select wind statistics(s) for resource map calculation

When choosing multiple wind statistics (selected by holding <CRTL> down), these can be distance weighted within each calculation point. A maximum weight can be entered, e.g., 80% and, thereby, non-logical "high/low spots" just at the wind statistics point can be avoided.
Distance weights can also be given manually (fixed at any calculation point) by unchecking "Update…".The terrain specification follows previous descriptions. For a resource map calculation, roughness roses are NOT possible no matter which WAsP version is used.

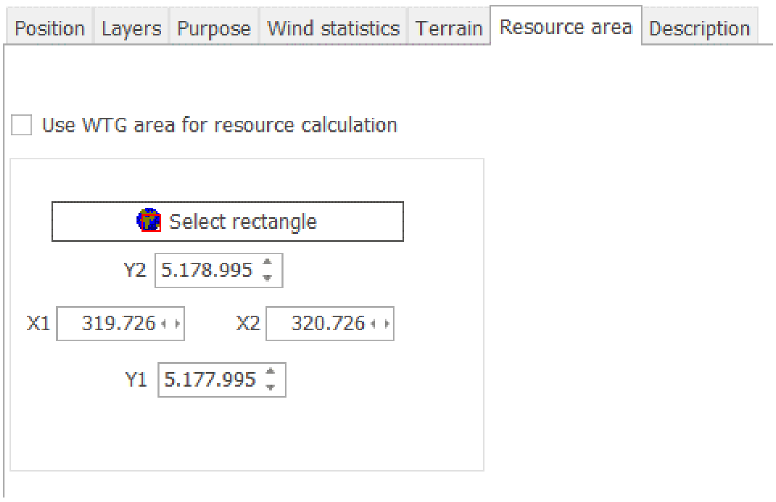


Figure 109 Resource map calculation area

The resource calculation area can be defined by a rectangle at the Site Data Object by manually entering the coordinates, drawn out on the map, or by use of a WTG-area object.

Having the Site Data Object defined, the calculation module can then be activated:

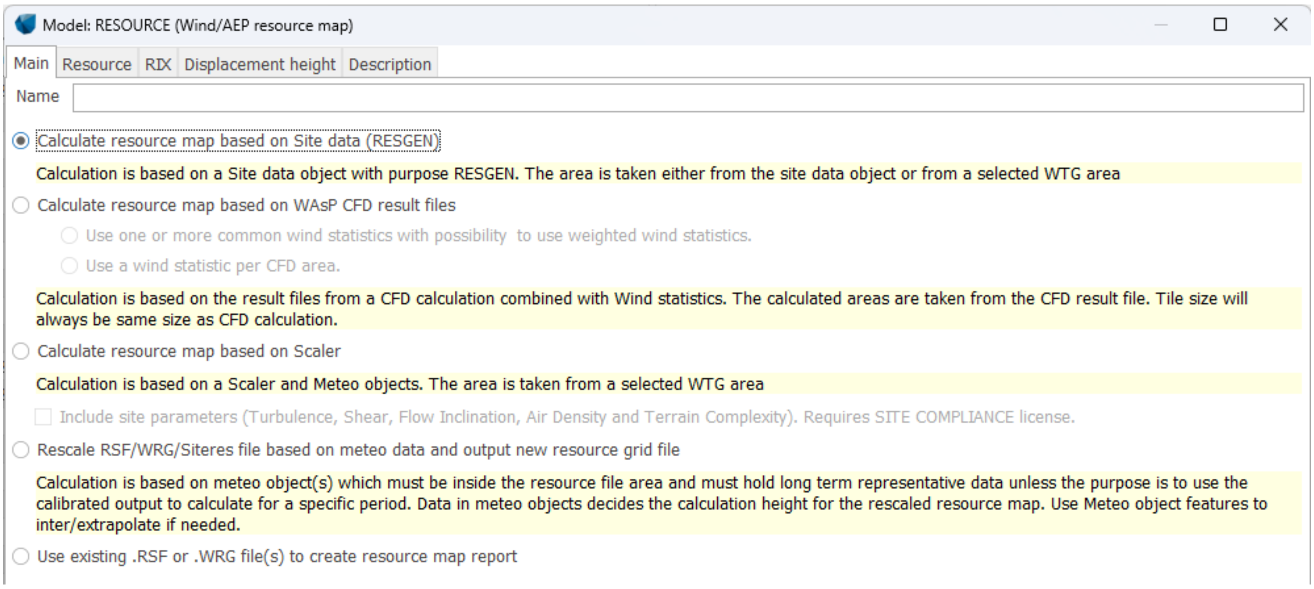


Figure 110 Resource map calculation options

The calculation variants are basically to either perform the WAsP based calculation or to utilize already calculated data from WAsP-CFD or other providers, that delivers resource map files in WAsP format. The siteres format developed by EMD can in addition to wind resource parameters also include parameters with relevance for e.g., load calculations, like TI, inflow angle etc. This requires the Site Compliance module to be licensed. Please note that calculations can take a long time to complete if this option is selected as Site Compliance tests have to be run for all grid points. The larger the area and the finer the grid, the longer this will take. We recommend starting with a coarse grid to test the speed of the calculation and refine it as required.

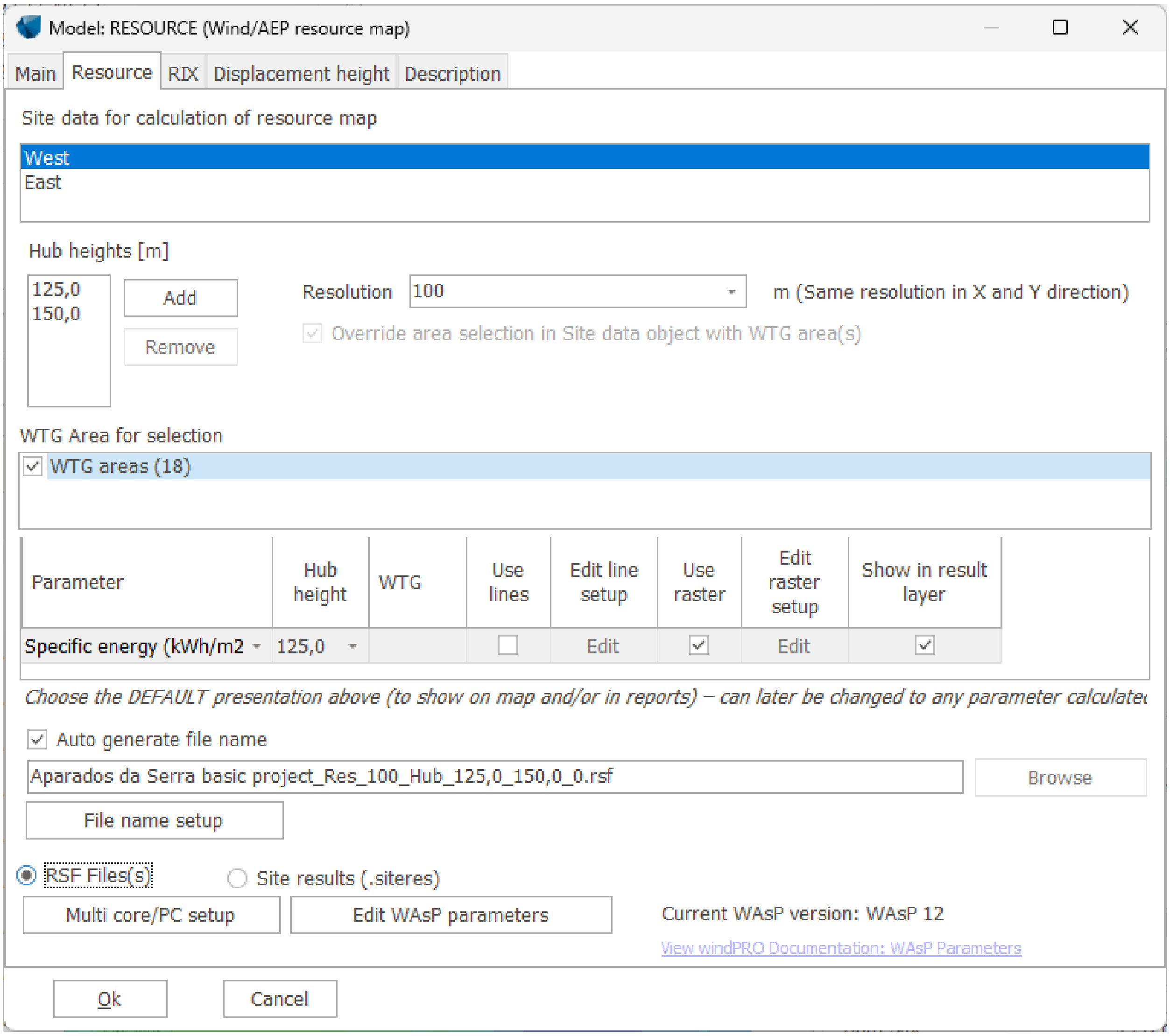


Figure 111 Resource calculation input options

The figure above shows how the resource specification of hub heights (multiple possible) and resolution are defined.

The calculation area can be defined in the Site Data Object (square) or it can be defined by one or more a WTG-area objects (freely digitized). The last option requires the box "Override area…" to be checked. The Parameter to show on map and/or in a result layer can be defined along with formatting the legend before the calculation. These choices can always be changed after calculation.

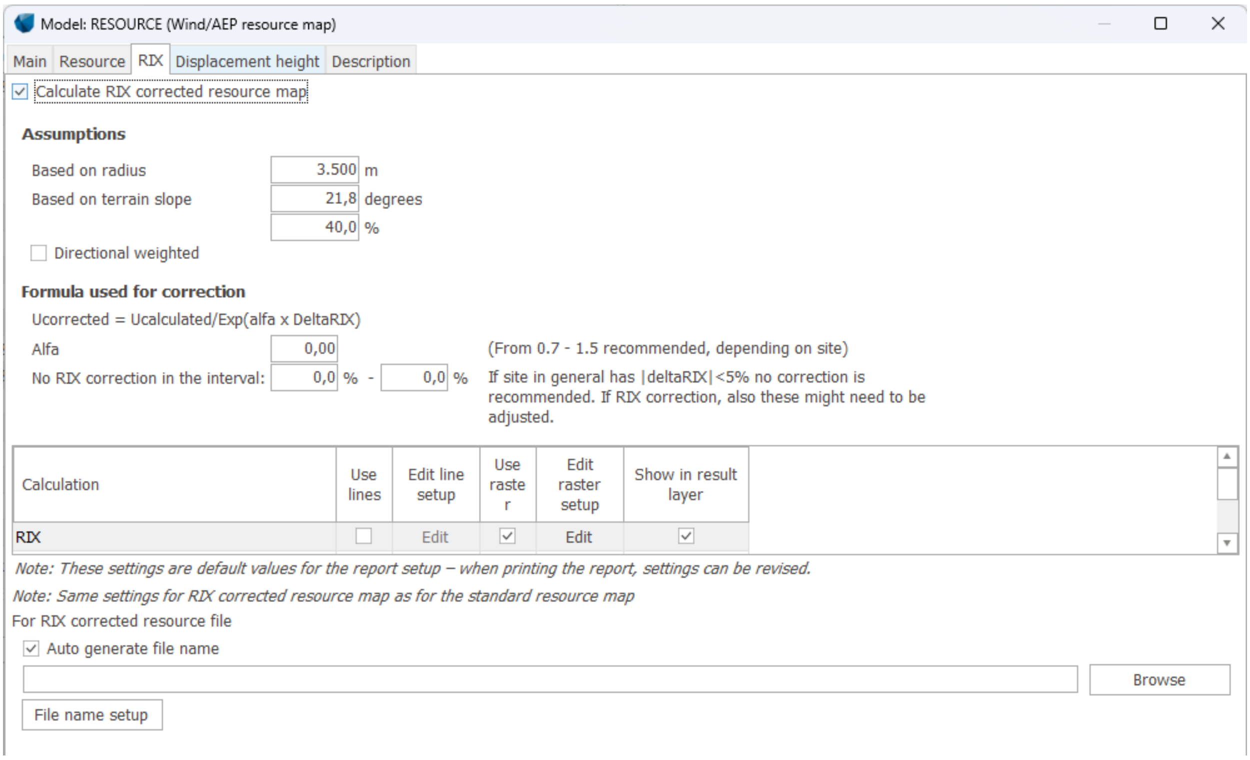


Figure 112 Input of RIX correction handling in resource map calculation

RIX correction can also be included (see Section 4.10 on “RIX correction” for details). When RIX calculation/correction is chosen, there will be (optional) 4 result layers:

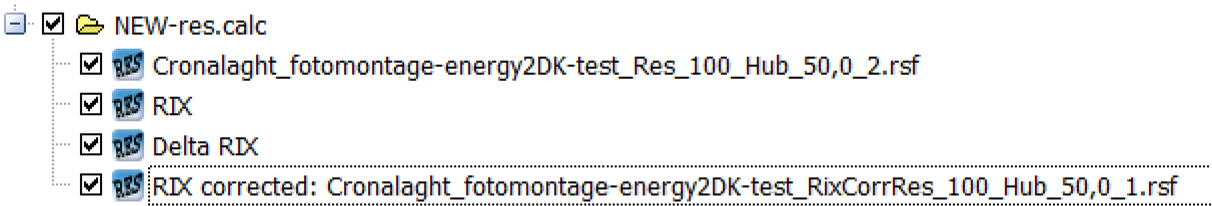


Figure 113 Result layer output from Resource map calculation with RIX

The uncorrected resource map as well as the RIX and Delta Rix maps can be seen along with the RIX corrected resource map. By establishing a compare layer, the difference between the Rix corrected and uncorrected resource maps can be presented.

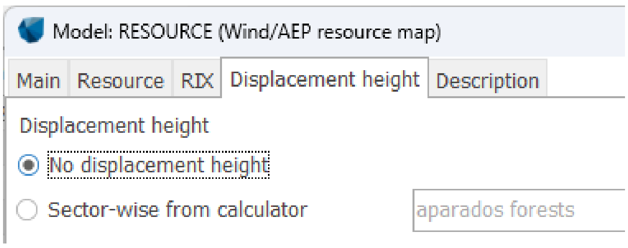


Figure 114 Displacement height input by resource map calculation

Finally, displacement height corrections can be included in the resource map calculations (see details in Section 4.9, “Displacement height calculator”).

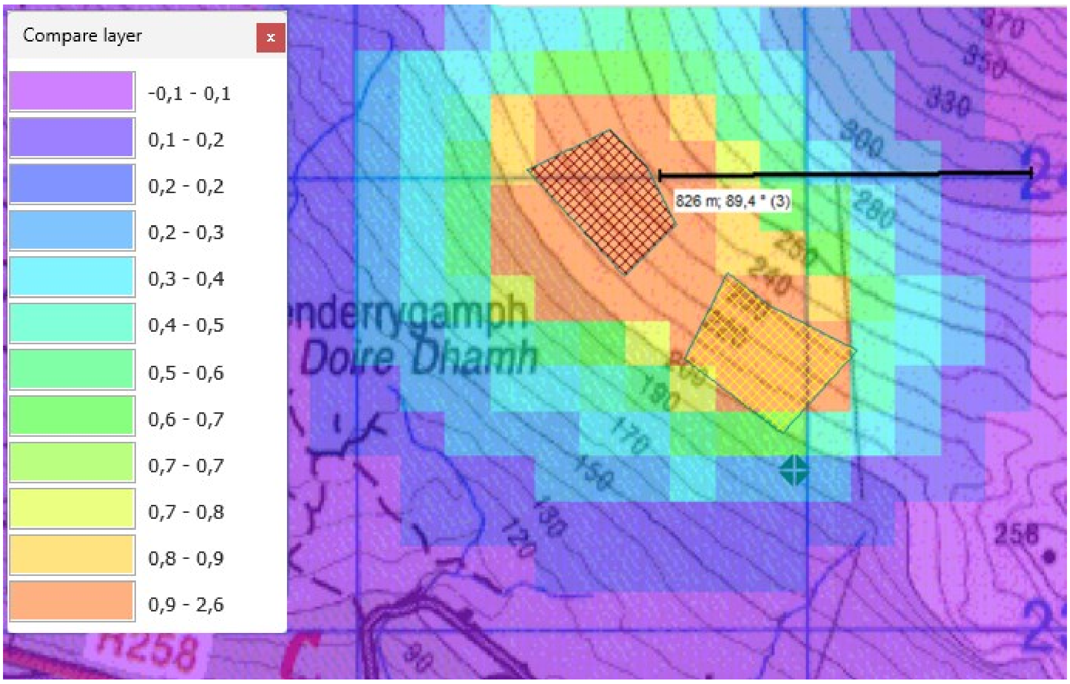


Figure 115 Example of resource map difference output with displacement height

Above, a test calculation with two forest pieces (hatched) with different heights are shown in a resource calculation. Then, a compare layer is established showing the wind speed without and with a displacement height calculation. It works as expected, with a gradual reduction as the distance to the forest increases.

3.5.5.2 Resource map calculation based on SCALER

A resource map can be based on the SCALER concept, meaning that each time step wind speed is scaled to each point in the resource grid. The data are collected in TAB files at each grid point, which are Weibull fitted and then saved in .RSF file.

Input:

- WTG-area object for defining the calculation area
- Height(s) and grid resolution
- SCALER, including wind data selection (more wind masts/mesoscale data points can be used with interpolation), terrain/model and eventually post scaling.

Optional:

- Obstacles digitized on the map
- Displacement height calculation setup
- RIX calculation and RIX correction setup

Output:

- Resource map report
- Resource map file (can be used in PARK and OPTIMIZE module as input for AEP calculation and visualized by RESULT layer on map). The format is .RSF, the native WAsP format OR the EMD defined .siteres format.

3.5.5.3 Resource map rescaling

Since windPRO 3.5 is has been possible to rescaling an existing resource map.

◉ Rescale RSF/WRG/Siteres file based on meteo data and output new resource grid file

Calculation is based on meteo object(s) which must be inside the resource file area and must hold long term representative data unless the purpose is to use the calibrated output to calculate for a specific period. Data in meteo objects decides the calculation height for the rescaled resource map. Use Meteo object features to inter/extrapolate if needed.

This can be convenient for e.g., large offshore sites with a mesoscale wind speed gradient or if an external flow modeling is available as a resource map, but based on a preliminary wind speed assumption. Then the wind speed level can be adjusted without having to rerun the flow model after local measurements have become available, for example.

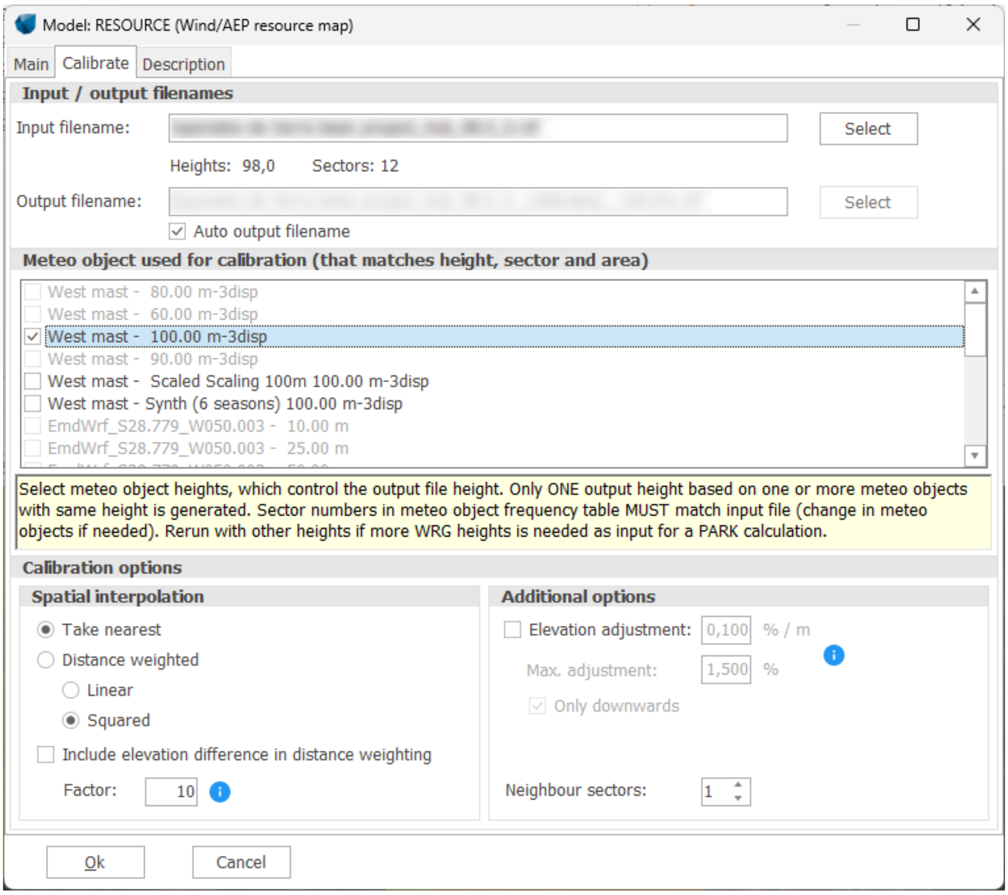
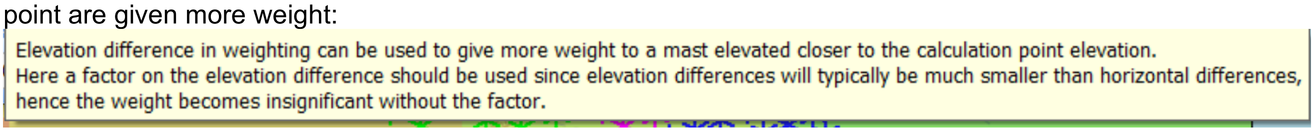


Figure 116 Input data for rescaling a resource map.

First a resource map is selected, in either a .rsf, .wrg or .siteres format.
Next, the meteo object(s) are selected. Since the rescaling feature uses the frequency table, the meteo object must have the same number of sectors as the resource map. The number of sectors can be changed in the meteo object. Only one height can be used in a rescaling, but multiple meteo objects with different positions can be used. When selecting one height all non-matching heights are greyed out.
If multiple meteo objects are selected, a spatial (horizontal) interpolation method can be activated. A special option is to include elevation difference in distance weighting. Thereby masts elevated closer to the calculation point are given more weight:



As an additional option, the elevation can be used for further adjustment of the resulting resource map. This can compensate for flow models tending to underestimate wind speeds at higher elevated areas compared to lower elevated areas of the site. Note that if the site has a steep terrain causing flow separation, then this can go in the other direction, that the flow model overestimates the highly elevated spots. For such sites, this option is not recommended. But in normal hilly terrain multiple cases show 0.3% flow model bias, so the default is rather conservative. An upper limit can be set, just remember to increase this to get the full effect of the adjustment, if it seems relevant to use with more measurements on a site. See validation chapter 3.9.5 Elevation model pitfalls.

The Neighbor sector option is default set to 1, meaning that when the model and observations are used to find the adjustments for a given direction sector, it looks in one neighbor sector to each side to come up with the revised frequency for the sector. Then a turn of the wind will be smoothed. At sites with much turn and a high sector resolution, like 10-degree sectors, it might be relevant to expand using two neighbor sectors, but normally one neighbor sector will be the best choice.

With the choices selected, the recalibration is performed with <OK>, and a rescaled/calibrated resource map will appear as result layer. This can be used as input in a PARK calculation.

3.5.6 STATGEN

The STATGEN module generates a wind statistics based on wind data in a METEO object and terrain data with the WAsP model or WAsP CFD result files as the generator. Also, mesoscale data can be used. Here although the mesoscale model terrain should be used. This is possible when using EMD-WRF data, while these includes mesoscale model terrain files in the meteo object with mesoscale wind data.

Input:

- METEO object with wind data
- Site Data Object with roughness data and orography (link to files/line objects/grid objects)
- ALTERNATIVE 1 to Site Data Object is WAsP-CFD result file(s)
- ALTERNATIVE 2 to Site Data Object is mesoscale terrain from EMD-WRF data in meteo objects
- Data period to be used

Optional:

- Obstacles digitized on the map (Can be turned on/off in Site Data Object)
- Displacement height based on object data OR advanced calculator (sector wise)

Output:

- Wind statistics (.LIB(WAsP original format) or .WWS (windPRO format) file)

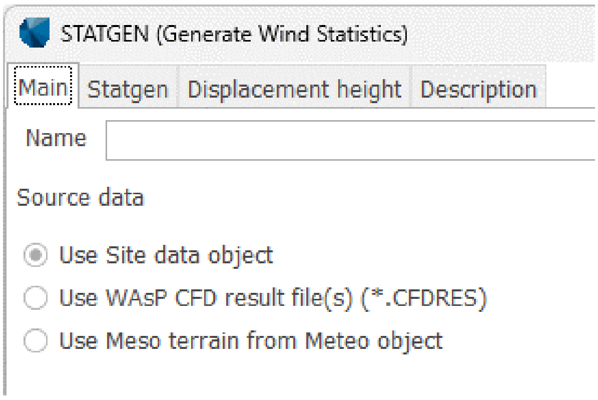


Figure 117 Main input for STATGEN calculation

In the main form, the “terrain source” is chosen. In a Site Data Object, the traditional WAsP input of roughness and orography + info on inclusion of obstacles is defined. WAsP-CFD result files include, indirectly, the terrain (results are processed with terrain). Making a wind statistics directly from mesoscale modeled wind data (currently, only from EMD) offers the possibility to use the mesoscale terrain when generating the wind statistics.

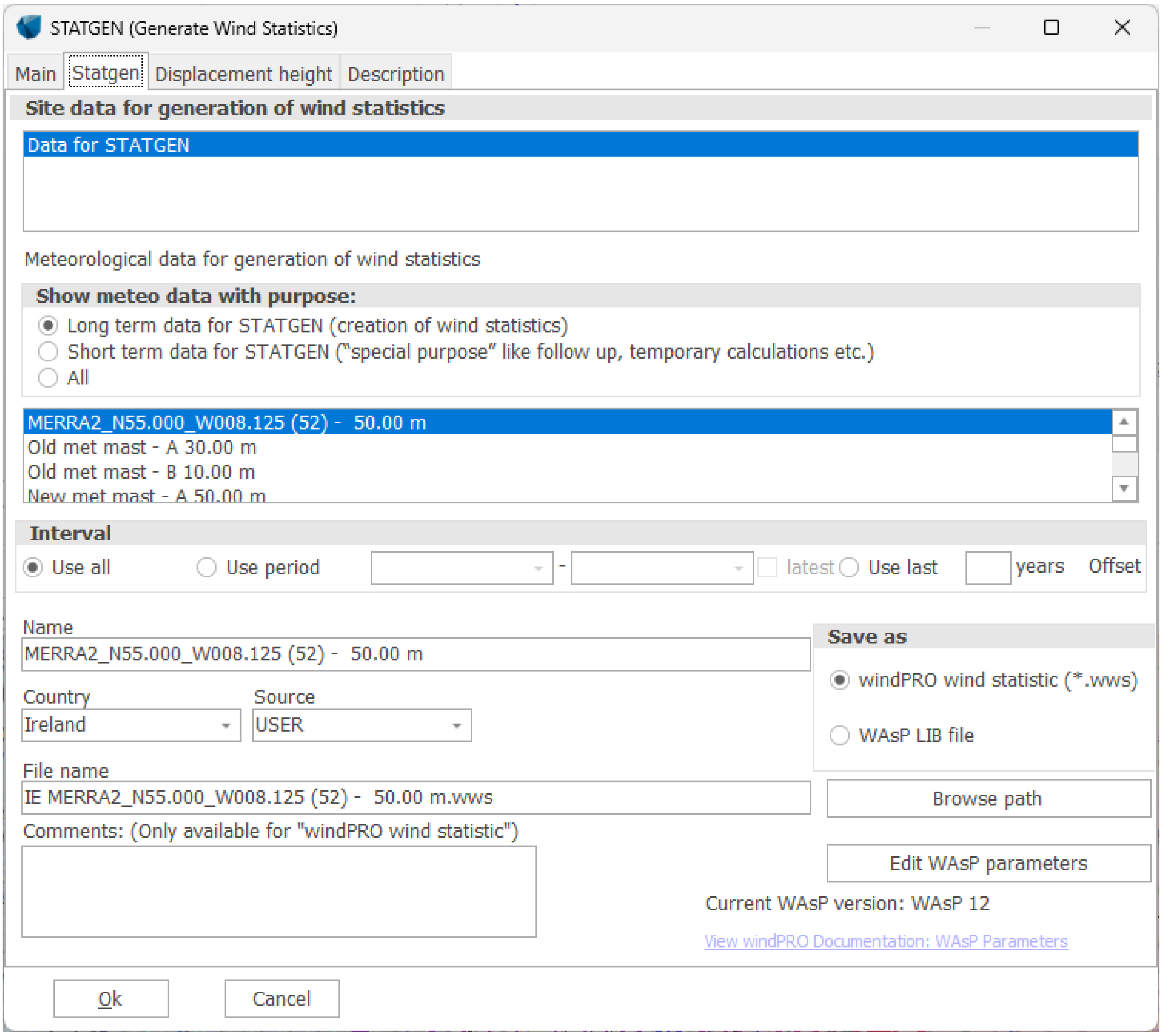


Figure 118 Statgen input form

On the "statgen" tab, the site data or CFD results or mesoscale data are selected as well as the wind data to be used.

The WAsP parameters can be modified (see Section 6.3.1 for details).
Saving the results as a .wws file, all relevant information will be included, like length of wind data series, WAsP parameters etc. This information can be printed as a part of all WAsP based calculation reports (see example below):

A new 3.1 feature is the selection of a specific period. Thereby measurements can be truncated to full years, or for mesoscale data it can be decided to use like last 20 or 10 years. In addition, the inclusion of the general Displacement height calculation tool, optional sector wise by calculator is new in 3.1.

WAsP interface - Wind statistics info

Calculation: test

Main data for wind statistic

File	C:\Users\per.EMD\Documents\WindPRO Data\Projects\Ireland\Cronalagth\IE New site mast (heights uncertain-DIR subst) (Regressions-MCP anvender Malin Head).wws
Name	New site mast (heights uncertain-DIR subst) (Regressions-MCP anvender Malin Head)
Country	Ireland
Source	USER
Mast coordinates	ITM East: 586.278 North: 923.969
Created	05-06-2012
Edited	05-06-2012
Sectors	12
WAsP version	WAsP 6-9 RVEA0011.dll 1, 0, 0, 13

Comments
Fra MCP

Additional info for wind statistic

Based on measurement height	40,0 m
Base elevation for measurement mast	301,0 m
Long term correction information	
Method	Regressions-MCP
Source data	Malin Head
Distance to source data	3,9 km
Long term period from	01-01-1991
Long term period to	01-01-2001
Concurrent period from	01-09-1999
Concurrent period to	01-09-2000
Concurrent data records	5254
Concurrent record interval	60 minutes
Concurrent data recovery	59,8 %
Number of years with long term data	10,0 years
Number of months with concurrent data	7,2 Months
Correlation test based on Concurrent monthly windindices	
Power curve used for index	Simpel effektkurve der mætter ved: 14,0 m/s
Data availability demand for inclusion of month	60 %
Number of months	6
r^2 - wind index	0,9803
r - wind index	0,9901
s - wind index	4,7691

Note
To get the most correct calculation results, wind statistics shall be calculated with the SAME model and model parameters, as currently chosen in calculation. For WAsP versions before 10.0, the model is unchanged, but thereafter more model changes affecting the wind statistic is seen. Likewise WAsP CFD should always use WAsP CFD calculated wind statistics.

Figure 119 Wind statistics info report output generated from MCP

A wind statistic can also be generated from MCP, which normally are recommended, while this includes the long term correction.

See further information in Section 3.2, "wind statistics," for more details on the structure of the wind statistics.

3.5.7 Flow request export (FLOWREQUEST - FLOWRES format)

A new windPRO 3.1 feature is a flexible data exchange with external models.
It consist partly of creation of a flow request file, which basically is an export of the terrain data lined up in the windPRO project, partly of the capability to use flow model results from external model providers. The flow result file format FLOWRES is detailed described so any model providers can establish this format as output from their models. Then windPRO can use the flow result files in relevant calculations, like Resource map calculation, PARK calculation etc.

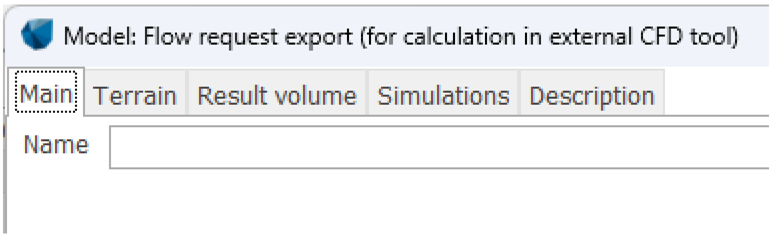


Figure 120 Flow request export

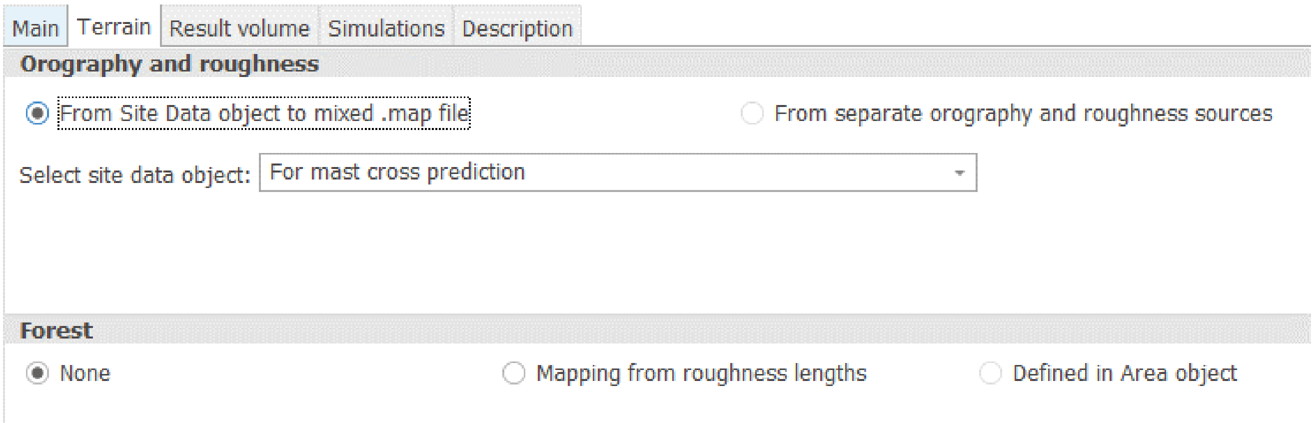


Figure 121 Terrain setup for flow request files.

The terrain (roughness and orography) need to be specified in a Site Data Object.
Forest data can be included based on roughness map files. The Roughness lengths interval that shall generate forest data output must be specified. Then forest height and forest density can be specified.

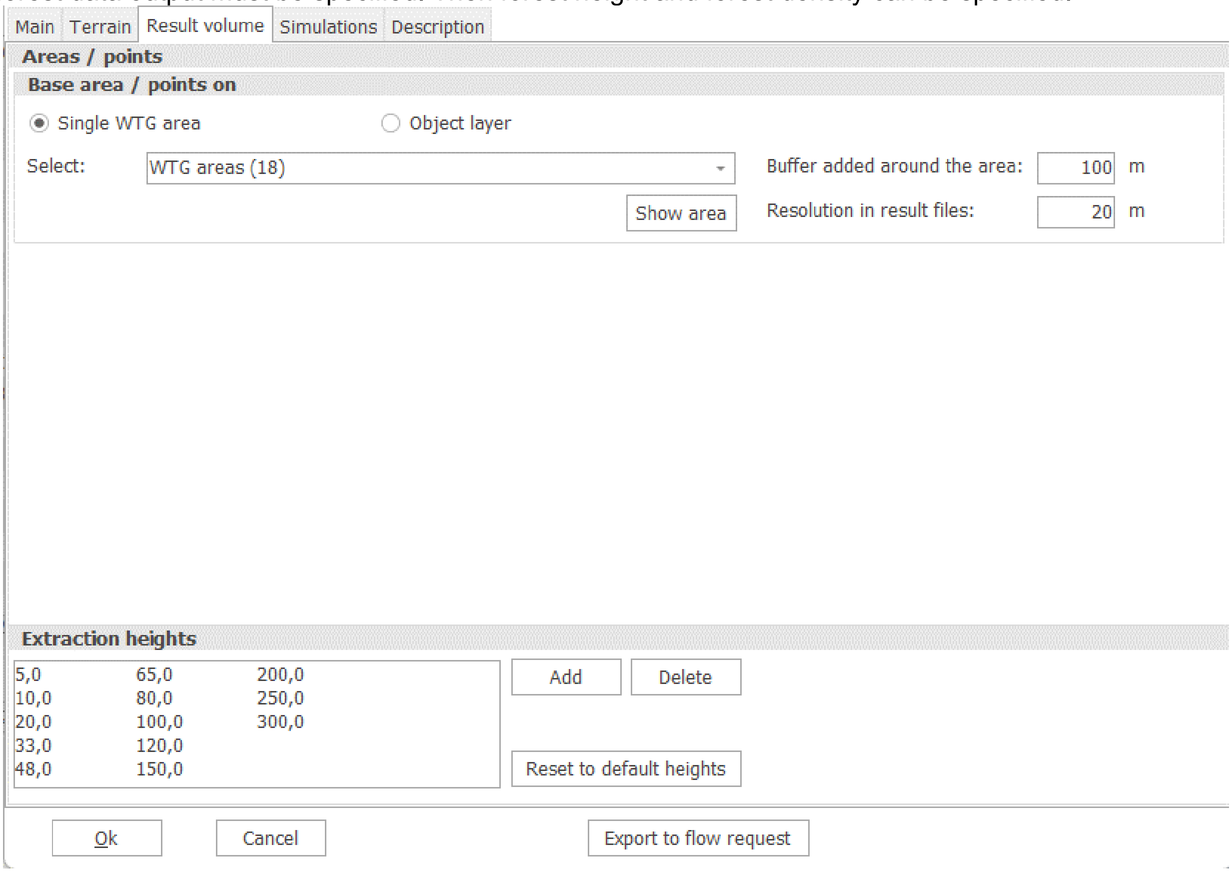


Figure 122 Definition of the Result volume.

Here the volume to be calculated is specified. Partly by horizontal limits, given either by a WTG area object or by object layer. Last option simply draws an area around the objects at selected layer. Partly by extraction heights. Depending on which model that uses the flow request file, there might be limitations in calculation heights. And some models might not read this information but require manual input by the model run.

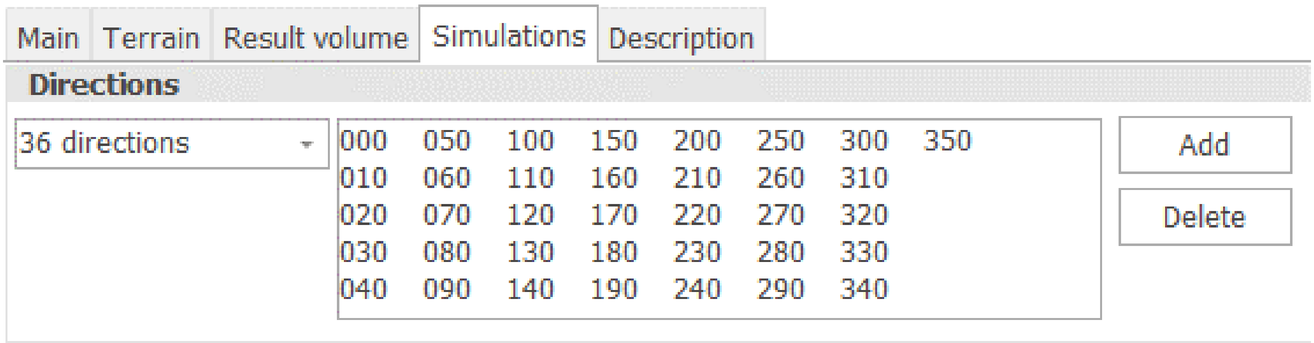


Figure 123 Definition of direction sectors to be simulated.

Finally the number of, and which direction sectors that model calculations are wanted for can be defined.

When all is defined, the “Export to flow request” button is pressed. Then a name and where to save it must be specified.
If OK is pressed, an assumption report is generated for documentation of the settings.

Next step will then be to start the external software, read the file and start a calculation.
When calculation is done, a FLOWRES file can be exported from the external software.
This can then be used from windPRO similar to where like WASP-CFD result files can be used, e.g., from a PARK calculation.

3.6 PARK calculation

The PARK calculation is the “center” within an energy calculation. It partly models the wind distribution at each turbine position in hub height and partly the wake losses, thereby creating the calculated AEP for each turbine. Further refinement of the AEP expectations can be given by taking a PARK calculation result into the Loss & Uncertainty module.

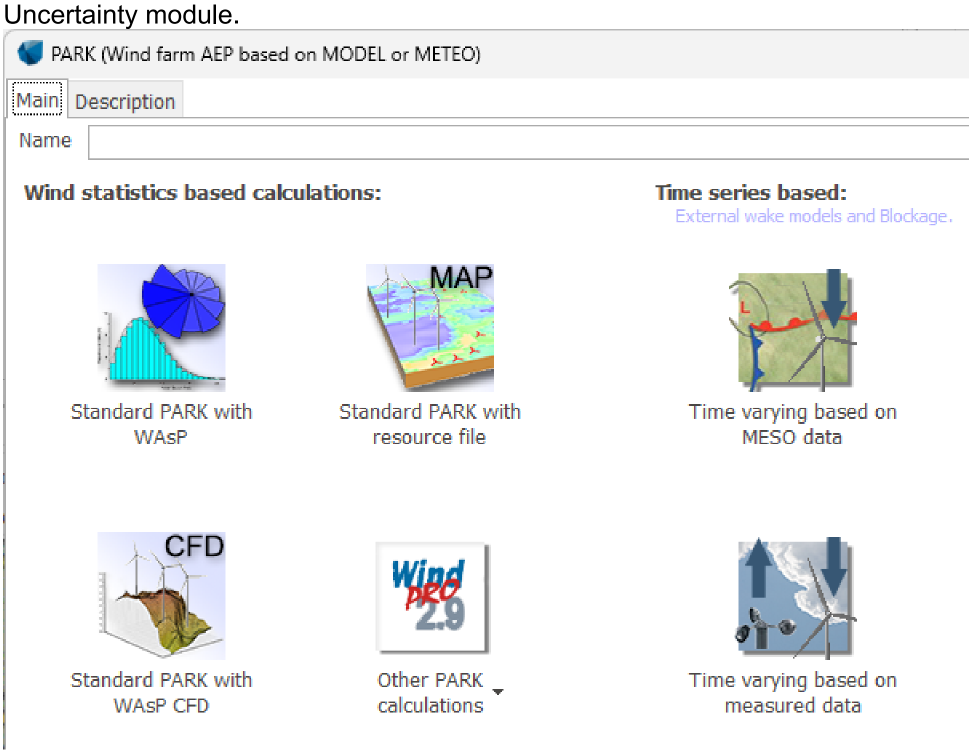


Figure 124 PARK calculation, selection of method

Above is the start dialog box of the PARK module. 6 main groups of setting up a PARK calculation are available. External wake models and Blockage are described in document available from link. From 3.4 the WakeBlaster model is available as external model, only within the time series concepts so far.

Additional options are available under Other PARK calculations, such as:

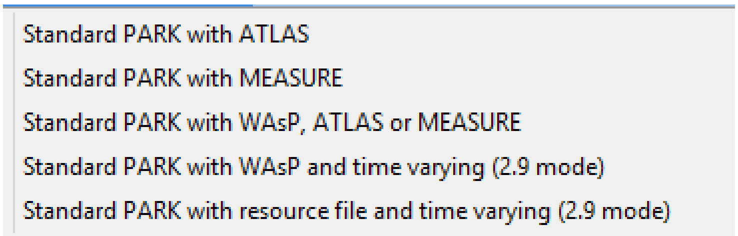


Figure 125 2.9 compatible PARK model choices

The windPRO 2.9 options are kept for backward compatibility - but can also still be relevant (though these options are rarer, nowadays). These will not be documented in this manual, but documentation can be found in the windPRO 2.9 manual.

3.6.1 The wake loss (PARK) models

The PARK module calculates the wake losses due to the shadowing effects between WTGs sited close to each other (wind farms or clusters). PARK offers more different models for calculating wake losses, including Blockage as option, which reduces wind speeds upwind.

Wake model overview	Statistical	Time step	Blockage	Note
Original N.O. Jensen (PARK1)	x	x	x	Long time usage
Improved N.O. Jensen (PARK2)	x	x	x	Recommended
EMD variant: NO2005	x	x	x	With special tuning for e.g., single row wind farms
Ainslie 1988 with DAC	x	x	x	New in windPRO 3.5
Third Party (WakeBlaster)		x	No	Advanced flow modelling
Third party (local)		x		Allows you to inject your own wake model results
TurbOPark	x	x	x	Offshore
Outdated: (to be removed)				
EWTS II (Larsen) 1999	x			Not good for large wind farms
EWTS II (Larsen) 2008	x			Not good for large wind farms
Ainslie 1986	x			Outdated implementation

From windPRO 3.6 the TI input to the wake models (and thereby also WDC for N.O. Jensen models), can now be hub height dependent, when letting the terrain type decide TI. This can be a large advantage for e.g., calculating repowering projects, where hub heights can differ much for the turbines in a calculations, and thereby also the TI.

Since windPRO 3.6 is also possible to use two time step variants for WakeBlaster: One, where a number of scenarios is calculated and used for a lookup of the result each time step. Another, where the model calculates for each time step, and thereby can take the individual turbulence by time step into account, see section 3.6.13 PARK with Third Party wake model.

From windPRO 3.5 a fully new Ainslie 1988 with Deep Array Correction (DAC) has been implemented. All non-outdated models run as well based on statistical wind distributions as time series wind. For all models except the external WakeBlaster model, a Blockage (induction) model can be chosen to run along with the wake models.

The present scientific state of the art blockage models is implemented (Forsting and Branlard). However, these models do not take turbulence or stability into account, and we must admit that they do not bring any significant improvements to the wake modelling. The models calculate typically an added loss of 0.5% for larger wind farms. This is probably in a right size order seen over a year, but at low TI or stable wind, the actual blockage is probably higher. But these conditions typically only appear in a smaller fraction of a year.

In relation to testing the new Ainslie/DAC model a more comprehensive wake modelling test has been performed. This gives good confidence that even large offshore areas can be modelled quite precisely. See Validation Chapter 3.8. The new Ainslie1988 can be run without the DAC model, but this will not work for larger wind farms as the Ainslie model itself only captures near wakes.

The Turbulence Intensity (TI) which correlates well with stability, is a very deciding parameter in wake modeling. This is used as direct input for Ainslie and WakeBlaster, and indirectly for N.O. Jensen models via the Wake Decay Constant (WDC). Over many years, EMD has tested wake models on operating wind farms with high focus on finding a relation between WDC and TI that work best.

Due to the high importance of TI, an option for scaling the TI is made available in PARK. This should e.g., be used for: EMD-WRF Europe+ and similar datasets, which is seen to have a factor 1.41 too low TI – at least offshore, but also seen for several onshore sites. This is not the case for the former EMD ConWx mesoscale dataset or the present EMD-WRF On Demand data. For onshore sites, the new EMD-WRF Europe+ dataset has shown to perform better regarding TI than the previous setup based on tests against more than 200 masts onshore. Therefore, TI is not corrected with√2=1,41, as done in EMD ConWx data. However, onshore TI is in general very uncertain in mesoscale model data.
It is therefore preferred to use the measured TI on site or similar site to find a scaling factor for the mesoscale TI. This scaling factor can then be applied when running an onshore PARK calculation.

Alternatively use the DTU recommendations in table below, which performs well on average, but do not capture deviations for less typical sites.

Table 6 Recommended settings for N.O. Jensen PARK models

	DTU recommendations:		EMD recommendations from windPRO 3.6 :	
	N.O. Jensen (PARK1)	PARK2	PARK1	PARK2
Offshore and low TI onshore*)	0.05	0.06	WDC = TI x 0.67	WDC = TI x 0.8
Onshore	0.075	0.09	WDC = TI x 0.5	WDC = TI x 0.6
Advanced offshore low TI				WDC = 2 x TI -0.07

It should be noted that DTU previously recommended 0.04 for offshore sites with PARK1.

From windPRO 3.6 the recommendations on the factor on onshore TI has been increased from 0.4 to 0.5 for PARK1 and from 0.48 to 0.6 for PARK2! This partly removes the previous inconsistencies in the transition zone between on- and offshore, partly it is observed in more validation studies, that the new values has a better match. It is important to mention that there not is one true value for all sites. The above is based on what we have experienced work best for most sites tested.

The Offshore TI is illustrated below by examples:

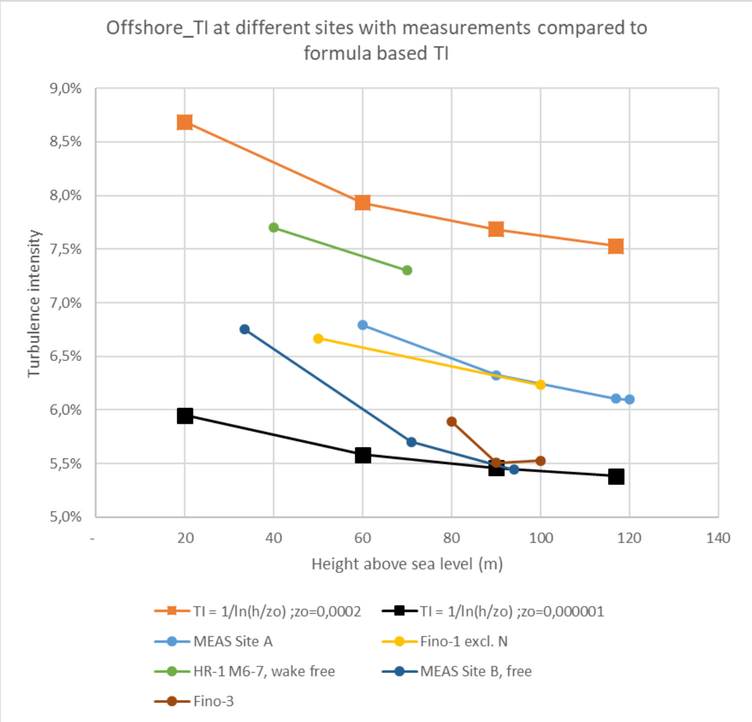


Figure 126 Offshore TI, formulas, and examples of measurements

EMD has collected TI measurements (5-15 m/s where wake loss appears), from multiple different offshore sites to illustrate which “band” of TI can be expected offshore.

The formula, that give a rough idea about TI, is illustrated in the figure above. This is not that useful, when it comes to offshore locations, as it is extreme sensitive to the roughness length, and what is this offshore? Zo = 0.0002 is normally used, while this can be extrapolated from shear measurements. But also Zo= 0 is seen used in other contexts. If 0 is entered in the formula, a division by 0 is seen, and this will not work. But lowering to Zo= 0.000001, shows that the TI is lowered much. The sensitivity to roughness lengths offshore in the TI formula is probably the reason why the fully formula-based concept with WDC = 0.4 x TI (see TI formula below); introduced in windPRO 3.2, does not work well for offshore locations. Stability although also plays a role.

The measurements shown in the graphic above, indicates partly the “band” TI is within, but also how it changes with hub height.
For new 8+ MW offshore turbines hub heights 100-120 m will be seen. Here the TI could probably vary from 5.5% to 7.5%, depending on specific location.

Our recommendation for a simplified approach will be to go with 6% or 7.5% TI for low-high TI offshore sites and thereby the mentioned WDC values for the two PARK variants shown in the table below:

The recommendations for offshore leads to these examples for comparison to DTU recommendations:

	PARK-1	PARK-2		PARK-1	PARK-2
TI	High TI = 7.50%	High TI = 7.50%		Low TI = 6.00%	Low TI = 6.00%
Factor	0.67	0.8		0.67	0.8
WDC	0.050	0.060		0.040	0.048

The DTU recommendations were previously 0.04 for PARK1, today 0.05 for PARK1 – these correspond to the two low and high TI examples in table above. For PARK2 the DTU recommendation 0.06 correspond to the high TI site.
e.g.,
TI will depend on the site. For rough estimates is used:

$TI = A*k/\ln(h/z_o)$

Where;
A = 2.5

k=0.4
h = calculation height
z_o = roughness length

The chosen constants are primary based on this paper:
http://orbit.dtu.dk/files/122284235/On_the_application_of_the_Jensen_wake_model.pdf

Citation (APA):
Pena Diaz, A., Réthoré, P-E., & van der Laan, P. (2016). On the application of the Jensen wake model using a turbulence-dependent wake decay coefficient: the Sexbierum case. Wind Energy, 19, 763–776. DOI: 10.1002/we.1863

From this part of the conclusion:

> Further, we demonstrated the ability of an engineering wind farm wake model based on the Jensen wake model to simulate the single and double Sexbierum wake cases outperforming (for these particular cases) two more advanced ones: a linearized CFD model, Fuga, and a nonlinear CFD RANS wake model that uses a modified k-ε turbulence model. It was shown that the wake decay coefficient for these simulations should be lower ($k_w = 0.038$) than the value recommended by WAsP ($k_w = 0.075$) when accounting for atmospheric stability during both campaigns, as the observed TI is too low compared with that estimated from surface layer parameters assuming a neutral atmosphere.

Figure 127 N.O. Jensen model better performing than more advanced models.

Table 7 Basic assumptions for hub height dependent WDC with examples for PARK2

Basic input for WDC		Calc. height:(m)	50		100	
Terrain type	Rou.Class	Rou. Length	TI	WDC	TI	WDC
Very stable	-1,4	0,0000002	0,051	0,041	0,050	0,040
Offshore (lower TI)	0	0,00001	0,065	0,052	0,062	0,050
Offshore	0	0,0002	0,080	0,064	0,076	0,061
Offshore (higher TI)	0,5	0,0024	0,101	0,081	0,094	0,075
Very open	1,0	0,03	0,13	0,081	0,12	0,074
Open	1,5	0,06	0,15	0,088	0,13	0,080
Mixed farmland	2,0	0,11	0,16	0,098	0,15	0,088
Closed	2,5	0,20	0,18	0,109	0,16	0,097
Very closed	3,0	0,39	0,21	0,123	0,18	0,108
Dense forest	3,50	0,74	0,24	0,142	0,20	0,122

The table illustrates how the formula-based TI is calculated for two different hub heights, 50 and 100 m. The corresponding WDC is simply TI x 0.8 for offshore, TI x 0,6 for onshore.

Conversion from roughness class to length is derived from the simple table below as simple linear relations in a logarithmic plot. Note there are two linear relations, one below class 1 and one above.

Table 8 Roughness class and length relations

Class	Length
0	0,0002
1	0,03
2	0,1
3	0,4

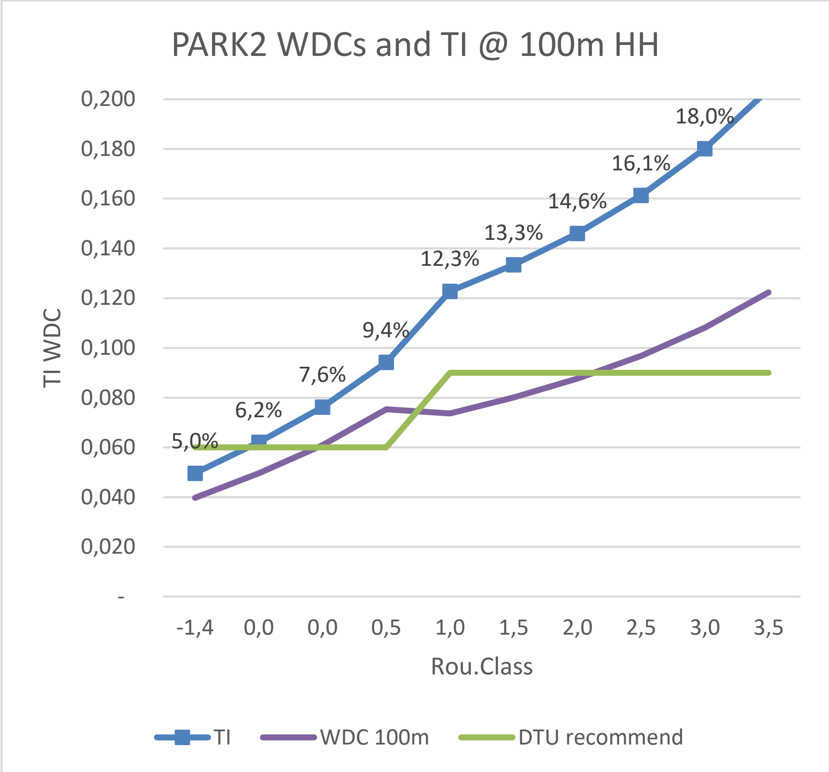


Figure 128 The WDC recommendations by roughness class for 100m hub height.

Note the recommendations are related to PARK-2. For N.O. Jensen original model. the WDC must be divided by 1.2.

A new feature from windPRO 3.6 is to allow the ambient turbulence based on terrain to directly control the WDC by hub height. Since windPRO 3.3, it has been possible in time step calculations to make the WDC hub height dependent by using a time series TI signal.

For the ones who like the more core science behind the new WDC recommendations based on TI, look into this:

2.1.2. The wake decay coefficient.

Until recently, the wake decay was the only adjustable parameter in the Jensen wake model. Peña and Rathmann[12] suggested the relation $k_w = u_{*free}/u_{hfree}$, where u_{*free} is the free friction velocity and u_{hfree} the free hub height wind speed, for the estimation of the value of the wake decay coefficient in models based on the Jensen wake model, based on Frandsen's findings.[13] The results of such a relation are much smaller k_w values compared with those commonly used (e.g. WAsP's default k_w value for an onshore site is 0.075). Therefore, we believe that most of the work carried out so far using Jensen's approach tends to underestimate the wake losses when performed over terrain with low roughnesses. Further, assuming that the aforementioned relation for k_w is correct, we can relate k_w to atmospheric stability and TI. Using the surface layer theory,[14] one can find that within the surface layer over flat and homogeneous terrain, the following holds,

$$u_{hfree} = \frac{u_{*free}}{\kappa}\left[\ln\left(\frac{h}{z_o}\right) - \psi_m(h/L)\right] \quad (3)$$

where κ is the von Kármán constant (≈ 0.4), h the hub height, z_o the surface roughness length and $\psi_m(h/L)$ the local atmospheric stability correction, which is estimated at a given height (in this case at hub height), for the specific stability condition (measured by the Obukhov length L[15]).

The surface layer diabatic wind profile in equation (3) is only valid within the surface layer accounting for the lowest ≈10% of the atmospheric boundary layer. Therefore, its ability to accurately predict winds at turbine operating heights depends on the boundary layer height (BLH); for unstable and neutral conditions in middle latitudes, the BLH is about 500 m or higher, thus, equation (3) is valid at least for the first 50 m from the ground. On the other hand, under stable conditions, the BLH might be as low as 100 m for such latitudes; thus, equation (3) might be valid within the first 10 m only. This means that surface layer expressions can be used within a broad range of stability conditions for small to medium size wind turbines, but should carefully be applied for large turbines or extended to account for other parameters such as BLH.[16,17] Equation (3) has however been found to be valid over nearly flat and homogeneous terrains up to ≈40–60 m in very stable conditions and at heights above 100 m in neutral and unstable conditions.[17,18]

Assuming equation (3) is valid at the turbine height, k_w can be expressed as

$$k_w = \kappa\left[\ln\left(\frac{h}{z_o}\right) - \psi_m(h/L)\right]^{-1} \quad (4)$$

The standard deviation of the free stream flow (in this case at hub height), $\sigma_{u_{hfree}}$, can be assumed as a function of the free friction velocity of the form, $\sigma_{u_{hfree}} \approx A\ u_{*free}$.[19] The parameter A depends on atmospheric stability and BLH. Here, we assume that it is constant ($A \approx 2.5$) for practical reasons as $A\ \kappa \approx 1$. Such value is close to the average of estimates of A reported by Panofsky and Dutton[19] based on a number of campaigns over flat terrain under neutral conditions ($A = 2.39 \pm 0.03$).* We test our assumption regarding A with data from a wide range of stability conditions in the next section.

Defining the TI as $\mathrm{TI} = \sigma_u/u$, it is easy to demonstrate

$$\mathrm{TI} \approx \left[\ln\left(\frac{z}{z_o}\right) - \psi_m(z/L)\right]^{-1} \quad (5)$$

$$k_w \approx 0.4\ \mathrm{TI}_h \quad (6)$$

where z is the height above ground and TI_h the hub height TI, which can be found by evaluating equation (5) with $z = h$. These two relations are only valid for flat and homogeneous terrain and within the surface layer, thus, under stable conditions, in particular when $z/L \geq 1$, large deviations can occur when estimating wind and turbulence characteristics outside of this layer.[20] Unfortunately, it is difficult to observe, account for and estimate the BLH because of the dynamics of the atmosphere. Further, there are other phenomena, such as baroclinity, influencing the wind profile higher up.[21]

Figure 129 WDC calculated from TI based on theory.

Note the TI to WDC converter here are found to ~0.4, PARK1 related (0.48 for PARK2). Based on numerous validation cases this constant is found to be slightly too small.

3.6.1.1 The PARK 1 & 2 implementations

PARK1 or "Original N.O. Jensen model" has been part of windPRO from the very beginning, is regularly checked against the similar implementation in WAsP. This is often referred to as the "industry standard". But when DTU made PARK2, this should replace PARK1 as it is seen to perform slightly better and is based on more correct physics.

PARK2 model has some formula revision, see;

http://orbit.dtu.dk/files/139682596/PARK2Validation_Poster.pdf

The main issue is that the combination model is changed from Root Sum Square wind speed deficit summation to linear summation, while mirror wakes have been removed, but also other formula revisions. Due to these changes, a higher WDC must be used to compensate for this.
The Wake Decay Constant (WDC) is the main parameter for the PARK 1 & 2 models, already comprehensively described in previous chapters.

3.6.1.2 The Ainslie/DAC implementation

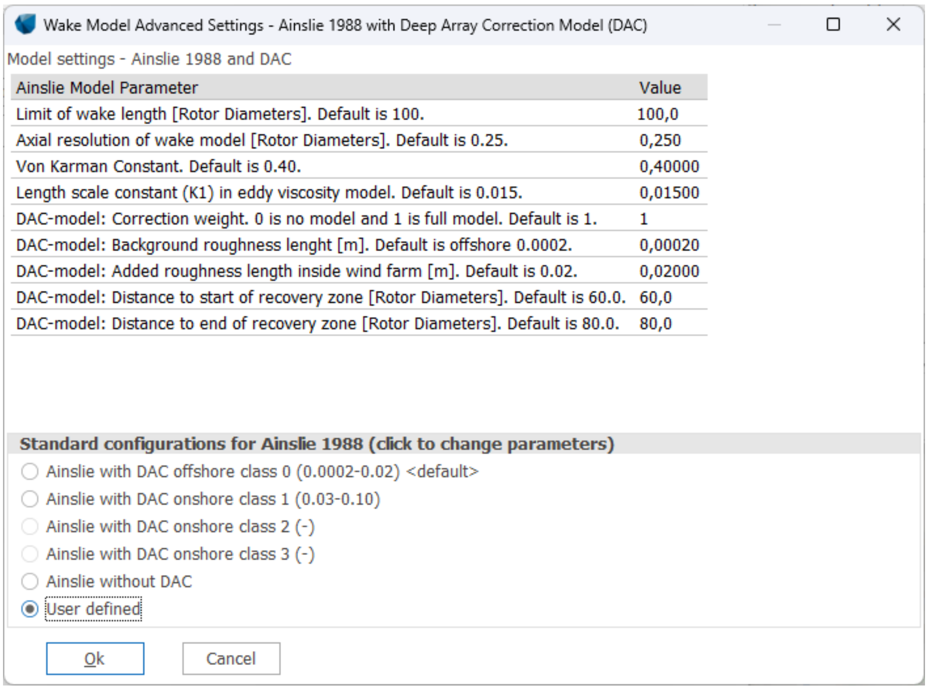
Ainslie 1986 was implemented in windPRO in 2005, but it was seen that this model did not perform well for larger wind farms and thereby there was little focus on this model. In 2021, based on user requests, the model was re-implemented, now based on the Ainslie 1988 improved model descriptions. But this still does not handle large wind farms particularly well, with calculated wake losses far too low.

Other software packages have therefore introduced deep array correction models to be used along with Ainslie model. These models basically increase the roughness to compensate for the too low calculated wake losses when the windfarms are larger (more than ~20 WTGs).

EMD has implemented its own Deep Array correction (DAC) model based on available scientific papers. This is not fully like other deep array correction models, but comprehensively tested and found to work well for a number of wind farm configurations, see validation chapter 3.8.

The new Ainslie 1988 with DAC calculates wake loss in same size order to the N.O. Jensen and WakeBlaster concepts. However, it is less sensitive to TI changes as it does not increase the calculated wake losses enough when the TI is low. Additionally, the model is too conservative for the new 8MW+ turbine generation (it calculates too high wake losses).

For Ainslie/DAC, there are several parameters:



Ainslie Model Parameter	Value
Limit of wake length [Rotor Diameters]. Default is 100.	100,0
Axial resolution of wake model [Rotor Diameters]. Default is 0.25.	0,250
Von Karman Constant. Default is 0.40.	0,40000
Length scale constant (K1) in eddy viscosity model. Default is 0.015.	0,01500
DAC-model: Correction weight. 0 is no model and 1 is full model. Default is 1.	1
DAC-model: Background roughness lenght [m]. Default is offshore 0.0002.	0,00020
DAC-model: Added roughness length inside wind farm [m]. Default is 0.02.	0,02000
DAC-model: Distance to start of recovery zone [Rotor Diameters]. Default is 60.0.	60,0
DAC-model: Distance to end of recovery zone [Rotor Diameters]. Default is 80.0.	80,0

The main input for Ainslie model is the TI, selected similar to the WDC for N.O. Jensen models. In addition, there are several parameters, where defaults for onshore and offshore is established as simple selections. The most important parameter is the DAC roughness settings. These have been comprehensively tested for offshore. For onshore projects, only Roughness Class 1 parameter suggestions are given so far. With user defined it is possible to define freely the parameter settings. See validation chapter 3.8 for more details.

3.6.1.3 The NO2005 implementation

EMD has implemented the N.O. Jensen model in a variant named NO2005. Comprehensive tests performed 2016 has revealed a difference in the NO2005 implementation compared to Original N.O. Jensen model. It has been known from the first tests, that NO2005 calculated slightly lower wake loses. see e.g., https://www.emd.dk/files/PSO%20projekt%205899.pdf

But with increasing wind farm sizes, the deviation became larger, see https://help.emd.dk/knowledgebase/content/TechNotes/TechNote_5_Park%20model%20revision.pdf
The solution pinpointed is to use 35% linear weight in the NO2005.

From windPRO 3.2 the Original N.O. Jensen model (PARK1), as well as PARK2 can be used in the time step based calculation method. And these can be used with combined Linear and RSS weight.

The NO2005 model is kept as an alternative, while this has the experimental tuning: Change WDC by number of upwind turbines. This feature is still relevant for post construction analyses, where there is good data to fine tune wake model settings.

3.6.1.4 The WakeBlaster implementation

WakeBlaster as external model is an interesting alternative, while the calculation method differs from as well the N.O. Jensen as the Ainslie concept. This model does although calculate wake losses in similar size order as the N.O. Jensen models but can have some deviations based on the wind farm layout. See 3.6.13 PARK with Third Party wake model for a detailed walk through a WakeBlaster calculation setup.

From windPRO 3.6 it is possible to use WakeBlaster in real time step calculations, where the TI input vary by time step.

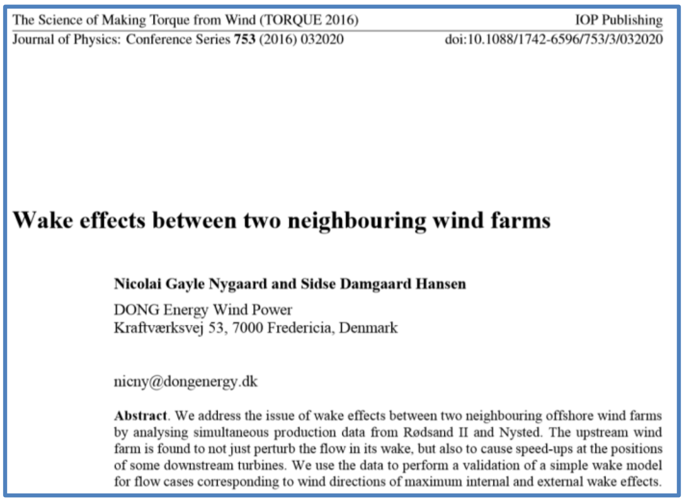
3.6.1.5 The TurbOPark implementation

TurbOPark is a modified Park wake model developed by Ørsted with the source code publicly available here: https://github.com/OrstedRD/TurbOPark. This model has been implemented natively in windPRO 4.0.

EMD has verified that the implementation in windPRO yield the same result as provided in the above github repository by recalculating their examples (2023). The example includes a varying background wind speed and a regular grid of 16 turbines of two different turbine types.
See also: https://help.emd.dk/knowledgebase/content/ReferenceManual/Wake_Model.pdf

3.6.1.6 Validation reports on deep array modelling and recommendations

Below conclusions from
http://iopscience.iop.org/article/10.1088/1742-6596/753/3/032020/pdf



The Science of Making Torque from Wind (TORQUE 2016) IOP Publishing
Journal of Physics: Conference Series **753** (2016) 032020 doi:10.1088/1742-6596/753/3/032020

Wake effects between two neighbouring wind farms

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Abstract. We address the issue of wake effects between two neighbouring offshore wind farms by analysing simultaneous production data from Rødsand II and Nysted. The upstream wind farm is found to not just perturb the flow in its wake, but also to cause speed-ups at the positions of some downstream turbines. We use the data to perform a validation of a simple wake model for flow cases corresponding to wind directions of maximum internal and external wake effects.

In general, the predictions of the simple wake model we have tested are in good agreement with the observations. However, the usefulness of the model for large offshore wind farms has been put into question by prior assertions that the model systematically underestimates the wake losses inside large wind farms. The existence of such a 'deep array effect' would imply that the model was insufficient or needed corrections. In this study, we find no evidence of a systematic deep array effect, despite comparing the model with observations along a row of 26 turbines! This matches the conclusion of previous research on other large offshore arrays [5]. When comparing the Nysted wake losses before and after Rødsand II, we find that the additional wake loss from the neighboring wind farm is roughly confined to the first few rows in the downstream wind farm.

See also: http://iopscience.iop.org/article/10.1088/1742-6596/524/1/012162/pdf

As seen, some of the probably most comprehensive studies on wake losses show that the original N.O. Jensen model handles wake loss calculation well, also for large wind farms.
In the last reference, it is mentioned that in one section tested in the London Array windfarm, the N.O. Jensen model under predict wake losses for the back rows. But here is also noted that the Turbulence is very low for the sample data. This is what EMD has seen for an Egypt wind farm, that when turbulence is low, wake losses increase radically. This can be captured in model calculation by decreasing the WDC.

EMD thereby recommend the (N.O. Jensen model) as preferred for pre-construction calculations. PARK2 seem slightly better than PARK1 (org. N.O. Jensen), and PARK2 should be the preferred choice. Pay attention to the turbulence and make the WDC choice based on this as previous described – this is the key parameter to make the model calculate correct. The best way to include turbulence is in the time step-based calculation with WDC as a function of TI on time step basis. Also pay attention to the Ct curves. It can be hard to judge if these are correct, but comparisons to other turbine models might give a hint if they seem realistic.

For single row projects, pay specific attention, here the wake loss is calculated too high with normal wake models, while they do not consider the added fresh wind from both sides of the single row. See validation chapter 3.8.

3.6.1.7 Park rotation by coordinate system

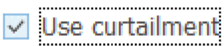
PARK and WAsP calculations requires rectangular coordinate systems. This mean that the park will be slightly rotated the more the given rectangular coordinate system is rotated relative to geographic north. Some coordinate systems have quite large rotations. It is therefore decided that before running the calculation, windPRO convert all data to UTM WGS84 system, and chose the UTM zone in which the Site centre is located. Thereby rotation is minimized to ~+/- 3 degrees in worst case, which appear when the wind farm is located just at the border between two UTM zones. What can be wrong by the rotation is that wind data typically are aligned, so 0 degree is geographic north. Then the wind and the array orientations do not match fully. It is a marginal problem with the chosen solution in windPRO. The user can although compensate the problem by adding an offset when importing the wind data. While the accuracy of the wind data directional alignment rarely justifies this, and the effect on the result is marginal, it is not a general recommendation. The used coordinate system and zone as well as the resulting rotation is shown on the PARK result main page. Thereby it is documented how slightly different positions of site center (in different UTM zones), is the reason for slightly different results.

3.6.2 Curtailment in PARK calculations

From windPRO 3.3 most curtailment calculations are included in PARK. Previously, only sector management was available in PARK with shutdown. In windPRO 3.3 prioritized curtailment rules can be defined shutting down a turbine or changing operation mode. The advantage of handling curtailments in PARK instead of LOSS & UNCERTAINTY is that the changes in wake losses will be handled. This can be of some importance especially with sector management, where e.g., every second turbine is stopped, when the wind comes along the row, just the situation where the wake losses appear.

All curtailments are defined on the individual WTG objects in a project. Thus, the curtailments applied to a PARK calculation is dependent on the configuration of the WTGs included in the calculation.

To activate curtailments in a PARK calculation simply check the Use curtailment checkbox in the Setup tab:



Each WTG can contain multiple curtailments like noise, bat and bird curtailments. In case two or more curtailment rules are valid at the same time, PARK will evaluate the rule with the highest priority first and attribute any production loss to this rule. Up until windPRO 3.6, only the first valid rule would be executed and attributed the loss for the entire timestep. In windPRO 4.0, multiple rules can be valid at the same time. Now, the next priority rule will then be evaluated, and if there is a further subsequent loss caused by rule number two, then the additional lost production is attributed to rule number two.

To use the old way of only allowing one curtailment rule to be activated per time step, simply check the checkbox “Allow only on curtailment per time step”

☑ Allow only one curtailment per time step

Any PARK calculations including curtailments created before windPRO 4.0 have this setting enabled by default.

Any curtailment rules define on the WTG objects included in the PARK calculation will appear in the Curtailment tab. Although curtailment rules are defined on the individual WTG objects they can also be edited directly from PARK by checking the “[x] Allow editing” box. This turns the “View” button into “Edit”.

Time-based PARK can utilize all the curtailment options in the WTG object, whereas statistics-based PARK can only use curtailment rules defined by wind speed and wind direction.

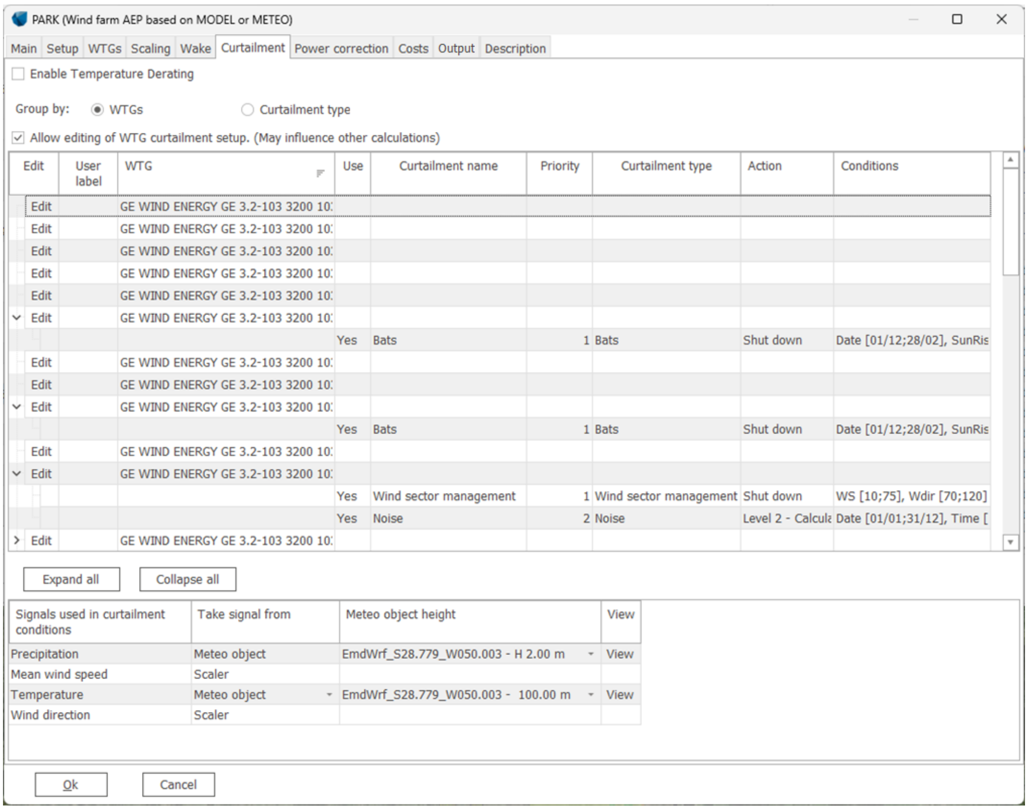
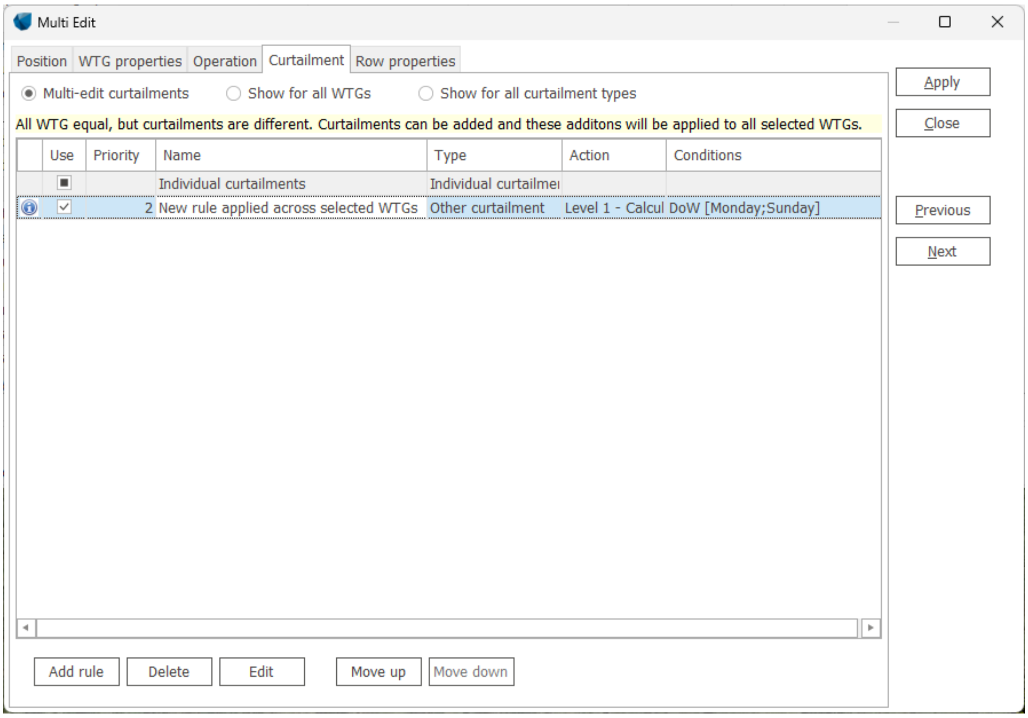
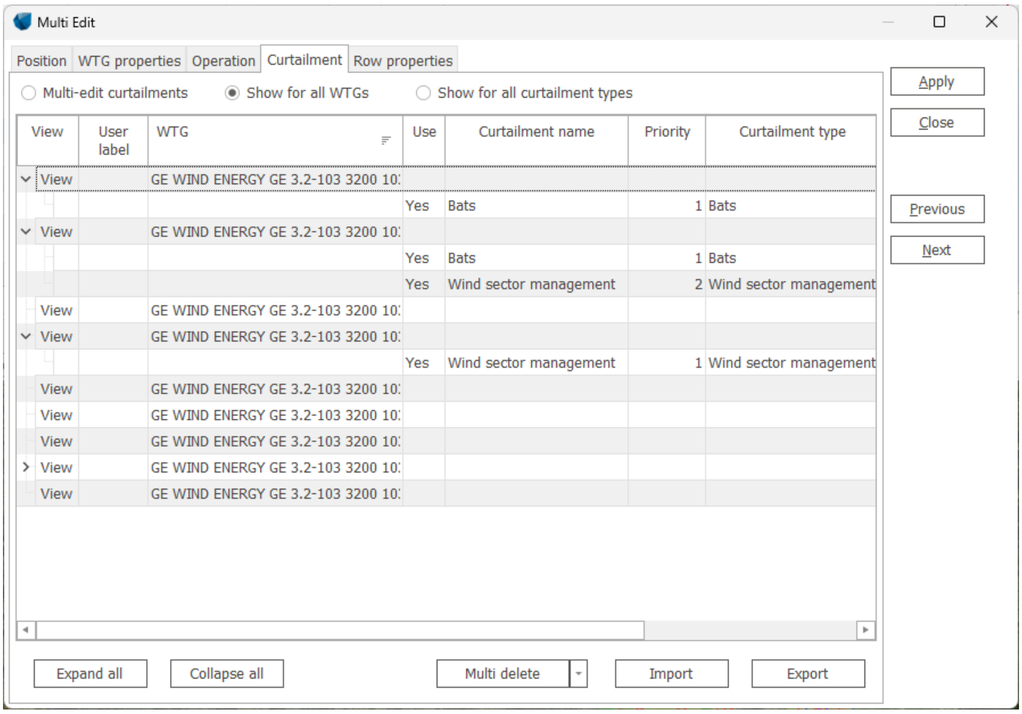


Figure 130 Curtailment settings in PARK

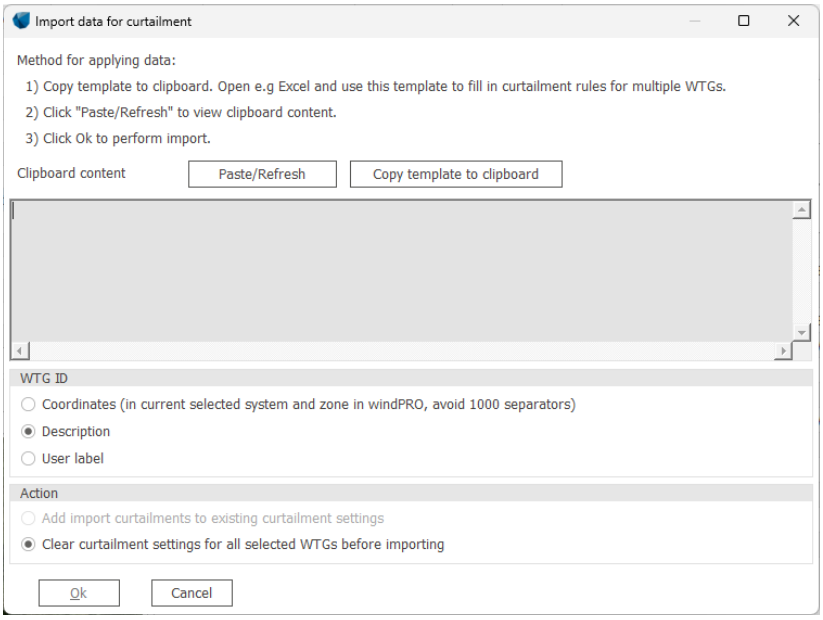
Curtailment rules can also be defined on multiple turbines when multi-editing multiple turbines. Only identical curtailment rules shared by all selected turbines can be edited in batch. New identical curtailment rules can always be added to the selected turbines in multi-edit:



It is possible to view all rules for the selected turbines by selecting “Show for all WTGs”, though the rules cannot be multi-edited from here:



Here, curtailment rules can be imported and exported to and from the clipboard with the “Import” and “Export” buttons:



The "Paste" requires that the content in clipboard follow the input data format. As a help, a template can be copied. The template shows the import format and the available signal abbreviations.

WTG1	Wind sector management	Mode3	WS	12	75	Wdir	165	185
WTG2	Wind sector management	Mode3	WS	12	75	Wdir	345	5

Data in Excel for paste into the "Import data for curtailment"

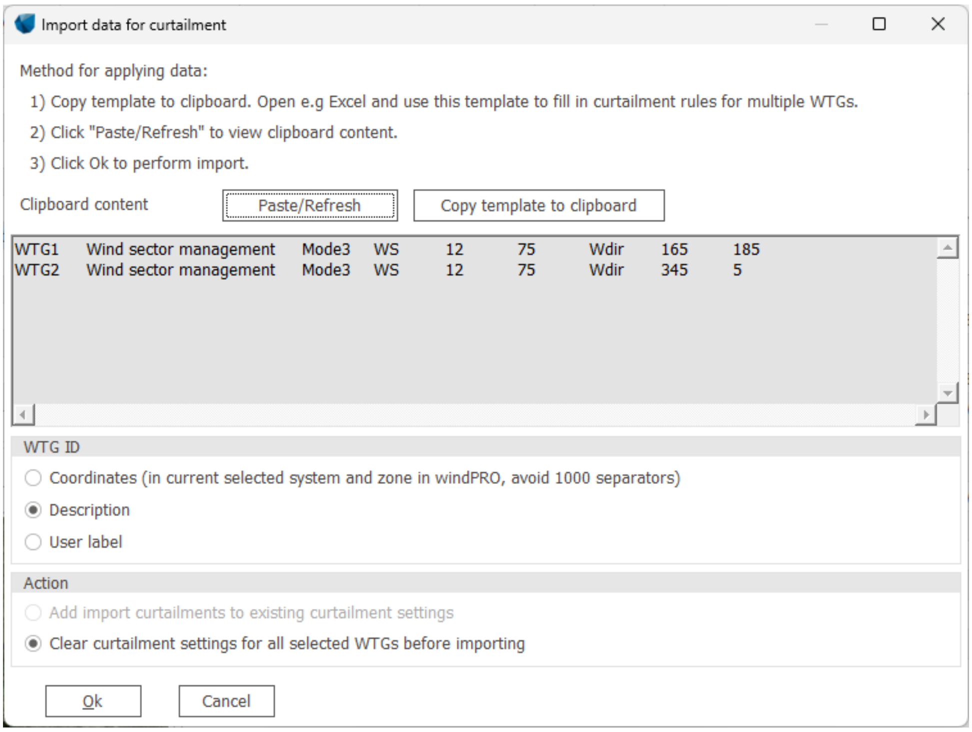


Figure 131 Import curtailment data to WTG objects

Here a WTG_ID is required in the first data column. This can be coordinates, Description or User label.

When importing from clipboard, all existing rules are cleared before the new rules are imported. The priority of the rules for each turbine is determined by the order they are imported. The priority number dictates in which order curtailment rules are evaluated. Once the conditions of a rule are met, the curtailment is applied, and no further rules are applied in the time step.

Always remember that changing the settings on the WTG objects can influence other calculations using the same objects.

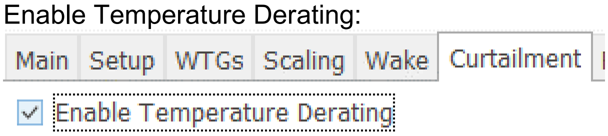
The result of a calculation with curtailment will partly be presented with curtailment loss in PARK report, partly as a new column in Result to file. And it will be added in Loss&Uncertainty, where it will get the same status as Wake losses. Where losses normally are combined as (1-Loss1) x (1-loss2), this will not be so for Wake and curtailment losses, while these in the PARK calculation already are combined. So these will simply be added before combined with other losses.
Note the added column in result to file might require update of like Excel templates and external software tools that utilize Result to file. The curtailment column will always be included.

3.6.2.1 Temperature derating

Some turbines located in high altitude and/or high temperature settings may need to be derated depending on their cooling equipment. Manufactures typically issue a dataset specifying at which points the turbine's maximum power output is limited from rated power. In windPRO 4.0 it is possible enter these temperature curves into the wind turbine catalogue. See BASIS manual section 2.6.4.6 on how to enter the data.

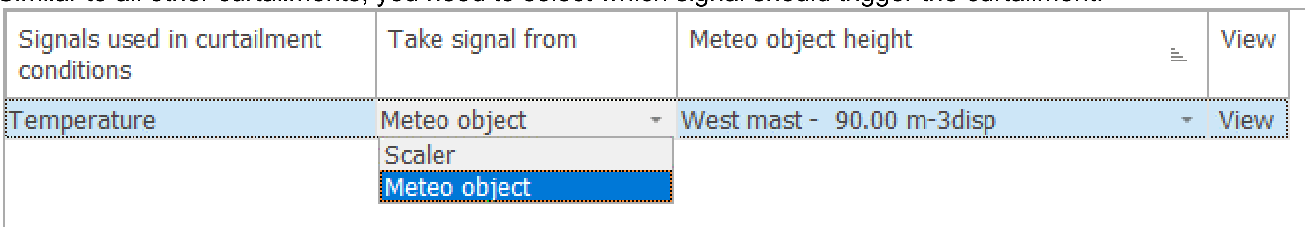
windPRO will interpolate between specified temperatures, but elevation is considered discrete. The elevation used to determine if a turbine is within the specified elevation envelope is TIN elevation + hub height.

Any turbine model which has a temperature curve defined in the turbine catalogue can be temperature derating in a time-varying PARK calculation. If a turbine model does not have a temperature curve defined, it will not be derated. To activate temperature derating in PARK, enable curtailments and go to the Curtailments tab and Enable Temperature Derating:



Once activated, all WTG objects included in the PARK calculation which has a temperature curve defined in the turbine catalogue will be derated once the turbine is operating within the specified temperature/elevation ranges. The loss is applied to the turbine before any other curtailment losses.

Similar to all other curtailments, you need to select which signal should trigger the curtailment:



The losses from temperature derating can be seen in the Production Analysis report and as an aggregate curtailment loss in the Main report. In the Curtailment Assumptions report it is possible to see how many turbines have been affected by the temperature derating.

Temperature Derating

WTG combination	Affected Turbines	No. Turbines	Loss [MWh]	Loss [%]
Wind farm	50	50	89413,20	5,33

3.6.2.2 Grid curtailment

A special curtailment is grid limits, as this is not applied on specific WTGs but on the windfarm as a whole. Therefore, this is treated separately and entered in setup form. The grid curtailment is only available for time varying calculations due to the nature of the loss.

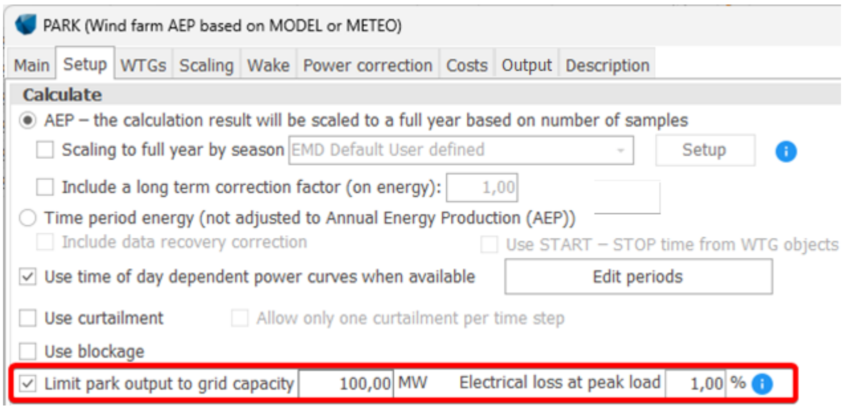


Figure 132 Entering grid curtailment settings.

The calculated production in PARK occurs before any losses in the collector system. Conversely, the limitation point is typically defined after the loss in the collector system. Therefore, peak grid loss can be added to the limit, enabling WTGs to compensate for the loss in collector system.

For any given time step the total park production (after adjustment for the electrical loss at peak load) is compared to the defined grid limitation. Any exceeding production will be subtracted proportionally from all "New WTGs" and all "Existing WTGs" which are "Treat as Park WTG" ☑ Treat as Park WTG ⓘ.

Existing WTGs which are not treated as Park WTGs will not be part of the grid limit calculation, as these are assumed to have separate grid access point.

As such, it is possible to control which WTGs shall be included in the grid curtailment calculation. Note the multi-edit tool can activate/deactivate the "Treat as park WTG" for existing WTGs.

The grid curtailment is reported as a separate, independent loss after the calculation of wakes and other WTG specific curtailments.

3.6.3 Common settings for all PARK calculation variants

3.6.3.1 Hub height dependent TI based on terrain selection

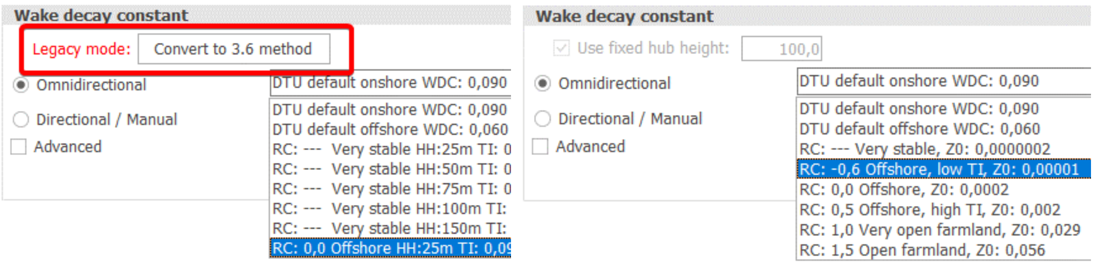


Figure 133 New 3.6 method for automatic TI calculation by hub height

To the left, a calculation made before ver. 3.6 can be converted to the 3.6 method (right). This has two advantages:

1) The drop-down list no longer has an entry for each hub height and terrain class. Just the terrain class. This makes selection easier.
2) The calculation automatically uses the hub height for each WTG to calculate the TI based on terrain class. Thus, it uses a turbine specific TI (instead of an average based on the selection in the dropdown list). This means that a project which was first calculated with 100m WTGs, then cloned and calculated with 159m hub height will automatically change the TI input. Previously, this had to be manually reselected.
   If the calculation contains WTGs with different hub heights, each WTG use the TI as input for this WTG, which again decides how much wake this WTG gives to its neighbours.

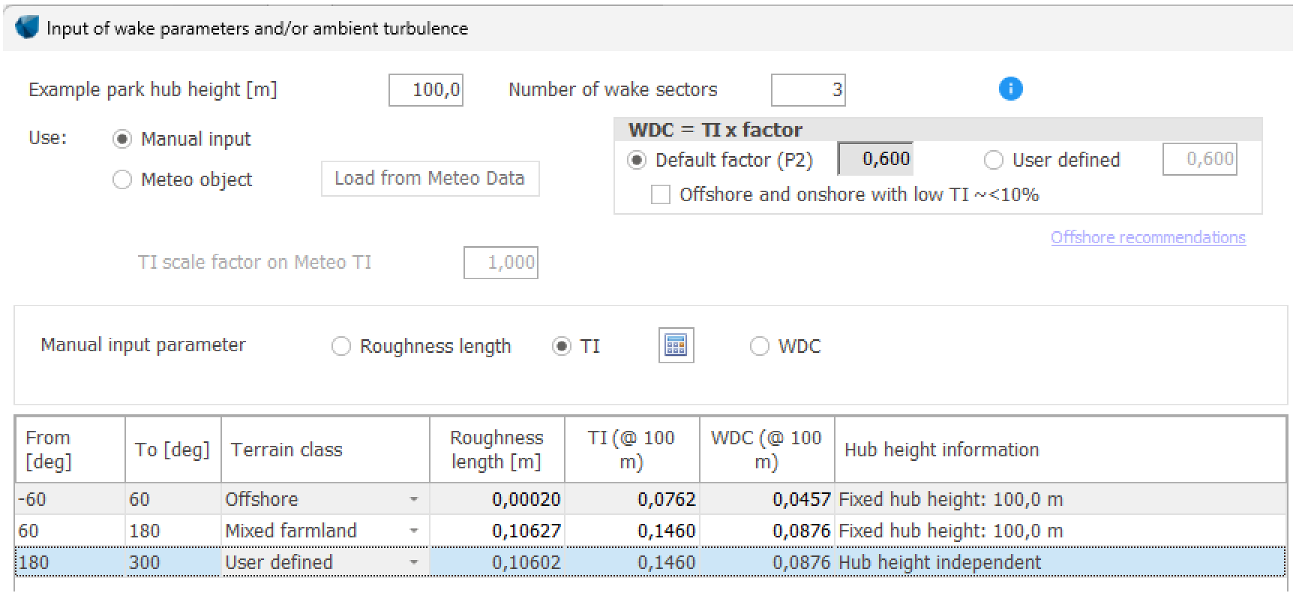


Figure 134 Input of sector defined TI also utilizes the new concept.

When the input is entered by sector, the hub height dependent TI values will also be used if terrain is selected under “Terrain class”. If “User defined” is selected, then the input values (roughness length, TI or WDC) will be used “as is”, as the automatic TI calculation only works when based on a terrain class.

3.6.3.2 Use Curtailment

Curtailments can be included in PARK calculation. This mean that if a turbine is reduced or stopped by specific wind speeds and/or directions (sector management), this will be considered in the wake loss calculation. For more refined curtailments, like BAT stop a specific period, this can only be handled in time step-based calculations. The sector management variant is included in all PARK variants (except the 2.9 variants and external models) from 3.2. See Section 3.7.2 Curtailment in PARK calculations for more details.

3.6.3.3 Use Blockage

Blockage, or induction, calculates the wind speed reduction caused by the wind farm upwind. There are two scientific models implemented:

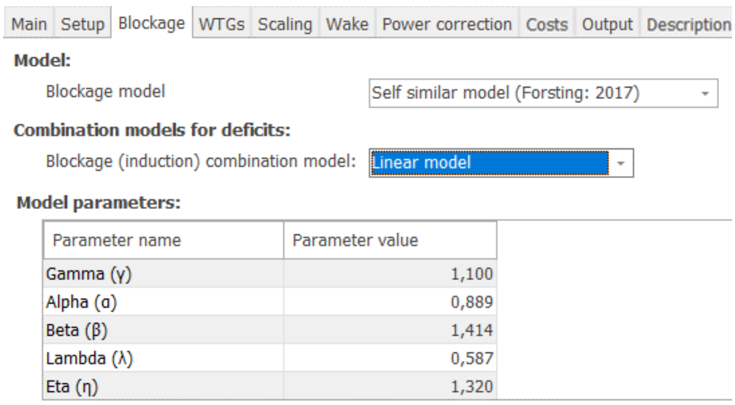


Figure 135 Forsting blockage model.

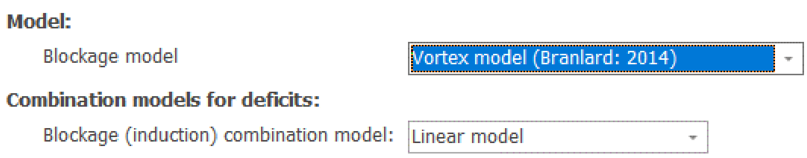


Figure 136 Branlard blockage model.

Parameter adjustments are for expert users that know the model background and wish to test model settings or have special knowledge.

Blockage reduction will be part of the calculated wake loss. To see the blockage reduction, it is necessary to run two calculations with and without and subtract results. Due to the very small impact, it is not judged worth to perform a double calculation to be able to include the blockage loss separately in the reporting.

3.6.3.4 WTGs

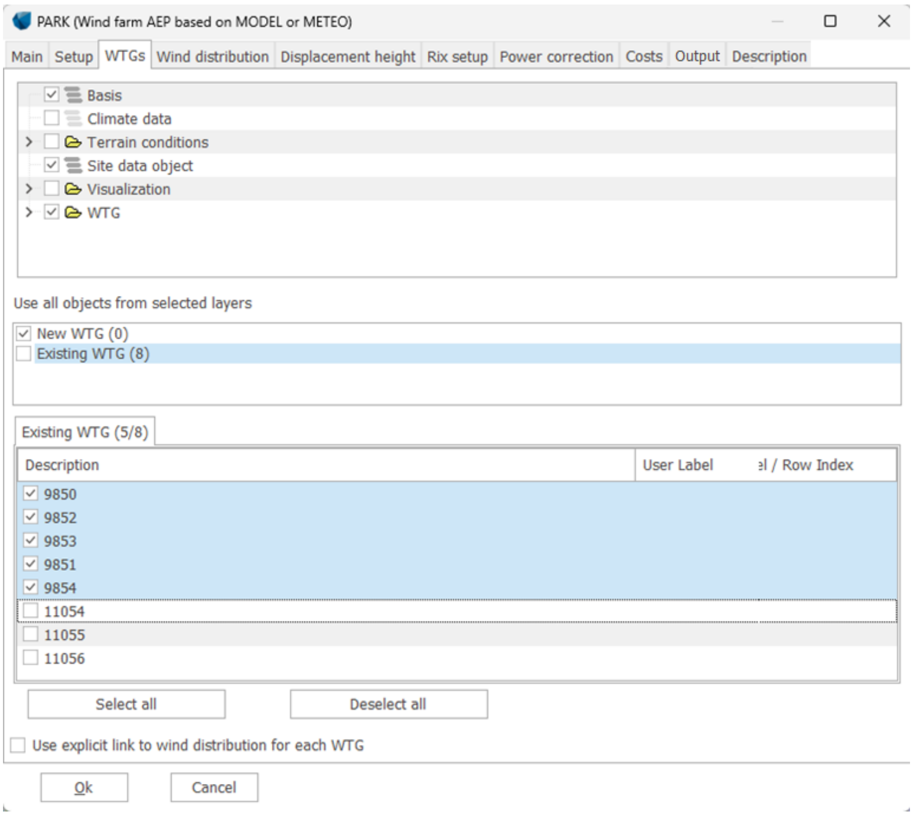


Figure 137 Selection of WTGs for PARK calculation

At the WTGs tab, the turbines to be calculated are selected. By default, the turbines from visible layers appear, but other layers can be activated and, by unchecking “use all objects from selected layers”, turbines can be individually selected.

Checking the “Use explicit link to Wind distribution for each WTG” adds another tab “Link site data to WTG”:

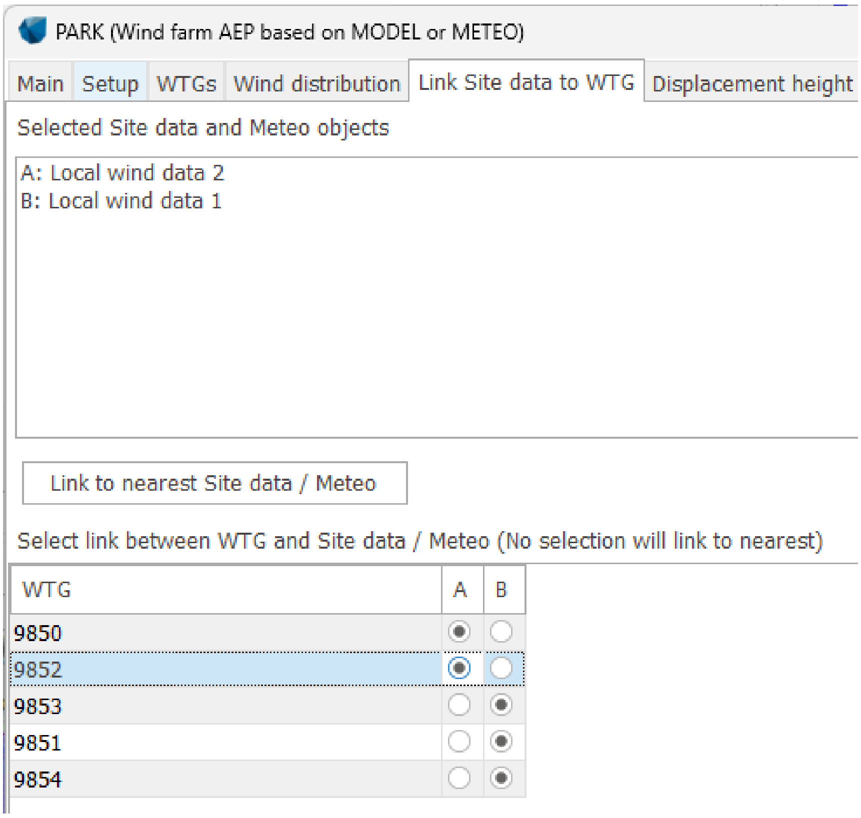
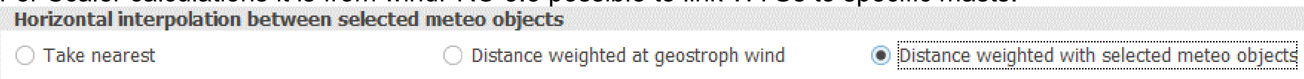


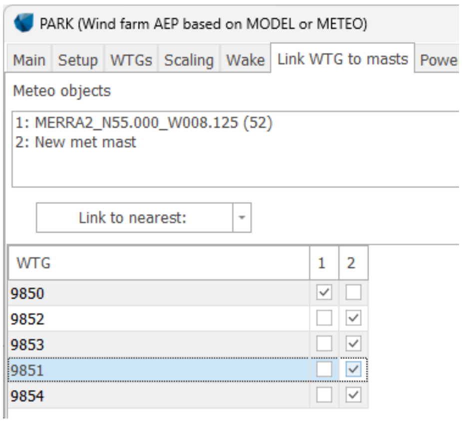
Figure 138 Explicit link site data – WTG, manual control

Before activating this option, wind distributions must be chosen. By default, each WTG “chooses” the nearest wind distribution object. In the matrix above, checkmarks can be moved so the user has full control as to which wind distribution object shall be used for which WTG.

For Scaler calculations it is from windPRO 3.3 possible to link WTGs to specific masts.



When selecting the rightmost option, a new tab “link WTG to mast” appear.



Here it is even possible to link a WTG to more masts, and the full flexibility to use more masts for some WTGs and only one for other WTGs exist. The Scaler basically scale the selected masts to the given WTG and distance weight the result at each WTG position. The distance weight is based on the inverse squared distance.

3.6.4 Common settings for Wind statistics based (standard) PARK calculation

3.6.4.1 Setup

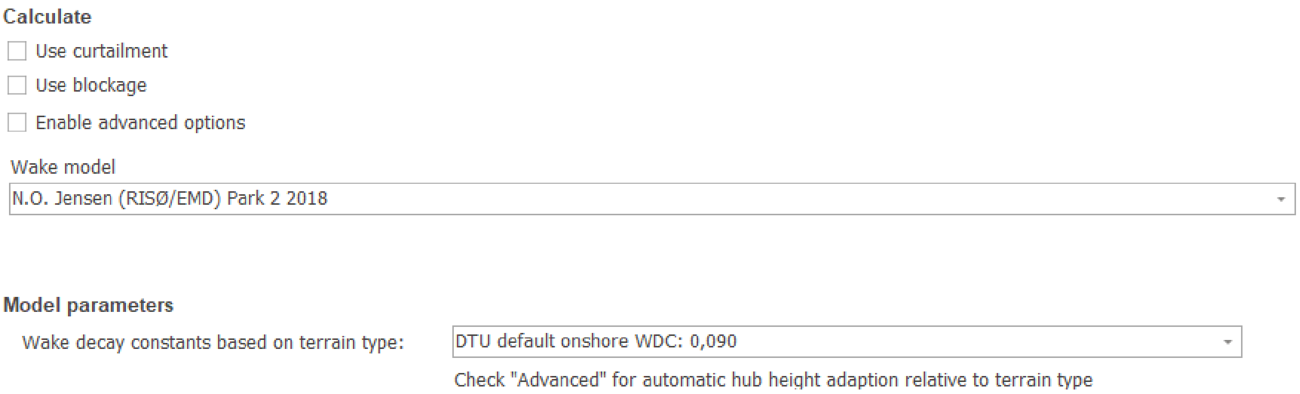
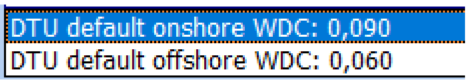


Figure 139 Model parameters features in “standard” PARK

Model parameters:
“Wake decay constants…” defines how much the wake expands behind the rotor. The example figure 0.09 means that, per meter behind the rotor, the wake expands 9 cm. In “non-advanced mode” the choices are:



Further details can be found in “The wake loss (PARK) model” (Section 7.1), where it is emphasized that, at larger hub heights, the WDC should be reduced due to lower turbulence.

A lower expansion (offshore) gives a higher reduction of the wind speed behind the rotor and, thereby, larger calculated wake losses. It is recommended to enable “advanced”, which gives more flexibility.

Enable advanced options:

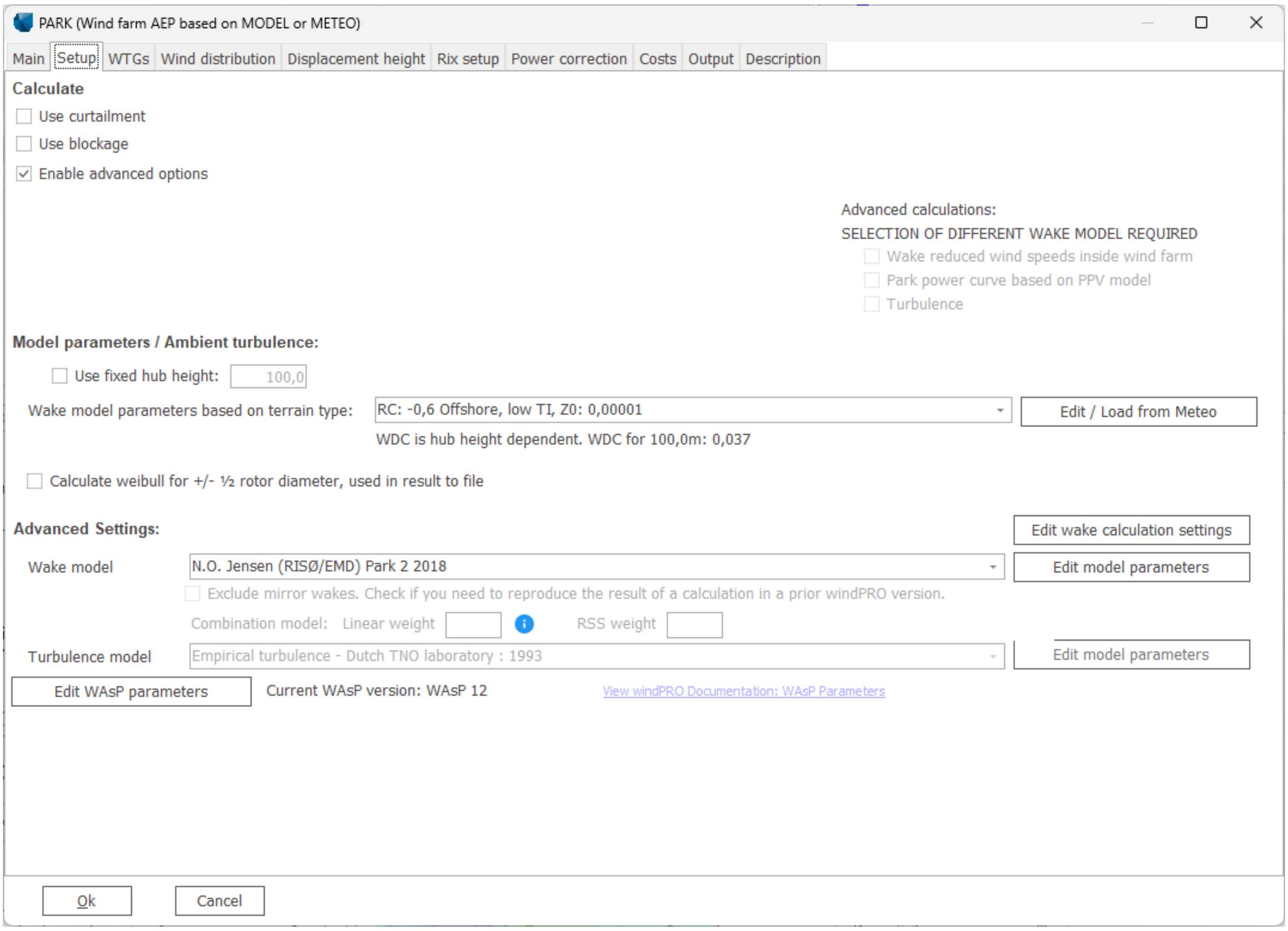
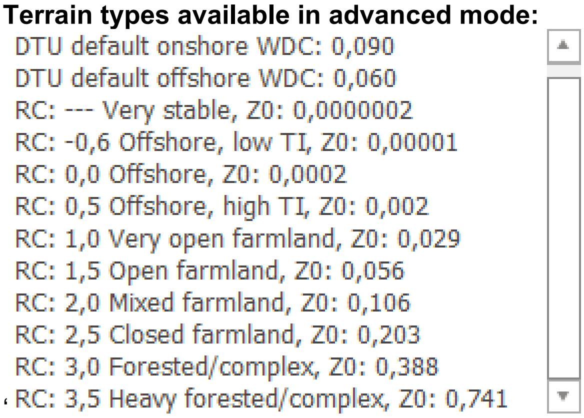


Figure 140 Advanced setup options in "standard" PARK

Terrain types available in advanced mode:



Here the terrain type is selected, where the corresponding roughness class and roughness length is shown. Based on terrain class, the TI is calculated by hub height for each WTG in the calculation. In the three N.O. Jensen models the TI is converted to a Wake Decay Constant (WDC), while the other wake models use the TI directly.

Sector wise Wake decay constant/turbulence parameters

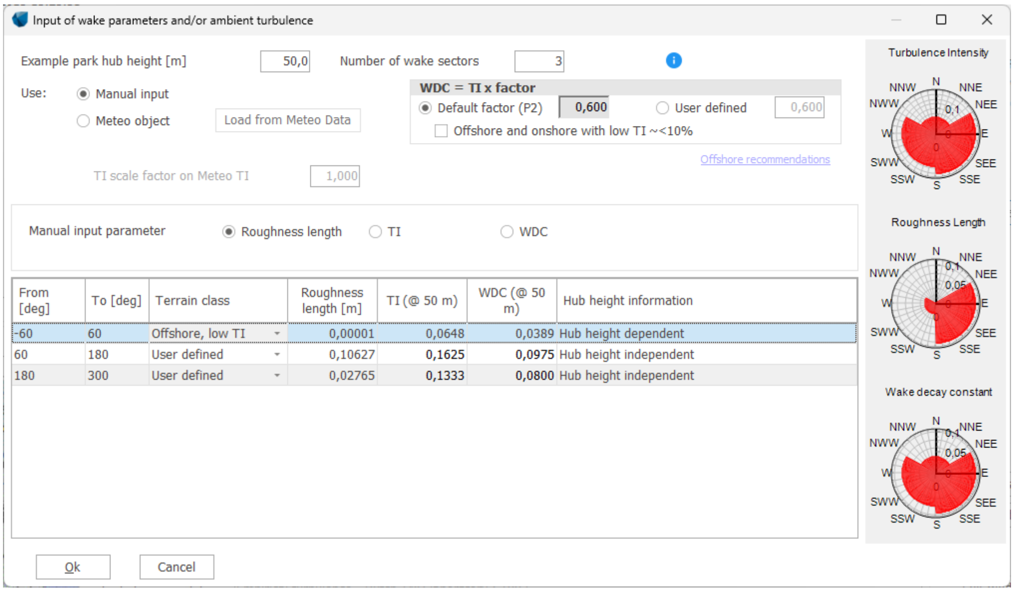


Figure 141 TI or Wake decay constant (WDC) by direction sector

Sector wise TI or WDC can be entered or loaded from METEO data. The input options:

- PARK hub height
- Terrain class
- Roughness length
- TI, measured
- Height for measured TI
- WDC

Are fully tied together with formulas. (see further details in 3.6.1 The wake loss (PARK) models).

New in windPRO 3.5-3.6 is partly:
Hub height dependent TI/WDC:
If the sectors are specified by a terrain type, the TI/WDC values can be recalculated to actual hub heights. Therefore, the hub height specified in top is of Figure 141 now is called “Example Park hub height”. If the terrain class is set to “User defined”, scaling to individual hub heights is not an option and input values will be used as is.

[x] Offshore and onshore with low TI ~<10%
It is seen by many validations that for low TI sites, the factor 0.67 (PARK1) or 0.8 (PARK2) is best choice, while 0.5 (PARK1) and 0.6 (PARK2) is the better choice for onshore (updated in 3.6).

TI scale factor on Meteo TI
This is included to be able to calibrate e.g., mesoscale model data TI to local site measurements. Mesoscale TI is very uncertain for onshore sites as the mesoscale models work on mesoscale level and thereby does not capture the micro-level TI. Having TI measurements for a shorter period (1 year) will often be sufficient to calibrate the mesoscale TI to the real site TI level, and thereby get access to long term TI data. Especially for the EMD-WRF Europe+ and similar datasets, it is seen that the TI level offshore is 1.41 (√2) too low, and multiplying with this is recommended. For EMD ConWx mesoscale data or EMD-WRF On Demand data this is not recommended. Here the TI is as expected offshore and should not be scaled.

When loading TI from Meteo, this is converted to example hub height TI, to give the correct input for the WDC calculation or the right level for models using TI direct (WakeBlaster and Ainslie).

NOTE: The factor from TI to WDC, above shown as 0.6, will, if PARK1 is chosen before this form is opened, be 0.50. It is thereby dependent on the wake model as described previously. If the wake model is later changed from PARK2 to another model, **this will not change the WDC unless the default selected “(o) WDC” is changed to “(o) TI” before leaving the form.** The default functionality of the form is that it is the WDC that is kept when leaving the form and the other parameters are recalculated based on the chosen wake model.

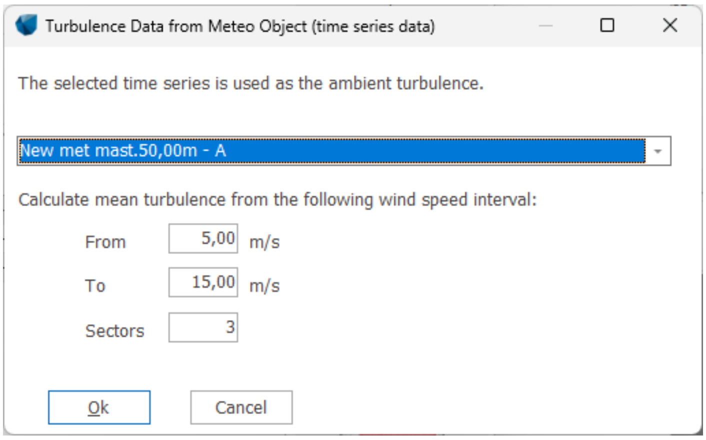


Figure 142 Import TI from Meteo object

Defaults are from 5 to 15 m/s, the wind speed interval where the wake loss appear, and therefore the TI within this interval is the relevant.

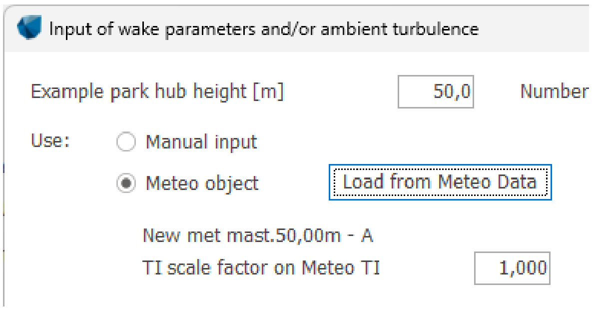


Figure 143 Example of conversion of TI by height

Above is seen how TI now, when loading from Meteo, is shown for measurement height along with for expected hub height, which decide the WDC.

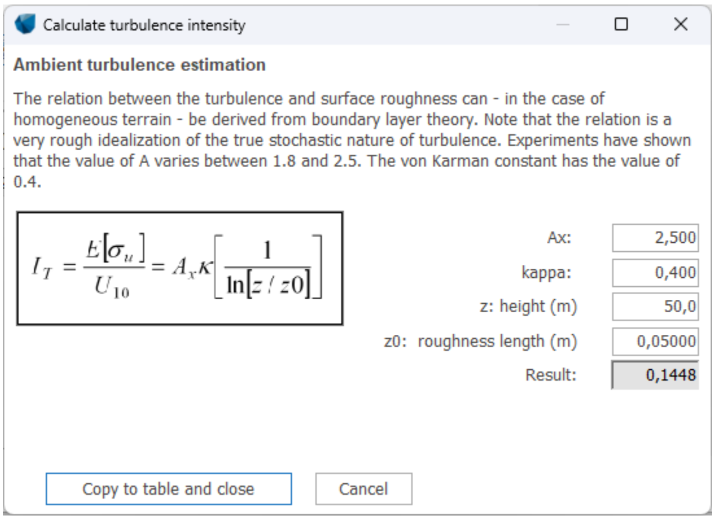


Figure 144 Simple turbulence calculator for PARK input

The calculator next to TI input selection, gives the formulas behind the Roughness to TI conversion. The calculator can be used to calculate TI based on the user's own assumptions.

Access to advanced calculations:

Advanced calculations:

- ☐ Wake reduced wind speeds inside wind farm
- ☐ Park power curve based on PPV model
- ☑ Turbulence

These Advanced calculations require you to choose another wake model than the default N.O. Jensen model.

The reduced wind speeds inside a wind farm create a matrix that can be used to lookup the calculated reduction at a specific point, for any direction and any free wind speed. A way to use this is to place a very small turbine (0.1 m rotor diameter) at the position where a measurement mast is located inside the wind farm, and, thereby, get the reduction in wind speed measurements due to surrounding turbines. Then the expected free wind speed can be established, which can be useful for performance check calculations.

Park Power curve based on a PPV model gives the calculated Park power output related to a specific measurement mast position outside the park. This can be useful for situations like prognosis systems, where the wind prognoses are given at a specific point (measurement mast position). With the table, the transfer function from wind speed and direction to Park output is given.

Turbulence calculations give the ambient + wake added turbulences for each turbine. NOTE this calculation is now transferred to the Site Compliance module (all versions after 2.8).

☐ Calculate weibull for +/- ½ rotor diameter, used in result to file

You can also add calculation results for +/- ½ rotor diameter in the result to file. This makes it easy to evaluate the variation of the calculation results over large rotors. With the present AEP calculation tools, it is always assumed the hub height represents the average for the entire rotor diameter. With a large increase in rotor diameters, this might require changes in future calculation methods.

Wake model selection:

N.O. Jensen (RISØ/EMD)
N.O. Jensen (EMD) : 2005
Eddy Viscosity Model (J.F. Ainslie) : 1986
EWTS II (G.C.Larsen) : 1999
EWTS II (G.C.Larsen) : 2008
N.O. Jensen (RISØ/EMD) Park 2 2018
Eddy Viscosity Model (J.F. Ainslie) : 1988
TurbOPark

Figure 145 Alternative wake models in "standard" PARK (Wind statistic based)

Regarding wake models, EMD recommends using the N.O. Jensen (RISØ/EMD) PARK2 model. If you need turbulence calculations, the N.O. Jensen (EMD) 2005 is recommended. The three models mentioned below N.O.Jensen : 2005 are intended for experimental use. Tests so far indicate that these models do not reduce calculation results enough when using the standard parameters. The parameters will be tuned based upon ongoing research in order to better correlate the predicted values to actual performance. New in windPRO 3.4 is that the Larsen model now can be used with linear combination model, but tests show that this do not make this model perform well. The performance of the model is too dependent on the wind farm size and is only recommended for experimental use. The Eddy Viscosity Model (J.F.Ainslie) : 1988 is a new implementation included from windPRO 3.5, which includes a DAC (Deep Array Correction) model, which is a requirement for making this model work well.

Turbulence model selection:

G.C.Larsen / EWTS II : 1999

No model (ambient turbulence only)
B.Lange: 2002 - Eddy viscosity turbulence
Danish Recommendation: 1992
G.C.Larsen / EWTS II : 1999
S. Frandsen: 1999 - Effective turbulence model
Quarton/Ainslie: 1989 - Empirical turbulence model
Empirical turbulence - Dutch TNO laboratory : 1993
DIBt: 2004 - Added Turbulence Model

Figure 146 Alternative turbulence models in "standard" PARK

For turbulence calculations, the S. Frandsen 1999 or the TNO model are recommended as the most-accepted ones at this time. NOTE: Turbulence calculations will be taken out of the PARK calculation in near future. The Site Compliance module has a much more refined and precise calculation of the wake added turbulence. The wake and turbulence models and other advanced functions of the PARK calculation are described in detail in the appendix on Wake and Turbulence Models.

Finally access to WAsP parameter changes are available here as well (see Section 6.3.1) But note that, from WAsP 11, the wasp parameters set when generating a wind statistic (when generated with WAsP 11), are the ones used in the PARK calculation.

3.6.4.2 Power Correction

By default, this option is always activated.

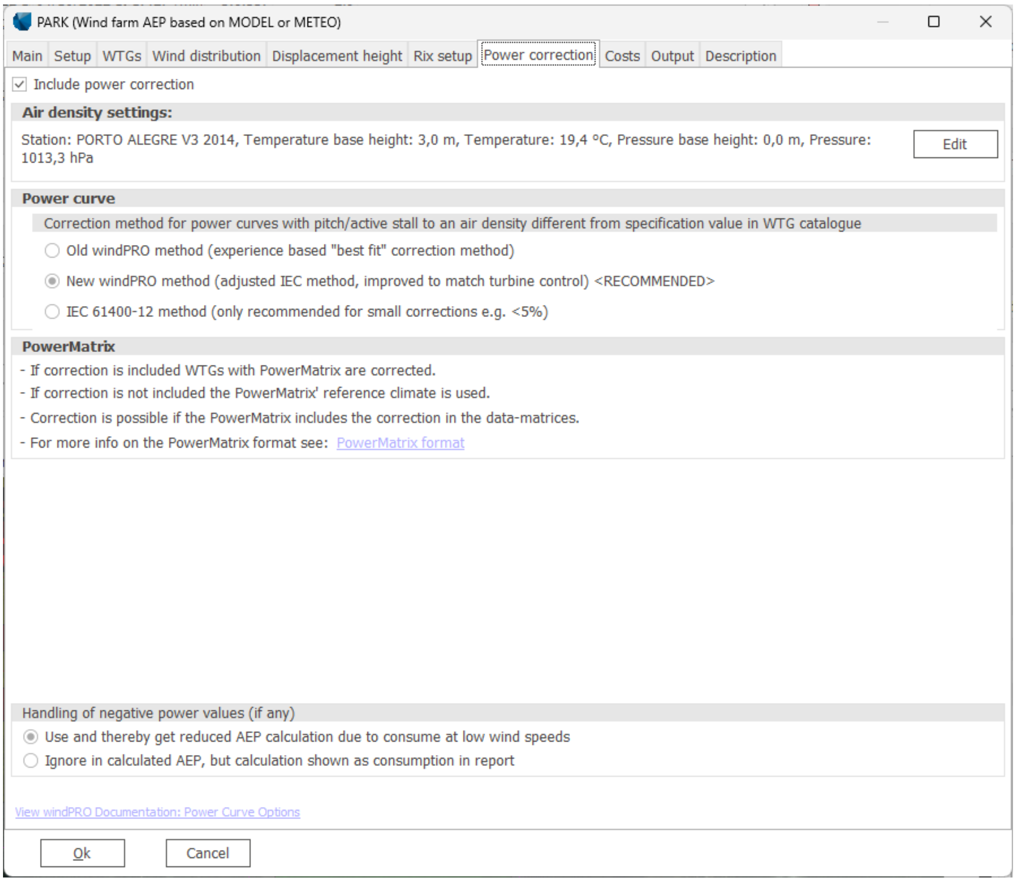


Figure 147 Power curve input (air density correction) for a wind statistic-based calculation

Power curves in the windPRO WTG Catalogue are only available for standard air density (1.225 kg/m^3) and are then recalculated by WindPRO to the site air density. Alternatively, the user can enter the local site air density-specific power curve in the WTG Catalogue and then deactivate the correction (obviously, if the default correction is activated with site air density available in Catalogue and in the air density setup, no correction will be made).

By default, windPRO will estimate the site air density from the closest weather station present in its embedded Climate Database. Click the Edit button to see the details, and/or to change this choice.

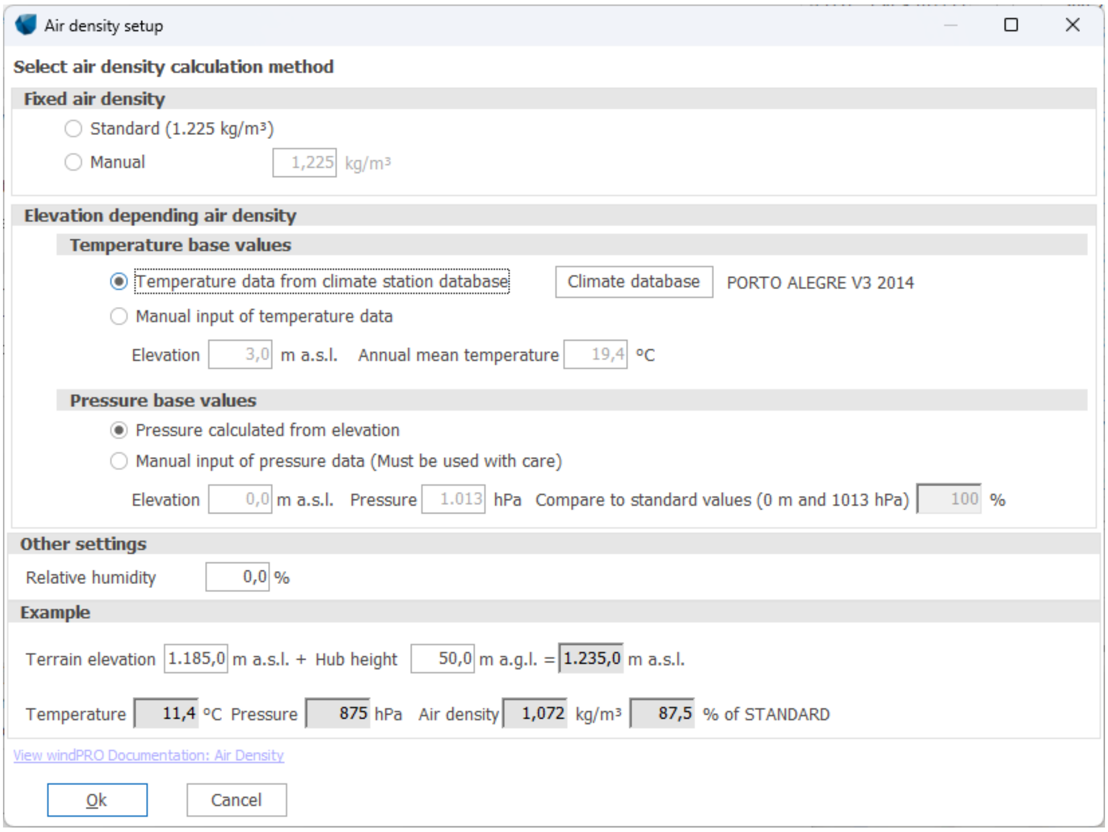


Figure 148 Air density setup form

In the air density window, it is possible to choose the Standard air density, or a manual input.

The default concept is to calculate air density at hub height for individual turbines. The crucial parameters are of course air temperature and pressure. Temperature (by default taken from nearest climate station) is converted to site using the temperature lapse ratio, applied on the climate station elevation and WTG hub height above sea level. Air pressure is by default taken from elevation, assuming Standard Atmosphere.

Alternatively, both parameters can be manually entered, together with the respective measurement elevations. As a minor influence, air humidity can also be entered.

Finally, it is possible to test (see section *Example* at the bottom) which results for air density the setup will give. This is based on any value of elevation and hub height. This allows to test the sensitivity of the estimate to the choices made.

Back to the Power correction main window, three different correction methodologies can be chosen.

Old windPRO method: based on the simple scaling of power values according to the ratio of site-to-standard air density, typically used for stall-regulated wind turbines. This scaling approach would change the level of the rated power if applied at all wind speeds. To avoid this, an empirical solution is made, such that the scaling stops shortly before the scaled rated power is reached, and instead a smooth empirical transition to the real rated power is made.
The drawback of this approach is that for large corrections (usually to low air densities) the empirical transition from the steep part of the power curve to the rated power is not smooth enough and the shape does not accurately mimic the behaviour of pitch-regulated wind turbines. Overprediction of AEP as for the IEC method can be the result for large corrections to low air densities.

IEC 61400-12 method: it is a two-step procedure. The power output at all wind speeds is assumed to have the standard ρu^3 dependence. Instead of scaling the power values at standard air density (P_{std}) by the ratio of site air density-to-standard air density (which would alter the rated power), step 1 scales the wind speeds of the standard power curve according to:

$$u_{site}=u_{std}(\rho_{std}/\rho_{site})^{1/3}$$

The resulting corrected power curve (u_{site}, P_{std}) is, however, sampled at the new wind speed values, u_{site}. To obtain the air density corrected power curve at the original wind speeds (u_{std}), step 2 interpolates the new corrected power values at the original wind speeds, i.e. (u_{std}, P_{site}), from the curve (u_{site}, P_{std}).

New WindPRO method: an improved air density correction, based on a simple adjustment of the IEC 61400-12 method. The assumption implicit in the IEC correction is that the efficiency of the turbine is constant at all wind speeds, which we know from the C_p curve is not fulfilled. As a result, the IEC correction does not perform well around rated power. **Therefore, the IEC 61400-12 correction should _only_ be used for small air density corrections!** The New WindPRO method uses the two-step approach identical of the IEC 61400-12 method, with the simple but important difference that the exponent in equation above is not constant at 1/3 for all wind speeds. Instead, the exponent is made a function of wind speed. A full theoretical description of this and the other methods can be found in Reference documents - Power Curve Options.

Finally, negative values in the power curve can also be handled. Most often, the power value in the interval from 0 to around 4 m/s is 0 W. But some power curves do exhibit negative values. If these are included, they can be handled in two different ways:

1. Default: the power consumed at low wind speeds is included in the AEP calculation, and the AEP result thereby reduced.
2. Ignore the negative values in the AEP calculation, but then report the calculated power consumed separately. This makes sense if a very accurate financial calculation is required, and the power purchase cost is higher than the price paid for delivered power.

3.6.4.3 PowerMatrix

PowerMatrix is a new format for power curves developed by EMD. This experimental format allows for multiple power curves in one structured file format. The idea is that manufactures instead of handing out multiple pages with all different power curve variants (Air density, turbulence, noise, load modes etc.), can write all variants into one file, in which windPRO can extract/interpolate to the one matching the specific situation. Especially for the time step-based calculation concept, this will add several benefits, while the relevant power curve for each time step can be chosen.

3.6.4.4 Cost

Under the Cost tab, it is possible to set up the parameters for calculating the Levelized Cost of Energy (LCOE). See section 3.6.15

Figure 149 Selection of LCOE presets

3.6.4.5 Output

The Output tab specifies how a couple of figures are presented in the report.

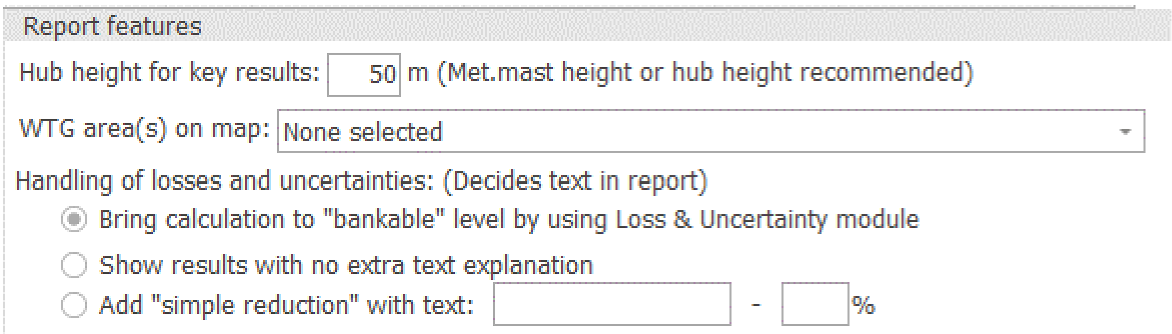


Figure 150 Setup for PARK report

Hub height for key results gives calculated mean wind speed, energy and the equivalent roughness class for this height at the location where the Site Data Object is placed.

WTG area(s) on map gives the option to include selected WTG Area's on the map as part of the report.

Handling of losses and uncertainties:
Here, it is decided how the user wants to integrate these variables into the reporting. It is recommended to use the Loss & Uncertainty module to give this important part of the AEP calculation the right focus. For "simpler" or preliminary calculations, the other options can be used. The "Add simple reduction" to compensate for bias, loss

and uncertainty reductions will add an extra column in the report with the reduced AEP result. You can define the text written at the printing stage. The default is “Result – xx%”

3.6.5 Standard PARK calculation with WAsP

3.6.5.1 Wind distribution

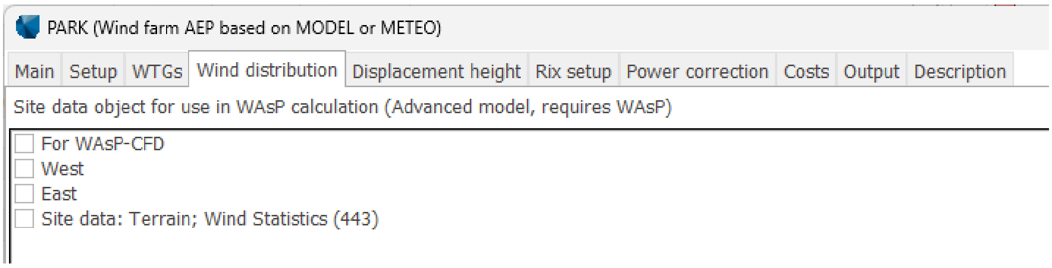


Figure 151 Wind distribution selection in standard PARK with WAsP

The Site Data Object(s) to be used are checked – the default is that the nearest will be used at any turbine position. At the WTGs tab, it can be decided, manually, to link a Site Data Object to each turbine. This can be usefully if, e.g., one Site Data Object is based on measurements on a hill and another downhill. Then turbines on the hill and downhill should be linked to the most representative Site Data Object.

3.6.5.2 Displacement height

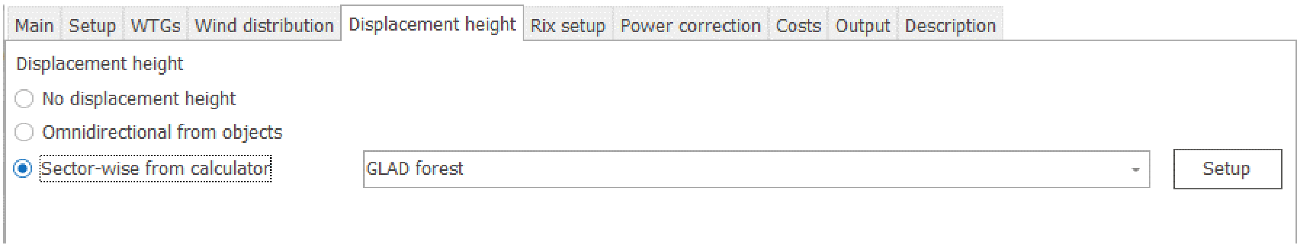


Figure 152 Displacement height setup in standard PARK

It is possible to use:

- No displacement height – the “original” hub heights for each turbine is used.
- Displacement heights from objects – the hub heights are reduced with the displacement height defined in the WTG object.
- Displacement height Calculator – Sector wise displacement heights from the calculator, object displacement heights are ignored (see Section 8.4 for a description of the Displacement height calculator.

3.6.5.2.1 RIX setup

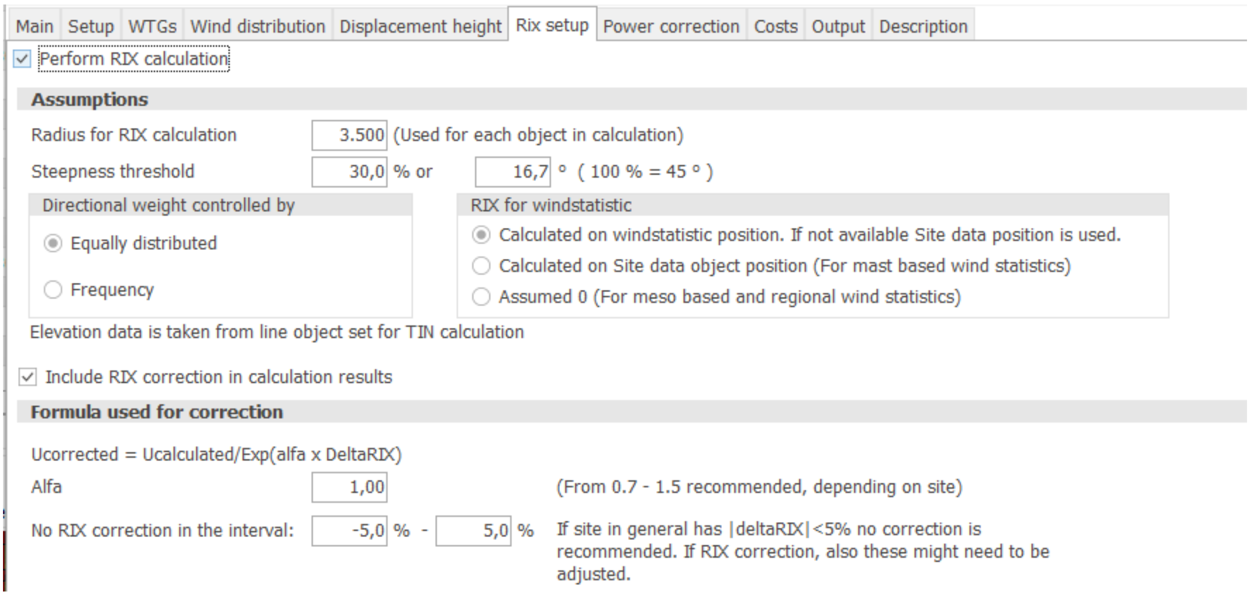


Figure 153 RIX input setup in standard PARK

The RIX settings are explained in Section 3.4.5 Rix correction.

3.6.6 Standard PARK calculation with WAsP-CFD

The calculation setup follows the same as "Standard PARK with WAsP" except for the wind distribution tab, which is replaced with two tabs: CFD result files and Wind statistics.

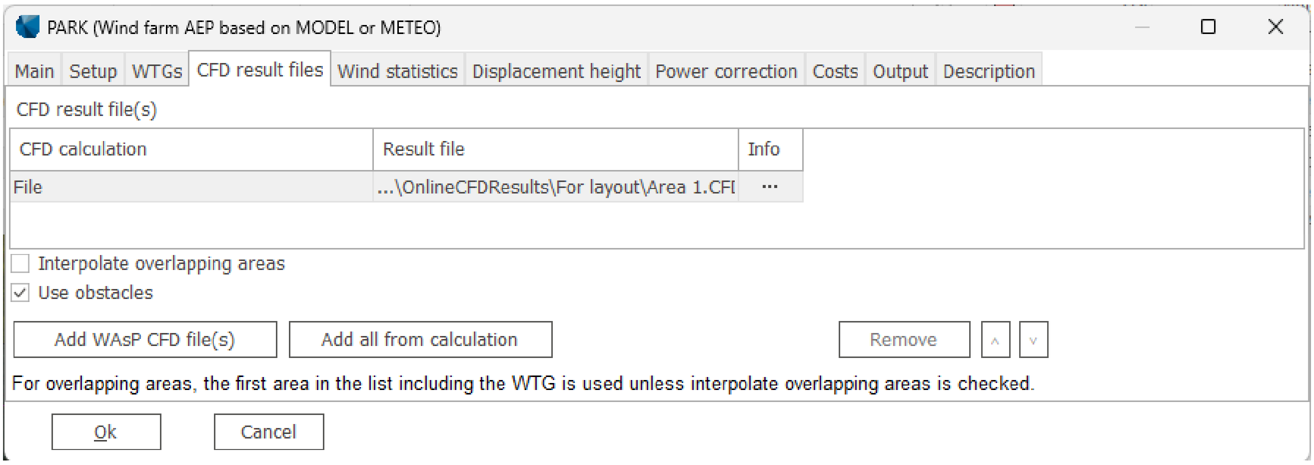


Figure 154 Wind distribution selection in standard PARK with WAsP-CFD

The CFD result files are added, typically "all from calculation", and the calculation "behind" the CFD results is pointed out. Individual CFD result files can also be pointed out, if coming from another project or a mix from more calculations.

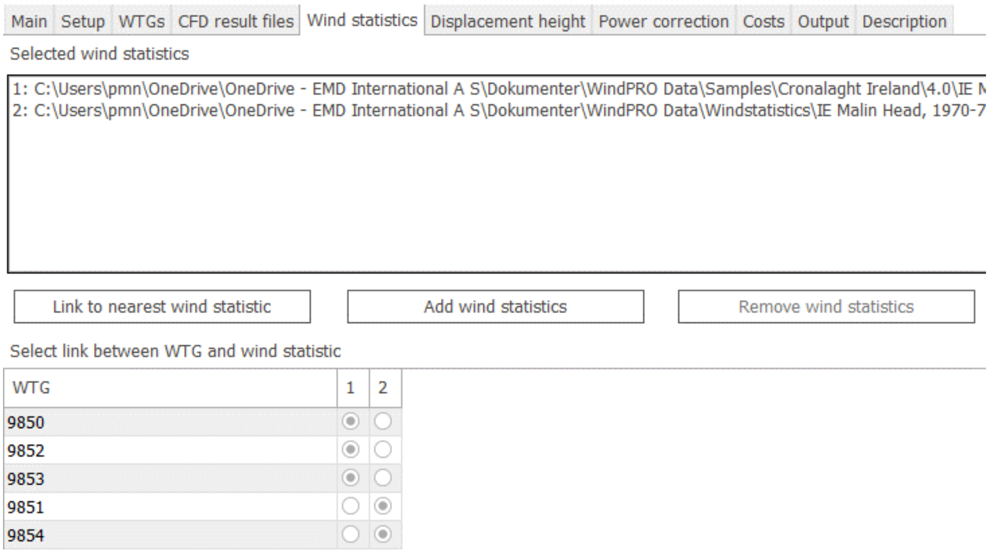


Figure 155 Wind statistics selection in standard PARK with WAsP-CFD

More wind statistics can be selected. **Note: When adding more wind statistics to a WAsP-CFD based calculation, these additional should be generated based on CFD result files** – if they come from a traditional WAsP Statgen, this can introduce a bias. More wind statistics can be linked individually to turbines.

3.6.7 Standard PARK calculation with resource file

The calculation setup follows the same as “Standard PARK with WAsP” except for the wind distribution tab, which is replaced with a “Resource files” tab:

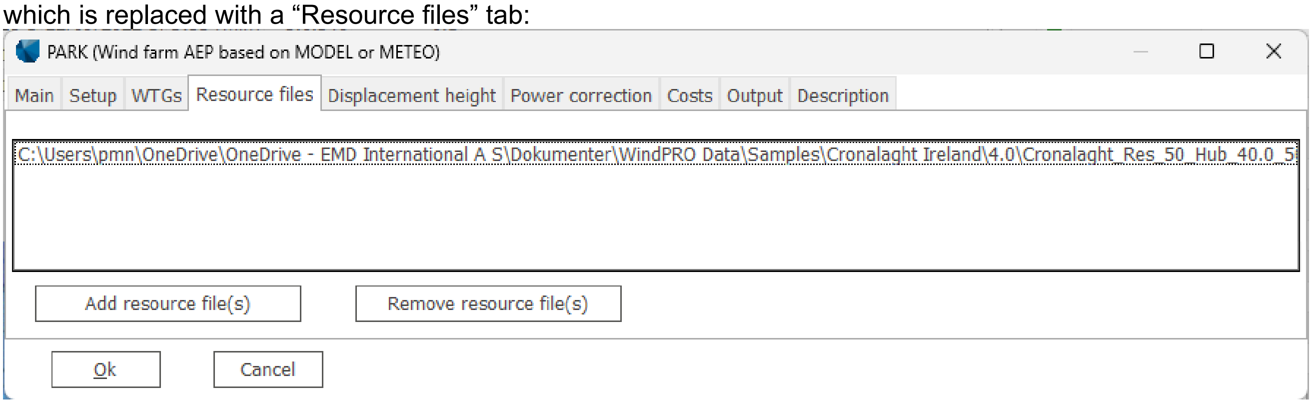


Figure 156 Resource files selection in PARK based on resource files

Resource map files (.rsf or .wrg or .siteres) are added and used as the wind data in the calculation. In overlapping resource files, these will be interpolated in the calculation points.
Note the new 3.5 feature: 3.5.5.3 Resource map rescaling

3.6.8 Common settings for Time series-based PARK calculation

Calculation in the time domain gives many new output options and more refined correction features, like seasonal correction of wind data, power curve corrections for each time stamp based on variables like temperature, shear, turbulence, etc., also, for the wake models, more advanced correction options are available.

3.6.8.1 Setup, time step based calculation

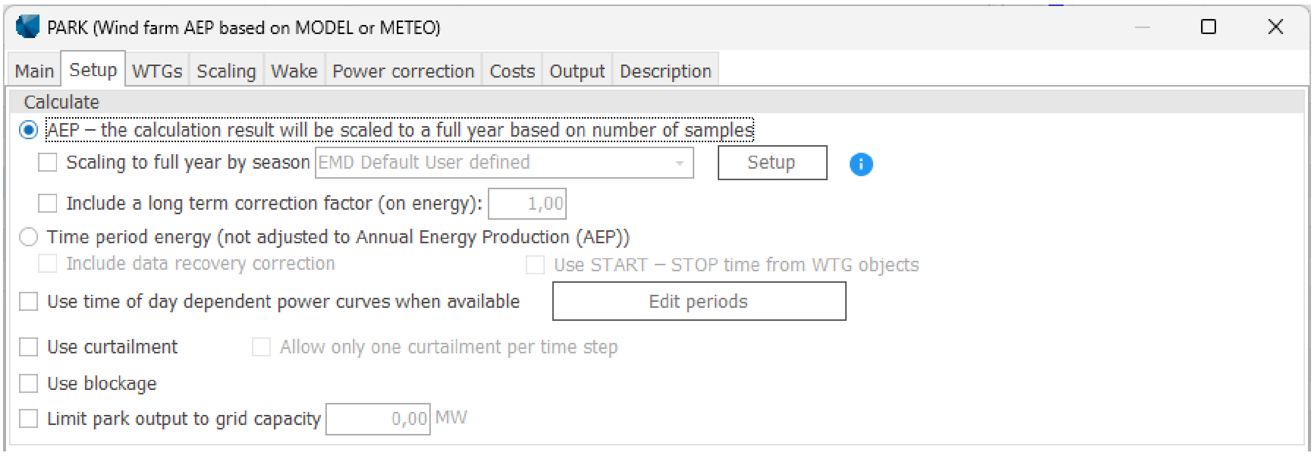


Figure 157 Setup input for PARK based on time series

The output can be:

(o) AEP – the average hourly-calculated production based on all used wind data is multiplied with 8766 (hours in an average year)

Include seasonal correction: Seasons can be defined, e.g., as months or 4-seasons (winter, spring, etc.). Within each season, the average hourly production is calculated. This is then multiplied with the relative time in each season and scaled to a full year with 8766 (hours in an average year). Thereby, each season is given the same weight (corrected for length differences in seasons), and, thus, compensation is made for, e.g., an overweight of winter data. If a season has less than 1% of all data, calculation is not possible while the season correction is judged to be random – and if a season has no data, the season correction calculation is not possible.

Include a long-term factor – if the wind data period is known to be biased relative to long term, it is possible to adjust the results by a factor.

(o) Time period energy – simply, calculated production in each time step and all values added. The result can, thereby, be for, e.g., ½ a year or 3 years, depending on the data period. This can be convenient for follow up on a specific period or to find the production that has been lost if a turbine has been out of order for a specific period.

Include data recovery correction – if some time records are missing during the data period (defined by first and last time stamp in the calculation period), the decision can be made to compensate for this, simply by finding the data recovery rate and dividing this into the calculated summed production.

Use START-STOP time from WTG objects – is a new 3.2 feature that makes it possible to calculate a wind farm where the operating turbines change in time – in ONE calculation. At the turbine object there is a new setting: Operation, where the date for START and/or STOP can be entered. This feature makes it very convenient when e.g., performing analyses in Performance Check, while the entire data period can be analysed in one process. It is even possible to utilise if a turbine has changed operation mode during time, simply by creating two WTG objects, having the different operation modes and set STOP for the one equal to START for the other. Then although the operation data imported in Performance Check must be divided into two files with different WTG ID. It is also possible to simulate future added wind farms based on this feature in combination with an offset on the timeseries used in calculation. Add e.g., 20y to past 20y data and the turbines put in operation during next 20y will be included from planned installation date set in the WTG object.

Use time of day depending power curves. This makes it possible to calculate like noise reduction modes that vary during the day. The setup looks like this:

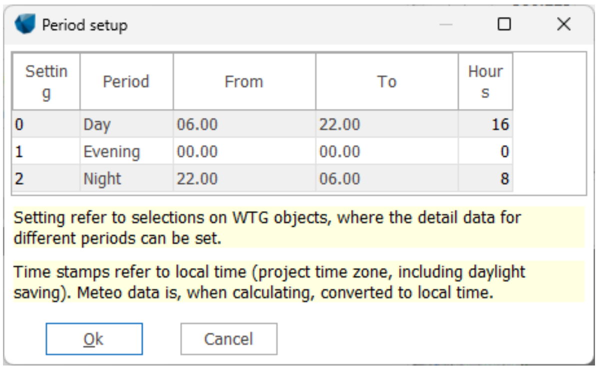


Figure 158 Time of day depending power curve setup.

Note the different power curves must be defined at the WTG object.

Use curtailment, see common settings for all PARK variants 3.6.3.
Use blockage, see common settings for all PARK variants, 3.6.3.3 Use Blockage
Limit park output to grid capacity, see 3.6.2.2 Grid curtailment

3.6.8.2 Wake settings, time step based

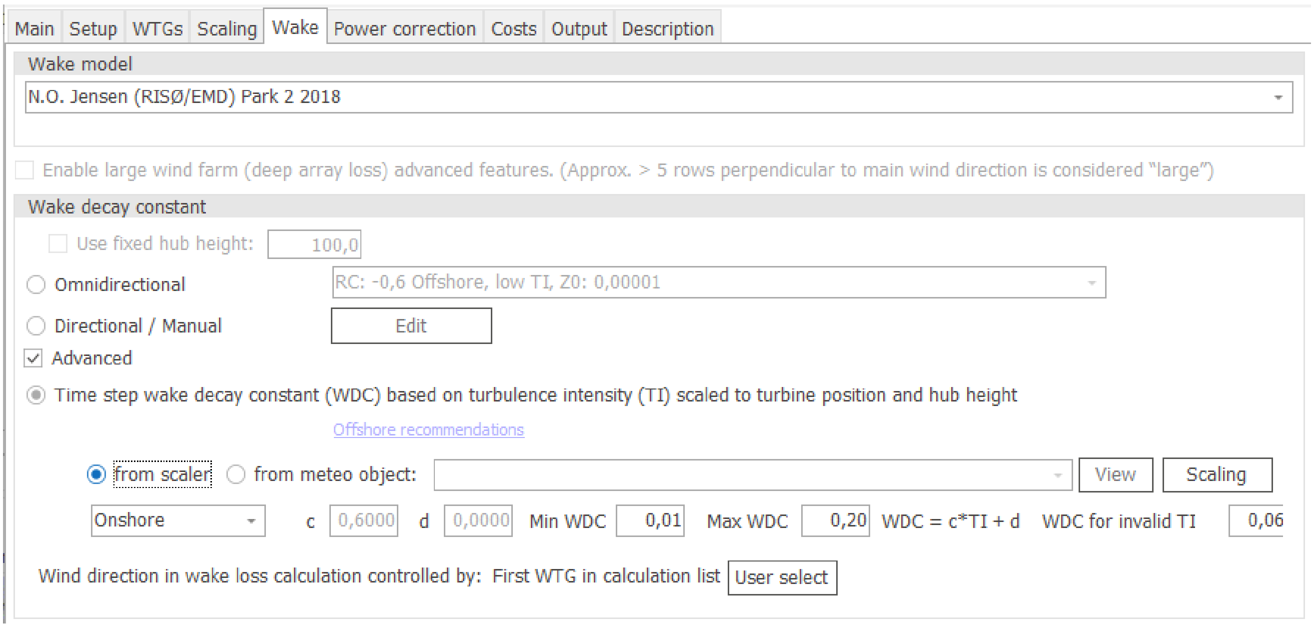


Figure 159 Wake setup in PARK based on time series

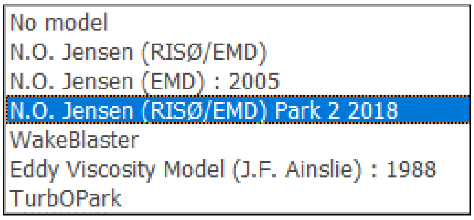


Figure 160 Wake models for time step calculations.

The recommended model is as for statistical based calculations the PARK2 model. For performance Check (model validation/tuning) although the NO2005 offers some more "handles" that can bring the model closer in alignment with real performance. Especially for single row projects this can be tuned to handle those correct, where the other models suffer from not being able to separate the "nature" of single row versus multiple row performance.
An interesting new option since 3.4 is the external WakeBlaster model, see 3.6.13.

The standard input options are as described for the wind statistics-based PARK are shown above. The interesting part is the new options - The wake model settings have this “advanced” expansion box for all models:

[x] Advanced – gives access to a time step turbulence-based correction.

Time step turbulence based requires a turbulence signal in a METEO object or when using “data from scaling”, more options are available, see 3.4.8.4 Turbulence in scaler. NOTE: The dataset must exist concurrent to the entire wind data period in the calculation! Based on the calculated wind speed at each turbine position, the turbulence is then found from the St.dev. The turbulence at each turbine position then decides the wake decay constant for the wake loss calculation at the given turbine. The translation from turbulence to WDC is based on a simple linear relation, where the parameters can be edited. The default is like this:

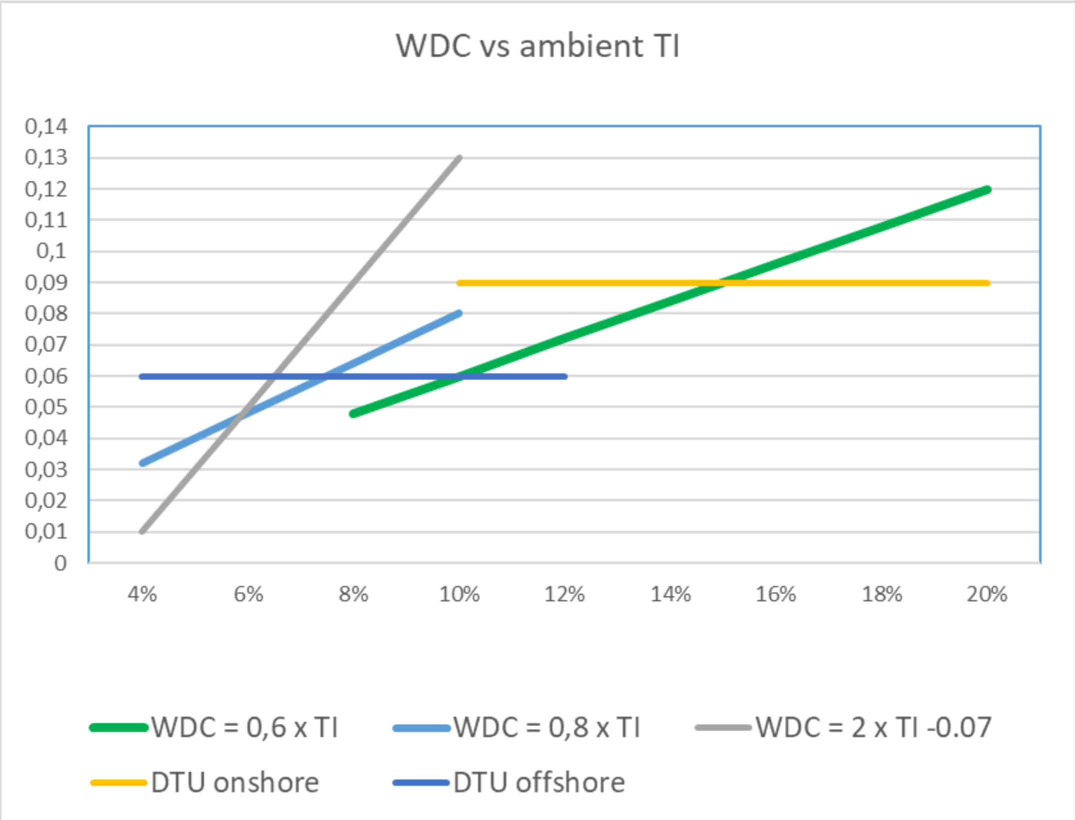


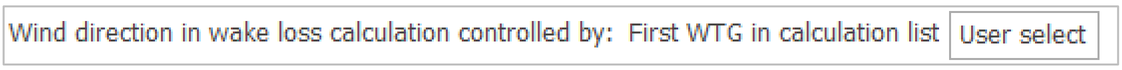
Figure 161 WDC versus turbulence, PARK2, for time step correction, recommendations.

Above, the relation between turbulence and WDC for PARK2. The DTU recommendations are limited to one value for onshore, one for offshore. It is although documented in numerous DTU papers, that the TI affects the wake losses significantly and thereby the WDC choice should depend on the site TI.
The latest EMD recommendations were shown in Table 6 Recommended settings for N.O. Jensen PARK models. In Figure 161 it is illustrated graphically. There is a grey area between on- and offshore, with TI round 10%.

By analyzing data from more offshore wind farms, the relation WDC = 2 x TI -0.07 is found to give the best match, when subdividing data into TI bins. This is although problematic as a generalized formula, as the average TI level impacts this formula. Thus, it will only be working well for sites with average TI round 6-7%.

The large advantage making the WDC controlled by TI is that it takes out the guessing required on an average WDC, and it does the weighting of the data against turbulence (see the test example in validation, Section 8).

With the fully formula-based TI to WDC concept from windPRO 3.2, the WDC for N.O.Jensen models can be fully set by the TI or indirect by terrain class.



As seen in the input form, it is possible to select the WTG that controls the wind direction for the wake loss calculation. It is so, when calculating wake loss in a time step, the wind direction must be defined. This can differ by turbine and a choice must be made. The default choice is the first turbine in the list.

The reason for this input option is: when comparing two calculations, e.g., one with an existing wind farm and one with a new + existing wind farm, the existing wind farm might get slightly different results in the two calculations (apart from the influence from the new). Meanwhile, in the second, a new turbine comes in and controls the wind direction, because new turbines are first in the list of turbines to be calculated. For such a comparison calculation, it is then possible to manually select the same turbine to control the wind direction. In very complex terrain with large turns of the wind direction, it can also be convenient to be able to decide which turbine that decides the direction for the wake loss calculation, e.g., one in the middle of the site instead of the outmost.
The choice does also influence the calculated free wind speed aggregated by sectors. The reason for this is that the sectors are defined by the wake calculation direction and thereby by the turbine chosen for controlling the direction.

3.6.8.3 Large wind farm advanced features (Deep array losses or single row)

[x] Enable large wind farm advanced features – gives access to modifying the wake combination model with two different variants for NO2005, and one for PARK1.

The here described features are for POST construction evaluations, where there is a wish to tune the Wake model to reproduce the measurements. The found needed tunings can of cause be used for PRE construction, if a similar wind farm is planned in similar environments.

In the original N.O. Jensen wake model, the wind speed deficits when having wakes from more turbines are summarized by Root Sum Square (RSS) method. An alternative is to summarize the deficits, are the Linear method (simple sum). Tests show this method reduces the wind speeds far too much, but, on the other hand, the RSS method might to reduce too little when there are many arrays. Combining the two methods might give a better reproduction. It is now possible to control the weighting of the two methods with full flexibility. For PARK2 the summarizing is fully linear, but based on revised formula set, so not direct comparable.

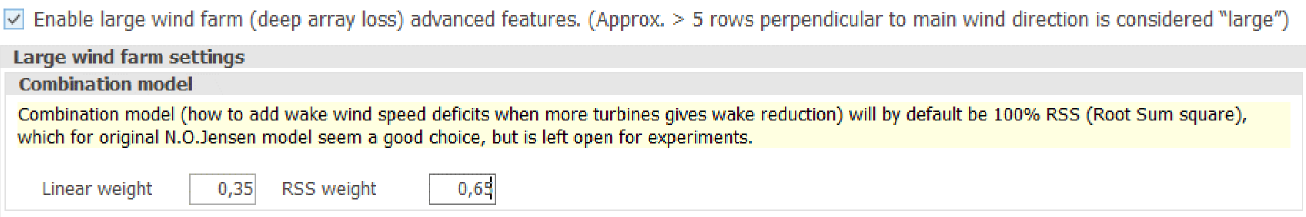


Figure 162 Linear and RSS weight in PARK combination model

The simple modification is not to give the RSS wind speed deficit calculation full weight, but to give some weight to a linear sum of the deficits. An experimentally found reasonable weight for NO2005 is 35% linear weight, given as the default (see further details in the Park model validation chapter, Section 8.2. The method is, e.g., supported by the work RES: OFFSHORE WAKE MODELLING, Presentation at Renewable UK Offshore Wind 2011, by Gerd Habenicht, Senior Technical Manager, 29th of June 2011.

But, this combination tends to give too high of reductions inside the wind farm. An additional correction proposed in "Evaluation and Benchmarking of Wind Turbine Wake Models" by Mathieu Gaumond, DTU, June 30th 2012, is to decrease the WDC by number of upwind turbines.

Some experiments have been performed and resulted in 3 different versions of the way the change in WDC by upwind turbines are calculated. The version 3 is the recommended, ver. 1 & 2 are only seen as relevant for backward combability. This option is ONLY available for the NO2005 model variant.

Version 1: Semi aggregated reduction by number of upwind turbines.
Version 2: Full aggregated reduction by number of up wind turbines starting from WTG 2.
Version 3: Full aggregated reduction by number of up wind turbines starting from WTG 1.

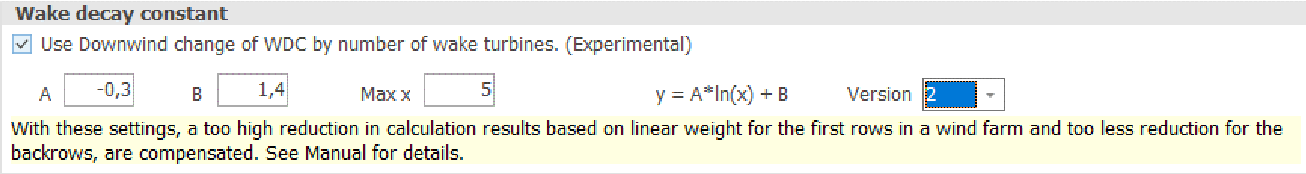


Figure 163 reduction of WDC by number of upwind turbines, Version 2 & 3.

This more advanced/experimental added modification of decreasing the WDC for the more upwind turbines is found to improve the result, especially handle row by row more accurate, where the average only changes slightly by the use of the shown defaults (see examples in validation, Section 8).

We recommend stopping the reduction after row 5.

How version 3 works, including recommended input data, is illustrated below. Set 1 is recommended as initial input. If the results (seen in Performance Check module) show that row by row not is reproduced correct, set 2 (less aggressive) or set 3 (more aggressive) can be brought in.

Table 9 Decreasing WDC by upwind turbines.

Multiple rows: decrease WDC by upwind turbines			
	set1	set2	set3
A	-0,3	-0,2	-0,5
B	1,4	1,3	1,5

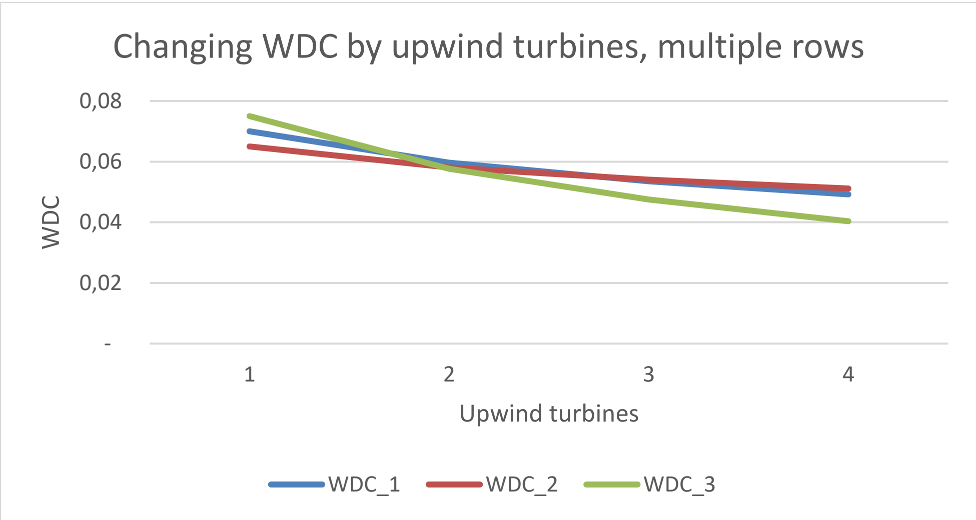


Figure 164 Decreasing WDC by upwind turbines.

For multiple row wind farms, there will typically be seen a need for decreasing the WDC by number of upwind turbines. This can be done more or less "aggressive" illustrated by the three sets of constants, resulting in the three shown graphs where it can be seen how a "base WDC" of 0.05 converts to WDC values used for WTGs with one or more upwind WTGs.

Table 10 Increasing WDC by upwind turbines.

Single rows: increase WDC by upwind turbines			
	set1	set2	set3
A	0,6	0,3	0,9
B	0,6	0,8	0,4

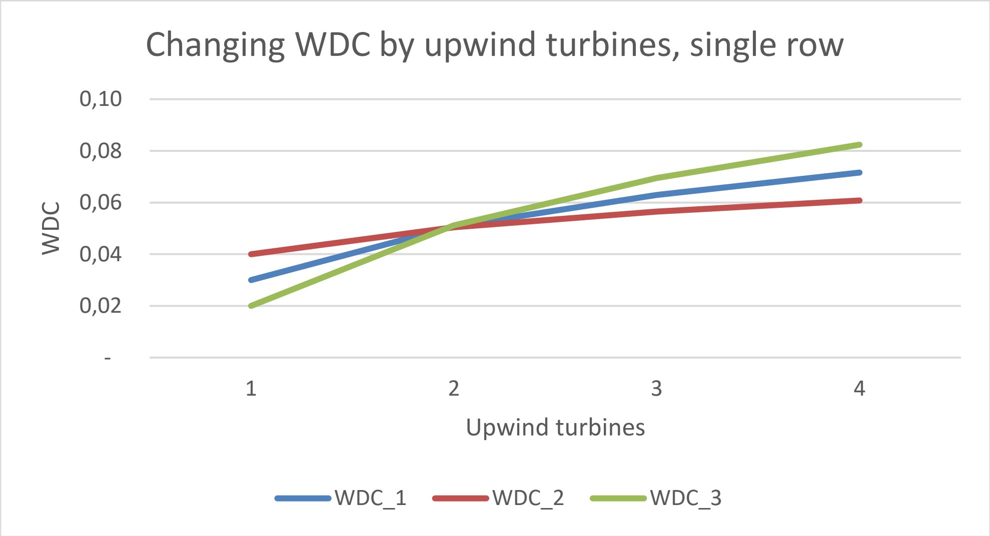


Figure 165 Increasing WDC by upwind turbines.

For single row wind farms, there will typically be seen a need for increasing the WDC by number of upwind turbines. This can be done more or less “aggressive” illustrated by the three sets of constants, resulting in the three shown graphs where it can be seen how a “base WDC” of 0.05 converts to WDC values used for WTGs with one or more upwind WTGs.

IMPORTANT to notice is: A correct wake loss calculation is a balance of the chosen model (e.g., the N.O. Jensen 2005 implementation), the WDC and evt. Deep array settings (Linear weight and WDC decrease by upwind turbines). Ongoing experiments show that a 35% Linear weight in combination with turbulence based WDC gives the best reproduction of the measured wake loss when using NO2005. If Linear weight of 100% is used, the increase of WDC should be 0.03 (from 0.04 to 0.07 offshore). But then the wake loss along the rows is over predicted, but the 360° result is fine for the test case HR1. See validation chapter.

3.6.8.4 Power curve corrections by time series PARK calculation

Power curves are traditionally used as an “annual average” power curve in AEP calculations. With the time step calculation method, it is possible to introduce corrections for power curves based on the meteorological parameters present at each time step. This will, typically, not change much in the calculated AEP, but, for sites with, e.g. very low or high turbulence, it can create improvements on the AEP accuracy. And, when doing Performance Check analyses, the corrections can explain periods with high/low performance based on the influence of the meteorological parameters on the power curves.

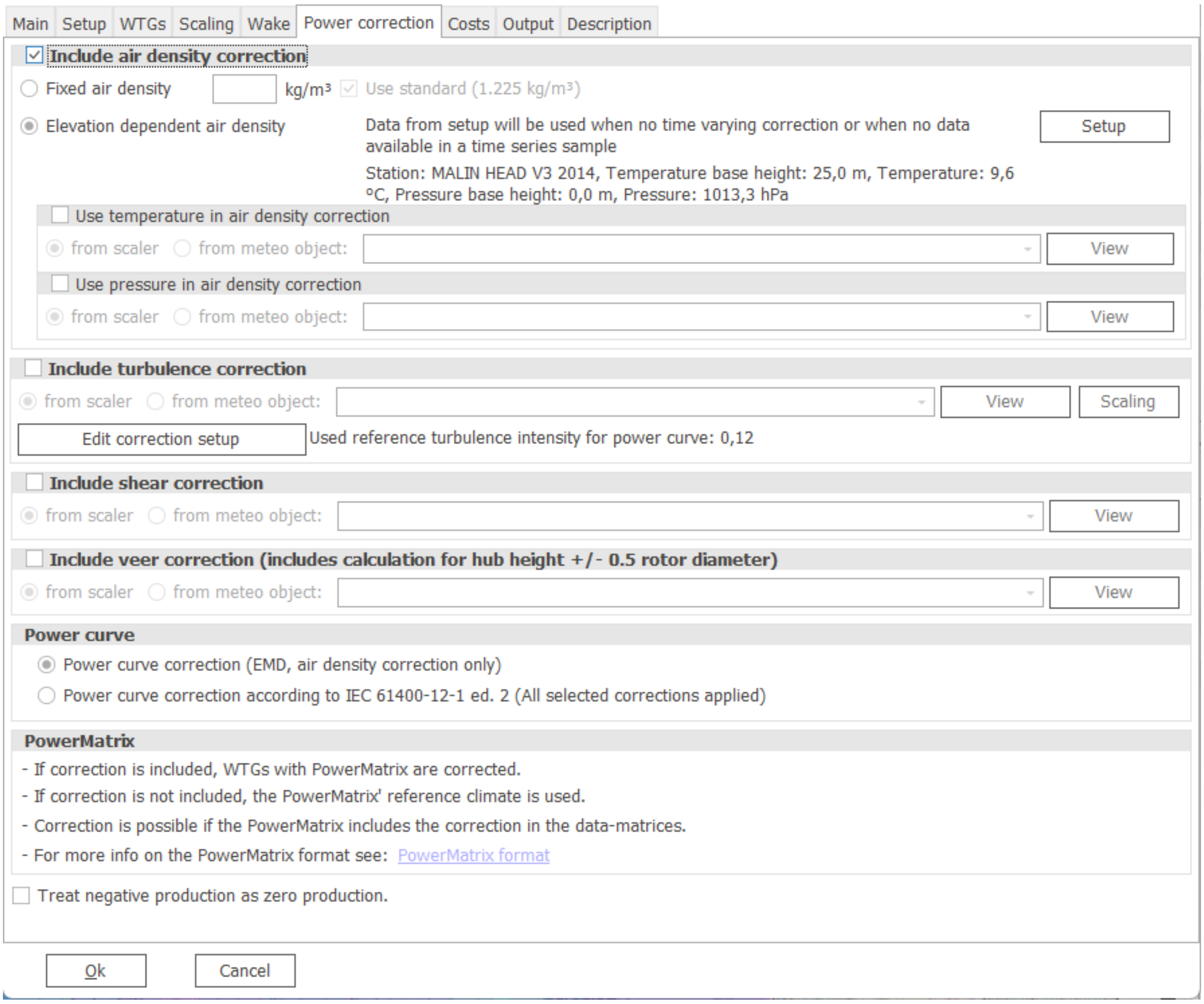


Figure 166 Power curve correction options in time domain

The possible corrections are:

- Air density (by temperature and/or pressure)

Selecting the "according to IEC 61400-12-1 ed.2" OR using PowerMatrix, gives following extra:

- Turbulence (only pitch regulated turbines)
- Shear (based on shear heights selected in Scaler)
- Veer (based on Veer signal in Meteo object or mesoscale shear)

The Air density correction follows the formulas described in the IEC standard 61400-12-1 ed.2, and differs slightly from the "Adjusted IEC method" described in Section 3.6.4.2. A full theoretical description of the two methods can be found in https://help.emd.dk/knowledgebase/content/ReferenceManual/PowerCurveOptions.pdf

It should be noted that the IEC standard describes how to correct a measured power curve to standard conditions based on the meteorological parameters. Here, the methods are "reversed" so they correct the standard power curves to modified power curves based on the parameters. To make the concept work smoothly, some decisions have to be taken upon implementation.

By default, windPRO will estimate the site air density from the closest weather station present in its embedded Climate Database. However, in a timeseries-based scenario, it is certainly wiser to extract temperature and pressure from the METEO object with the wind data selected in the SCALER tab. (Use data from Scaling). Then, it will be required that ALL METEO objects (if multiple) have the required signals present at EACH time stamp. For example, wind speed AND direction must be present in all METEO objects for the given time stamp. The calculation, however, allows for a time offset of up to 50% of the sample time, if more METEO objects are used. Thereby, non-syncronised time stamps in different METEO objects can be used.

If temperature or pressure are taken from ONE METEO object, the demands on data recovery are less. Here, up to 13 time steps (equal to 2 hours+ having 10min wind data) is allowed to be missing or disabled and a linear interpolation is used between two nearest time stamps to find the value. This means that calculations based on 10 min. wind data can use, e.g., mesoscala data with hourly temperature and pressure values as calculation basis for the air density correction. In that case, up to 2 hour values can be missing, and the calculation will still be performed for each 10 min. value based on the interpolated signals.

Same rule for turbulence, where the SCALER from 3.1 partly can scale the turbulence based on more source data(more masts, heights or mesoscale points). Partly take the turbulence from model calculations, if e.g., WAsP CFD result files or FLOWRES files are used in the SCALER. Turbulence Intensity (TI) is scaled to each calculation position assuming a constant Standard deviation by height. From the source data, the standard deviation is calculated from TI and wind speed. Then, based on the calculation point wind speed, the TI is calculated. This is a quite simple approach, not taking into account if there are parts of the site with large turbulence deviations. If the turbulence information is missing in a time step (outside the interpolation frame), no turbulence correction is performed, but the data point is still calculated. Before a calculation is started, it is tested that at least 50% of the time steps has turbulence information, otherwise an error is reported, since it does not make sense, in that situation, to calculate with turbulence correction.

Turbulence can be taken from Mesoscale data (see Chapter 12 regarding METEO objects and how to establish turbulence data from mesoscale data in a METEO object).

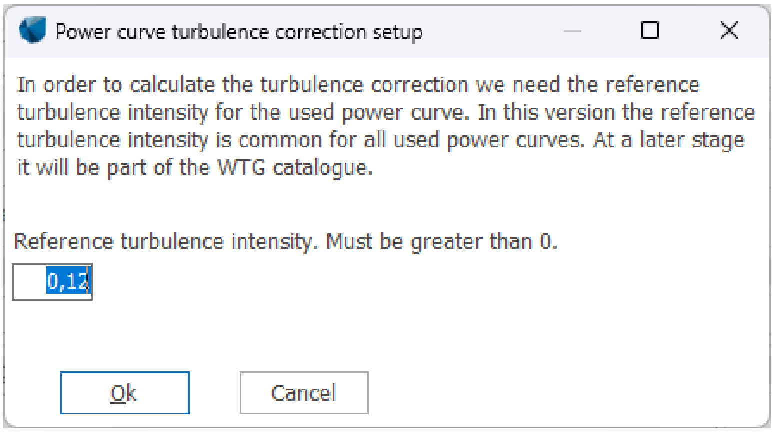


Figure 167 Reference turbulence for TI correction of power curve

The turbulence correction needs an assumption, for the turbulence at which the power curve used, that is representative. This value can be user defined.

Shear can be calculated by time step based on selected shear heights in scaler. For veer this is not an option, here the user must establish a veer signal in a meteo object. The reason is that having two wind vanes normally not will give a reliable veer signal for all time steps, and non valid results will appear. Therefore the user must import and screen the data before use. Eventually substitute part of the time series based on mesoscale data veer – or solely base veer signal on mesoscale data.

In the PERFORMANCE CHECK manual, examples on calculated air density and turbulence corrections are compared to measurements.

For details on the correction methods, please see the IEC standard. The corrections applied can be seen in details in the result to file with a time step calculation. Here as well, the signals used at each time step as the calculated corrections can be seen.

In some special cases at low wind speeds, a turbine can theoretically produce a negative production after the power correction has been applied. These few instances can be overridden to zero production by checking the “Treat negative production as zero production” checkbox.

3.6.9 Time varying calculation based on mesoscale data

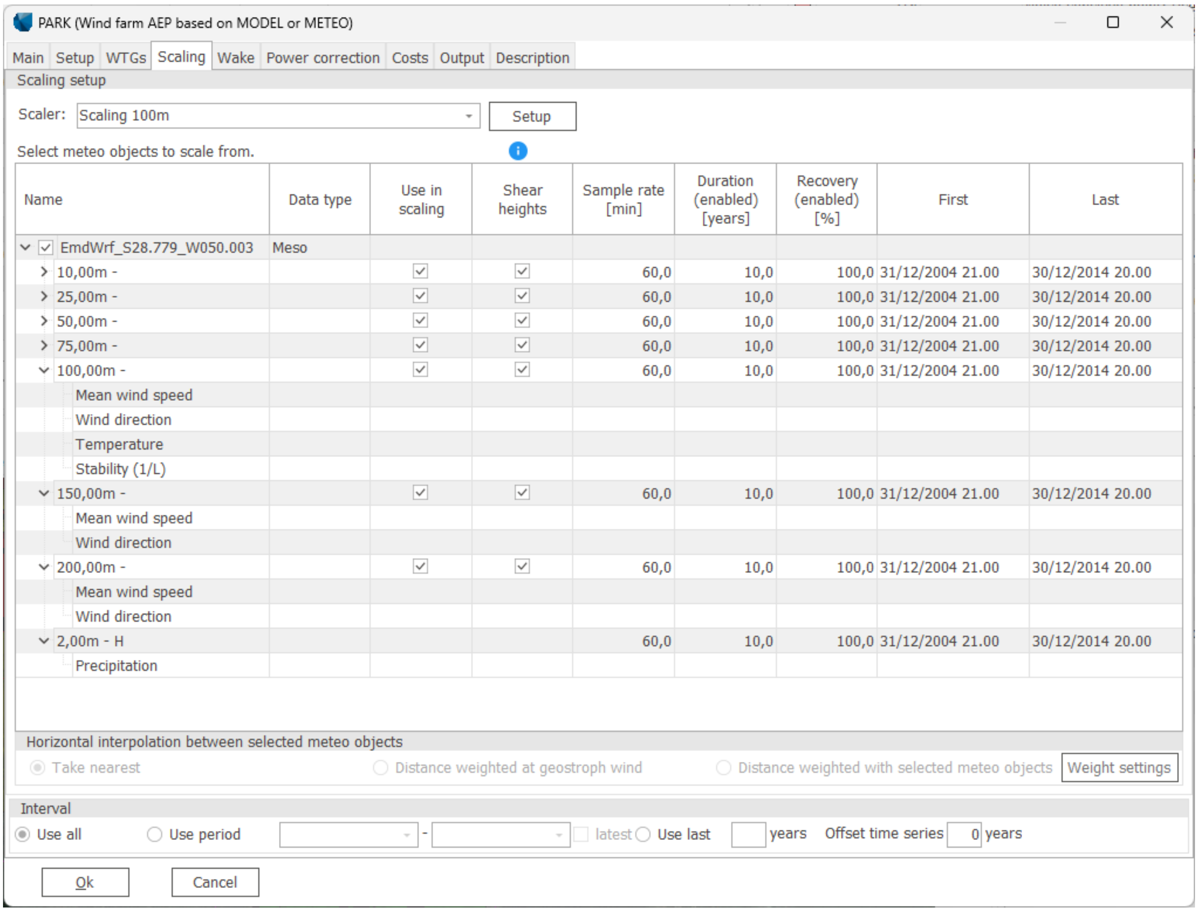


Figure 168 Selection of wind data and SCALER in PARK time series based

Basing the time step PARK calculation on Mesoscale data from EMD (The EMD-WRF model or the EMD-ConWx dataset), all heights of the mesoscale dataset are selected by default. Heights below the lowest calculation height and above highest calculation height MUST be included – no extrapolations are permitted in this calculation concept. The mesoscale data defines the shear and veer. It is, although, possible to also choose the "measurement SCALER" with Mesoscale data (e.g., mesoscale data from other providers), and let the WAsP model do the vertical scaling, then only one data height is used.
More mesoscale data points can be used, and horizontal interpolation can be chosen – the alternative is to "take nearest".

3.6.10 Time varying calculation based on measured data

This option is like time varying based on mesoscale data apart from:

- Instead of using mesoscale data, measured data is used (or an "artificial mast").
- Model is used for extrapolation in height, can be WAsP, WAsP-CFD, Flowres format or resource file. Only local terrain is used.
- The default scaling is based on the WAsP A parameter ratio.
- Heights for wind speed calculation and shear calculation can be individually selected.

3.6.11 Other PARK calculations

The "other" PARK calculations are included for backward compatibility to previous windPRO versions. Please refer to windPRO 2.9 manual for details on these options:

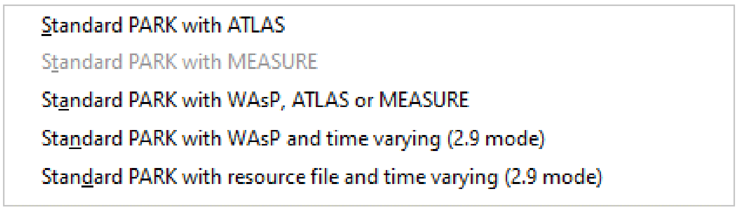
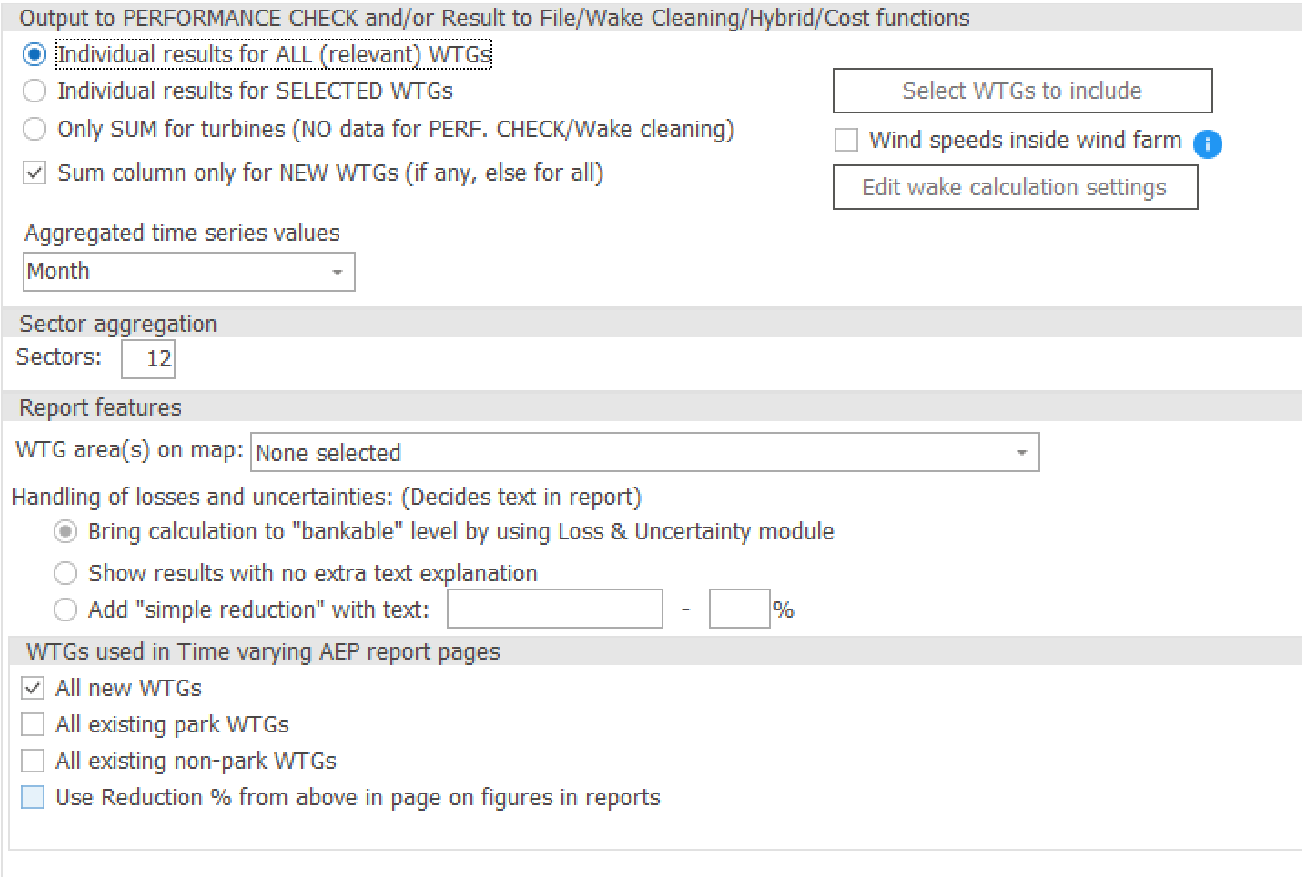


Figure 169 The 2.9 compatible PARK methods

3.6.12 Output from PARK calculations

The Output tab specifies how a couple of figures are presented in the report.



Output to PERFORMANCE CHECK and/or result to file, HYBRID etc.
The time step-based PARK calculation can deliver output files time step by time step, partly to be loaded into Performance Check module for comparison with measured data, partly to a file that e.g., can be further analysed in spreadsheet tools. Also the output for e.g., HYBRID module is controlled by selections made here. The data quantity can become VERY large. Therefore, some limitations can be set, like only having detailed data for selected turbines or only having the sum for all turbines. Finally, the time series can be aggregated to hourly, monthly etc. data records. By default, aggregation to monthly values is set to avoid storage of large data amounts that may not have any purpose. For a detailed Performance Check, 10 min. or hourly data is preferred, (assuming this data is available as measured production). For HYBRID output at least hourly resolution will be needed. Note the calculated data will be stored in the windPRO project file. Running many calculations with high resolution/long data period in non-aggregated mode will make the windPRO project file very large.

Report features is as described for the wind statistics based concept.

Report pages for time varying results. Here, it can be decided to include new and/or existing turbines. A special variant is to include existing ONLY if they have the property “Park WTG” checked in their object setup. Thereby, a calculation having both existing in the windfarm to be expanded + reference turbines nearby, can be “split”, so the time varying reports only show the result for a wind farm with some new and some existing, without considering other existing turbines in the report.

The results presented are in the following graphs:

- 24-12 table with MWh
- 24-12 table with MW
- Graph with monthly production
- Graph with diurnal production
- Table and graph with duration data

Result to file, the time step results are explained in 3.6.12.2 Output from PARK calculations, Result to file

Partly the report pages and partly the result to file options will be described here that give an output for taking the results to spreadsheets or other external software tools for further processing. It will also be explained how the output options will be different from a wind statistics-based calculation and a SCALER (time step) calculation.

One of the differences is that the SCALER based calculations will be able to provide the wake reduced wind speeds as well as the non-wake reduced, since the wind statistics-based calculation only provides the non-wake reduced wind speeds.

Another difference is that the wind statistics-based calculations deliver the modifications due to, e.g., hills and obstacles as percentages on AEP relative to flat terrain and no obstacles. This calculation is very fast, and extra calculations are automatically performed with/without e.g., hills. The SCALER based calculations are only one run, but, as an output, there will be the speed up factors (flow perturbations) from WAsP used in the SCALER. This means that the time step calculations deliver the speed-ups on wind speed due to hills, obstacles etc. as an alternative to the percent increase in AEP. The speed-ups are relative to flat terrain/no obstacles. If the speed up relative to a measurement mast position is wanted, this can be found as the ratio between the speed up at turbine position and mast position based on a calculation where both positions are included, where a turbine is included at the measurement mast position.

3.6.12.1 Output from PARK calculations, Reports

A feature from windPRO 3.3 that not many users are aware or is the option to copy graphs and tables to clipboard from the report preview:

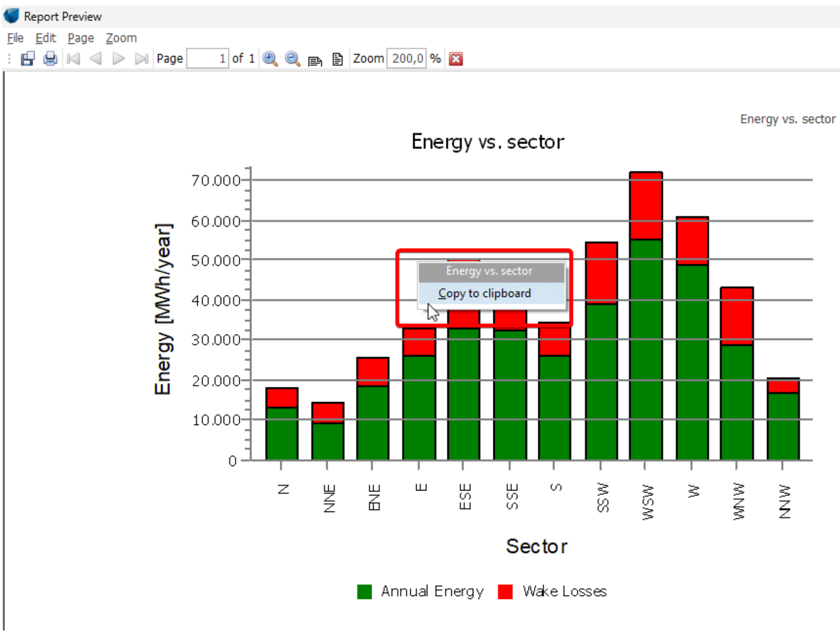


Figure 170 Right click on preview graph to copy to clipboard.

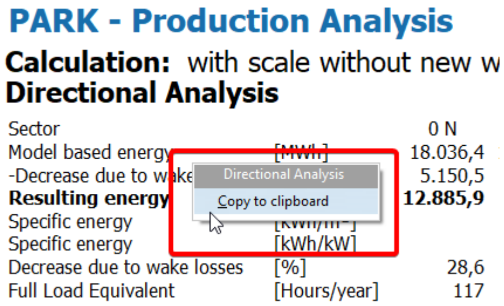


Figure 171 Right click on preview table to copy to clipboard.

When tables are copied, it is not “just” a picture, but the cells, meaning that pasting e.g., into Excel, the texts and values will be available for further processing.

Project:
Cronalaght_fotomontage-energy2DK-test

Description:
This project illustrate primary how to calculate energy production, partly based on EU-Wind Atlas data, partly based on local measurements. Also ATLAS contra WASP is illustrated, and the powerfull VISUAL module for excact positioning of the WTGs, measuremasts etc.

Licensed user:
EMD International A/S
Niels Jernes Vej 10
DK-9220 Aalborg Ø
+45 9635 4444
Per Nielsen / pn@emd.dk
Calculated:
01-07-2015 16:42/3.0.623

PARK - Main Result

Calculation: Std. PARK lt meso data

Wake Model N.O. Jensen (RISØ/EMD)

Calculation performed in UTM ED50 Zone: 29
At the site centre the difference between grid north and true north is: 0,6°

Power curve correction method
New windPRO method (adjusted IEC method, improved to match turbine control) <RECOMMENDED>
Air density calculation method
Height dependent, temperature from climate station
Station: MALIN HEAD V3 2014
Base temperature: 9,6 °C at 25,0 m
Base pressure: 1010,2 °C at 25,0 m
Air density for Site center in key hub height: 336,8 m + 50,0 m = 1,201 kg/m³ -> 98,1 % of Std

Wake Model Parameters
Wake decay constant 0,075 Open farmland

RIX correction used

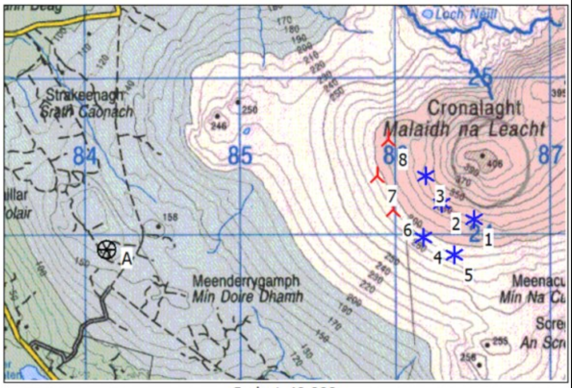
Displacement heights from Digitized test forest

Wake calculation settings

Angle [°]			Wind speed [m/s]		
start	end	step	start	end	step
0,5	360,0	1,0	0,5	30,5	1,0

Wind statistics IE Old met mast,Gillespie - A Scaled 30,00 m.wws

WAsP version WAsP 11 Version 11.04.0002



Scale 1:40.000
New WTG   Existing WTG
Site Data

Key results for height 50,0 m above ground level

Terrain ITM

	X(East)	Y(North)	Name of wind distribution	Type	Wind energy [kWh/m²]	Mean wind speed [m/s]	Equivalent roughness
A	584.140	923.899	MEso lt data calibrated at local mast	WAsP (WAsP 11 Version 11.04.0002)	7.532	9,4	0,4

Calculated Annual Energy for Wind Farm

WTG combination	Result PARK [MWh/y]	Result-10,0% [MWh]	GROSS (no loss)|Free WTGs [MWh/y]	Park efficiency [%]	Specific results¤) Capacity factor [%]	Mean WTG result [MWh/y]	Full load hours [Hours/year]	Mean wind speed|@hub height [m/s]
Wind farm	20.677,6	18.609,8	21.321,9	97,0	42,6	2.326,2	3.737	9,6
New WTGs only	8.817,9	7.936,1	9.032,9	97,6	45,7	2.645,4	4.008	9,6
Existing park WTGs only	11.859,7	10.673,7	12.289,0	96,5	40,6	2.134,7	3.558	9,7
Existing park WTGs without new WTGs	12.172,5	10.955,2	12.289,0	99,1		2.191,0		
Reduction for existing park WTGs caused by new	312,7	281,5						

¤) Based on Result-10,0%

Calculated Annual Energy for each of 3 new WTGs with total 2,0 MW rated power

Links	WTG type Valid	Manufact.	Type-generator	Power, rated [kW]	Rotor diameter [m]	Hub height [m]	Power curve Creator	Name	Annual Energy Result [MWh]	Result-10,0% [MWh]	Park Efficiency [%]	Mean wind speed [m/s]
6 A	No	VESTAS	V47-660	660	47,0	40,0	EMD	Level 0 - calculated - - 07-2001	2.856,8	2.571	97,93	9,32
7 A	No	VESTAS	V47-660	660	47,0	40,0	EMD	Level 0 - calculated - - 07-2001	2.921,9	2.630	97,64	9,51
8 A	No	VESTAS	V47-660	660	47,0	40,0	EMD	Level 0 - calculated - - 07-2001	3.039,2	2.735	97,30	9,90

Calculated Annual Energy for each of 5 existing park WTGs with total 3,0 MW rated power

Links	WTG type Valid	Manufact.	Type-generator	Power, rated [kW]	Rotor diameter [m]	Hub height [m]	Power curve Creator	Name	Annual Energy Calculated prod. without new WTGs [MWh]	After New WTGs [MWh]	Decrease due to new WTGs [MWh %]	Park Efficiency [%]
1 A	No	VESTAS	V39-600	600	39,0	39,0	USER	Rough estimate	2.442,7	2.396,1	46,7 1,9	96,43
2 A	No	VESTAS	V39-600	600	39,0	39,0	USER	Rough estimate	2.494,8	2.417,5	77,4 3,1	95,53
3 A	No	VESTAS	V39-600	600	39,0	39,0	USER	Rough estimate	2.587,5	2.477,1	110,4 4,3	95,33

Figure 172 The PARK main page report results based on wind statistics

The report page shown above is with “all inclusive”, meaning that existing PARK WTG’s as well as new WTG’s are included in the calculation. This includes extra information compared to “just” calculating a new wind farm. The status of “PARK WTG” can be set on the WTG object and means that the existing WTG is represented on the main page. Alternatively, is that the existing WTG’s are treated only as reference turbines and will only appear on the report page dealing with reference turbines.

Calculated Annual Energy for Wind Farm

WTG combination	Result PARK	Result-10,0%	GROSS (no loss)|Free WTGs	Park efficiency	Specific results¤) Capacity factor	Specific results¤) Mean WTG result	Specific results¤) Full load hours	Wind speed free	Wind speed wake reduced
	[MWh/y]	[MWh]	[MWh/y]	[%]	[%]	[MWh/y]	[Hours/year]	[m/s]	[m/s]
Wind farm	20.563,0	18.506,7	21.221,2	96,9	42,4	2.313,3	3.716	9,6	9,4
New WTGs only	8.821,4	7.939,2	9.026,8	97,7	45,7	2.646,4	4.010	9,5	9,4
Existing park WTGs only	11.741,7	10.567,5	12.194,4	96,3	40,2	2.113,5	3.523	9,6	9,4
Existing park WTGs without new WTGs	11.946,6	10.751,9	12.194,4	98,0		2.150,4			
Reduction for existing park WTGs caused by new	204,9	184,4							

¤) Based on Result-10,0%

Calculated Annual Energy for each of 3 new WTGs with total 2,0 MW rated power

	WTG type Valid	Manufact.	Type-generator	Power, rated	Rotor diameter	Hub height	Power curve Creator	Name	Annual Energy Result	Result-10,0%	Park Efficiency	Wind speed free	Wind speed reduced
				[kW]	[m]	[m]			[MWh]	[MWh]	[%]	[m/s]	[m/s]
6	No	VESTAS	V47-660	660	47,0	40,0	EMD	Level 0 - calculated - - 07-2001	2.868,0	2.581	98,14	9,28	9,18
7	No	VESTAS	V47-660	660	47,0	40,0	EMD	Level 0 - calculated - - 07-2001	2.921,3	2.629	97,51	9,45	9,31
8	No	VESTAS	V47-660	660	47,0	40,0	EMD	Level 0 - calculated - - 07-2001	3.032,0	2.729	97,54	9,77	9,63

Figure 173 Part of the PARK main result from time step calculation

As seen above, free and wake reduced wind speeds are also included as a mean across hub heights. The main results from a time step calculation show, by default, the long term expected AEP based on the wind data used and is expected to be long term representative (see further details in chapter 7.1.1: Setup of time step-based calculation).

3.6.12.2 Output from PARK calculations, Result to file

Result to file is the way to get structured output for further processing in e.g., Excel of by scripts.

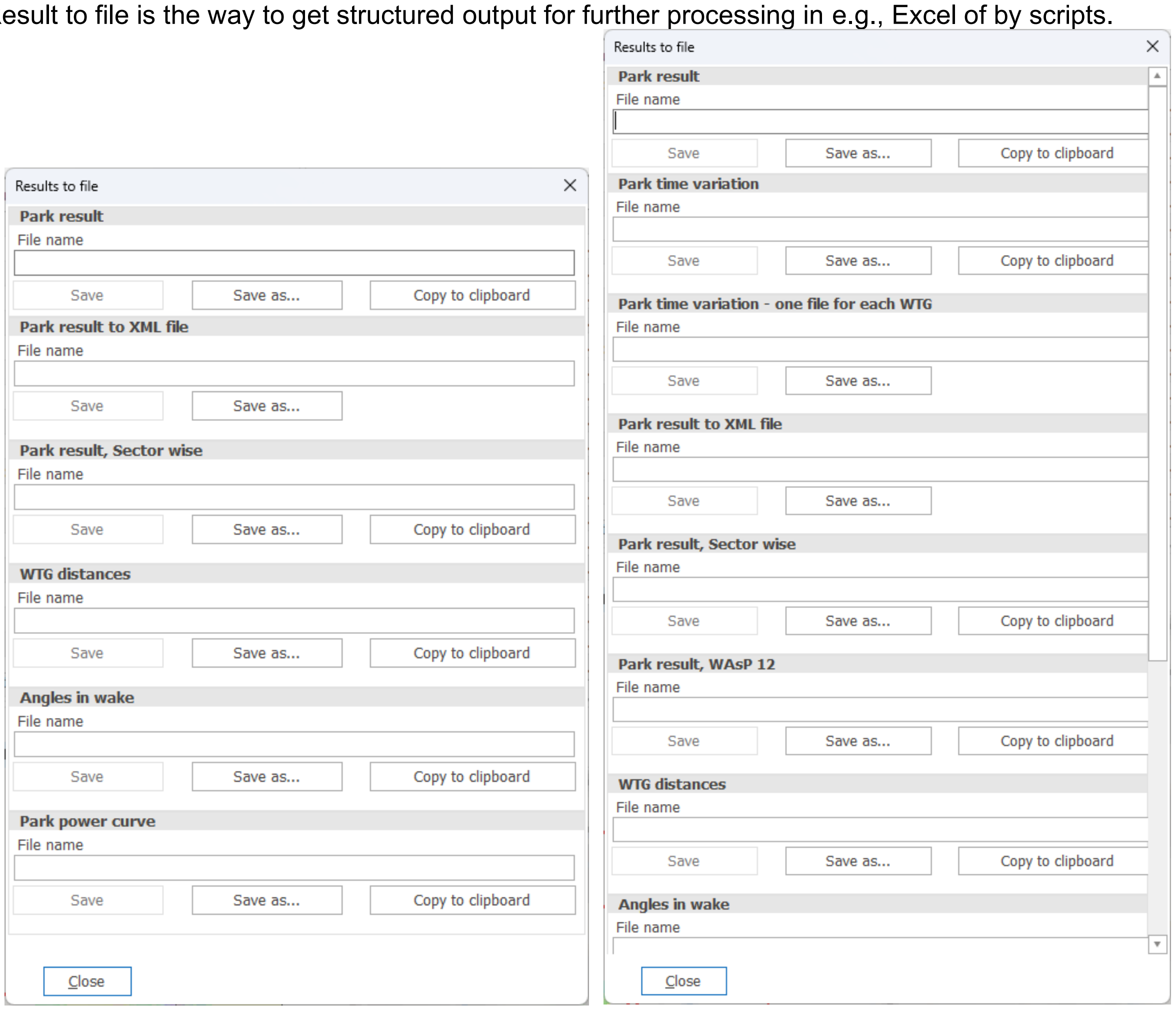


Figure 174 Result to file output options from PARK, left wst based, right time step based.

Above, the left form shows the output options from a wind statistics based calculation while the right form shows the time step-based calculation.

As seen, there are more options for time step calculations, like the "Scaler result dump", where the calculated speed ups can be seen for each calculation point.

The **PARK result** to file (upmost choice) differences by the two different calculation concepts is shown here:

Column:	Wind statistic					Time step					Comment
	Header	Column text	column unit	1. data line		Header	Column text	column unit	1. data line		
1	Name:	Label	Time:	6		Name:	Label	Time:	6		No. of WTG
2	Std. PARK	lt meso data	############	New		Lt Meso calibrated with RIX and DH 5		############	New		New/Existing wtg
3		LIB file		C:\Users\per.EMD\Documents\Wir			Scaler	RIX calibrated	EmdConwx_N55.070_\		Wind data input
4	ITM	X(East)		585.990		ITM	X(East)		585.990		
5		Y(North)		924.153			Y(North)		924.153		
6		Z	[m]	290,8			Z	[m]	290,8		
7	WTG type	Valid		No		WTG type	Valid		No		
8		Manufact.		VESTAS			Manufact.		VESTAS		
9		Type-generator		V47-660			Type-generator		V47-660		
10		Power, rated	[kW]	660			Power, rated	[kW]	660		
11		Rotor diameter	[m]	47			Rotor diameter	[m]	47		
12		Hub height	[m]	40			Hub height	[m]	40		
13		Row data/Description		VESTAS V47 660 47.0 !O! hub: 40,0 n			Row data/Description		VESTAS V47 660 47.0 !O! hub: 40,0 m (TOT		
14	Power cur	Creator		EMD		Power cur	Creator		EMD		
15		Name		Level 0 - calculated - - 07-2001			Name		Level 0 - calculated - - 07-2001		
16		User label					User label				
17	Annual En	Result	[MWh]	2.678,70		Annual En	Result	[MWh]	2.697,90		
18	Park	Efficiency	[%]	97,79		Park	Efficiency	[%]	98,04		
19		Regional Correction Factor		1			Regional Correction Factor				
20		Equivalent roughness		0,5			Equivalent roughness				NA for time step
21		Mean wind speed	[m/s]	8,96			Mean wind speed	[m/s]	8,93		Wake free
22		HP-value	[%]	99			HP-value	[%]	99		
23		Calculated prod. without	[MWh]	0			Calculated prod. without r	[MWh]	0		Only existing WTG
24		Actual wind corrected en	[MWh]	0			Actual wind corrected ene	[MWh]	0		Only existing WTG
25		Goodness Factor	[%]				Goodness Factor	[%]			Only existing WTG
26		Curtailment loss	[%]				Curtailment loss	[%]			
27		A (Sum)	[m/s]	10,12			Wake reduced mean wind	[m/s]			
28		k (Sum)		2,05			Free WS (0)	[m/s]	8,09		
29		A (0)	[m/s]	9,64			Red WS (0)	[m/s]	7,81		
30		k (0)		1,936			f (0)	[%]	5,6		
31		f (0)	[%]	5,5			Free WS (1)	[m/s]	7,1		

Figure 175 Result to file output comparison (shown transposed)

For the first 26 columns, the output is identical. Therefore, comparisons are easy to make. The only difference is in column 3, where, in the wind statistics based calculation, the wind statistics name is shown and, in the SCALER based calculation, the scaler name + the METEO object name is shown.

A new column from windPRO 3.2 is curtailment loss, inserted as column 26! In sector wise output curtailment loss by sector is included as well as a new block (rightmost).

From column 27, the output is different. The wind statistics based calculation shows the Weibull A, k and f by direction sector. The SCALER based calculation shows the Free and Wake reduced wind speeds and the frequency by sector.

Column:	Wind statistic					Time step					Comment
	Header	Column text	column unit	1. data line		Header	Column text	column unit	1. data line		
65		Air density	[kg/m³]	1,208			Air density	[kg/m³]	1,213		comparable
66		Displacement height	[m]	Sector wise			Displacement height	[m]	0		comparable
67	Park	Decrease due to obstacle	[%]	0,38		Park	Decrease due to obstacles	[%]	Sector wise		NA in time step
68	Park	Increase due to hills	[%]	25,86		Park	Increase due to hills	[%]	Sector wise		NA in time step
69		Sensitivity	[dAEP/dWS %]	1,29			Sensitivity	[dAEP/dWS %	0,36		comparable
70		Reference site RIX	[%]	0,5							wst based. In
71		WTG RIX	[%]	1,3			WTG RIX	[%]	0,0106		time step start-
72		Delta RIX (WTG site - Refe	[%]	0,8		Calc. period	Start		26-09-1999		stop dates
73		RIX correction	[MWh]	-26,38			End		03-06-2000		included

Figure 176 Result to file output comparison (shown transposed), rightmost columns

In the rightmost columns in the result to file, different values will appear depending on which corrections are included in the calculations. Changes due to hill/obstacles are shown as percentages for each WTG in a wind statistics based calculation, but NOT in a time step-based calculation. Note that the changes are on AEP without

Wake influence. Sensitivity is "comparable" although calculated differently. In a wind statistics based calculation wind statistics, it is calculated by running an extra calculation with 1% decrease of wind speed (Weibull A-par). In the time step calculation, similar 1% decrease is used, but for each time step and aggregated.

If the displacement height is non-sector wise, the displacement height will be seen.
The sector wise reports will give the details on displacement height, obstacles, hills and Rix .

Wind statistic		Time step	Comment
One column for each direction sector + 26 first columns from previous			
Annual Energy (MWh)		Annual Energy (MWh)	comparable
Park efficiency (%)		Park efficiency (%)	comparable
Decrease due to obstacles (%)		Obstacle speedup	different
Increase due to hills (%)		Orographic speedup	different
RIX correction (MWh)		Delta rix (%)	different
Displacement height (m)		Displacement height (m)	comparable

Figure 177 Result to file; Sector wise; output comparison

For the sector wise output, there will be similar results from the two calculation types, apart from effect from the obstacles, hills and Rix. The wind statistics based calculation shows the percent change, where the time step based calculation shows the flow perturbations (speed-ups = factors on wind speeds from model). Rix correction is shown as MWh change in a wind statistics based calculation, while the time step based calculation shows the Delta Rix value. The reason for the difference is as previously mentioned that a wind statistics based calculation is very fast, and, thereby, auto run more times with/without corrections, allowing the change in AEP to be found directly. The Time step calculation requires more time and, therefore, it is not calculated several times. Instead, the parameters calculated by the SCALER/WAsP is presented. If there is a need for identifying the change in AEP by different corrections more precisely, the only way is to run the calculation more times without the corrections, one by one, and then compare results.

WAsP 11 results	comment
Omnidirectional rix	Rix value for all directions
Emergent mean speed	Weighted sum of Weibull distributions from all sectors
The below appear for each direction sector and is relative to "non influenced" terrain	
Roughness speed (0)	Speedup due to roughness, relative to reference roughness
Orographic speed (0)	Speedup due to orography
Obstacle speed (0)	Speedup due to obstacles (always <1)
MesoscaleRoughness (0)	The reference roughness
Turn (0)	Calculated turn in degrees
Rix (0)	Calculated Rix for the sector

Figure 178 Result to file; Park results, WAsP 11

There is an option to obtain the native WAsP results. These are shown and commented on above. The roughness speedups are relative to a reference roughness set by WAsP, seen in the output as the Mesoscale roughness (as roughness lengths).

Time series output

The "Park time variation" output results for each WTG (or selected) for each time step – or aggregated time steps - depending on setup:

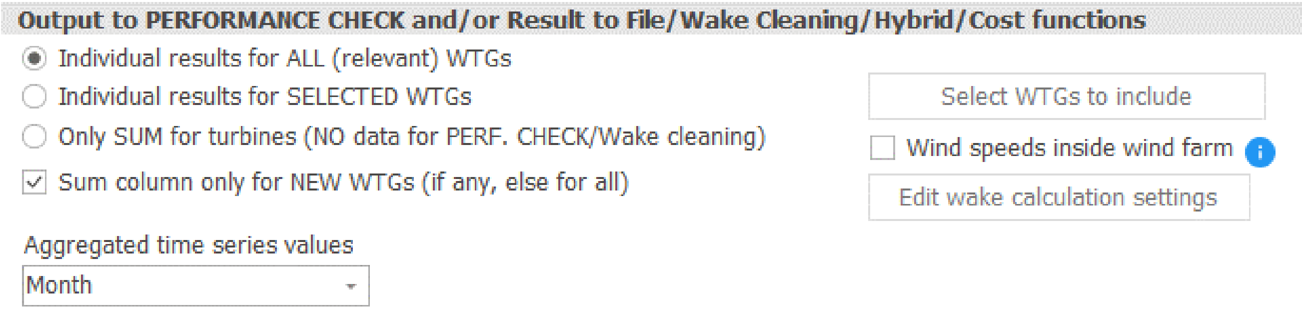


Figure 179 Setup can decide which WTGs and time resolution for Result to file output.

In the time varying Result to file, the following information can be found:

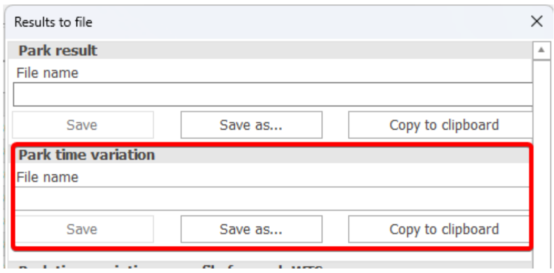
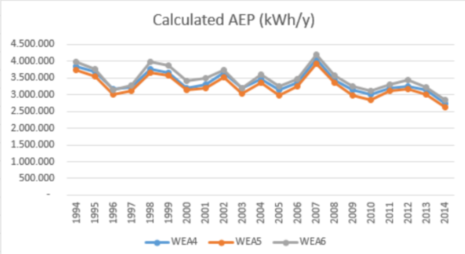


Figure 180 Result to file output from PARK based on time series

The results can be copied to the clipboard and pasted into Excel.

Table 11 Output from PARK based on time series to spreadsheet

				LONG +forest NE\	Scaler:	Calib2+foı	Meteo dat	EmdConwx_N50.000_E009.860 (94)																
				22-03-2015 13:52	Total		For reference WTG: [1] VESTAS V90 2000 90.0 !O! hub: 105,0 m (TOT: 150,0 m) (5)-WEA_4													1	1	1	1	1
				Time stamp	Power	Time	Free wind	Reduced \	Wind dire	Temper	Pressur	Air densit	WDC '	WDC	Turl	She	Veer			Power	Free wind	Reduced \	Wind dire	Temperat
	WEA4	WEA5	WEA6	Date-time	[kW]	[h]	[m/s]	[m/s]	[°]	[°C]	[hPa]	[kg/m3]	[]	[]	[]	[]	[°]	[]	[]	[kW]	[m/s]	[m/s]	[°]	[°C]
1994	3.845.201	3.726.955	3.993.228	01-01-1994	1320,4	8759	5,6	5,5	236,3	9,7	975	1,202		0,075						439	5,6	5,5	236,3	9,7
1995	3.688.836	3.543.420	3.775.560	01-01-1995	1256,6	8760	5,5	5,4	260,6	8,8	975	1,206		0,075						421,1	5,5	5,4	260,6	8,8
1996	3.181.565	3.008.520	3.151.699	01-01-1996	1063,5	8784	5,2	5,1	43,9	7,2	975	1,212		0,075						362,2	5,2	5,1	43,9	7,2
1997	3.211.416	3.118.560	3.279.744	01-01-1997	1097	8760	5,1	5	245,8	8,8	977	1,208		0,075						366,6	5,1	5	245,8	8,8
1998	3.762.420	3.660.804	3.972.660	01-01-1998	1300,9	8760	5,6	5,5	248,2	8,7	976	1,207		0,075						429,5	5,6	5,5	248,2	8,7
1999	3.667.812	3.576.708	3.873.672	01-01-1999	1269,2	8760	5,6	5,4	241,3	9,3	975	1,203		0,075						418,7	5,6	5,4	241,3	9,3
2000	3.206.160	3.143.794	3.418.733	01-01-2000	1112															365	5,2	5,1	236,6	9,7
2001	3.302.520	3.204.408	3.489.108	01-01-2001	1141,1															377	5,4	5,2	251	8,9
2002	3.662.556	3.519.768	3.732.636	01-01-2002	1246,1															418,1	5,4	5,3	239	9,3
2003	3.188.640	3.044.976	3.198.276	01-01-2003	1076,7															364	5,2	5,1	220,5	9,5
2004	3.478.464	3.354.610	3.612.859	01-01-2004	1189,2															396	5,4	5,3	258,2	8,9
2005	3.134.328	2.968.764	3.259.596	01-01-2005	1068,8															357,8	5,2	5,2	255	9,1
2006	3.348.948	3.253.464	3.469.836	01-01-2006	1149,8															382,3	5,4	5,2	225,8	9,7
2007	4.068.144	3.916.596	4.202.172	01-01-2007	1391,2															464,4	5,7	5,6	256,6	9,9
2008	3.445.963	3.355.488	3.578.602	01-01-2008	1181,8															392,3	5,4	5,3	238	9,5
2009	3.136.080	2.972.268	3.248.208	01-01-2009	1068,1															358	5,3	5,2	252,2	9,4
2010	3.010.812	2.850.504	3.119.436	01-01-2010	1025,3															343,7	5,1	5	283,6	7,8
2011	3.189.516	3.115.056	3.317.412	01-01-2011	1098,4															364,1	5,2	5,1	213,2	9,9
2012	3.252.715	3.156.970	3.444.206	01-01-2012	1121,8															370,3	5,3	5,2	241,4	9,3
2013	3.144.840	3.000.300	3.225.432	01-01-2013	1069,7															359	5,2	5,1	262,9	8,6
2014	2.739.990	2.628.118	2.850.988	01-01-2014	940,4	8740	4,9	4,8	220,3	10,6	974	1,197		0,075						313,5	4,9	4,8	220,3	10,6



Above is a part of the result, where results are aggregated to annual values, are copied to Excel. To the left is the inserted calculations, where “Time” column is multiplied with “Power” column to get the production. In this way the annual variations in expected production can be visualized and annual production indexes calculated. More detailed description of the result columns below.

Table 12 Output from PARK based on time series to spreadsheet – column documentation

Header row 1	Header row 2	Header row 3	Header row 4	1. data line	Explanation
LocalWind-PARK2 Wa	**18-02-2020 10:51**	Time stamp	Date-time	**19-01-2018 14:20**	
Scaler:	Total	Power	[kW]	**1044,8**	Sum of power for the wind farm in time step
Def.MeasureScaler		Time	[h]	**0,1667**	Hours in the time stamp, multiply with power to get production
Meteo data:	**For reference WTG: [**	Free wind speed	[m/s]	**4,4**	
WT1&4 Merge-period calibrated - dir -5		Reduced wind speed	[m/s]	**4,4**	Note: The values in first block are for the reference WTG, default the first in calculation list. This can be changed in PARK setup. The reference WTC control the inflow direction in PARK calculation and the used TI if TI used for Wake calculation. The shown signals are explained in the block below for WTG_1 NOTE1: Wake added TI is NOT included in any TI signal at present. NOTE2: The number of columns are dynamic in case Curtailment is used in calculation. FIRST 19 columns for each WTG although fixed, no matter calculation settings.
		Wind direction	[°]	**162,5**	
Bolded are variables		Temperature	[°C]	**1**	
		Pressure	[hPa]	**987**	
		Air density	[kg/m3]	**1,254**	
		WDC Turbulence	[]	**0,071**	
		WDC	[]	**0,057**	
		Turbulence	[]	**0,071**	
		Shear	[]	**-0,6**	
		Veer	[°]	**0,1**	
		Curtailment index	[]	**0**	
		Ref power	[kW]	**296,1**	
		All corrections	[-]	**1,44**	
		Air density correction	[-]	**1,02**	
		Turbulence correction	[-]	**0,97**	
		Shear correction	[-]	**1,45**	
		Veer correction	[-]	**1**	
		Temperature	[Deg C]		
		Inflow angle	[Degrees]		
		< Dynamic curtailment signals>			Below for WTG 1, similar to find for each WTG
	1	Power	[kW]	**296,1**	Average power in time step for WTG 1
	1	Free wind speed	[m/s]	**4,4**	Free wind speed (before wake reduction)
	1	Reduced wind speed	[m/s]	**4,4**	Wake reduced wind speed
	1	Wind direction	[°]	**162,5**	Below signal has only values if used in time step
	1	Temperature	[°C]	**1**	Used in Air density calculation
	1	Pressure	[hPa]	**987**	Used in Air density calculation
	1	Air density	[kg/m3]	**1,254**	Calculated for hub height
	1	WDC Turbulence	[]	**0,071**	Turbulence value (ambient) used if WDC (TI) used per time step
	1	WDC	[]	**0,057**	Wake Decay Constant (can be different by WTG) ONLY if wake
	1	Turbulence	[]	**0,071**	Turbulence value (ambient) used if power curve correction by TI used
	1	Shear	[]	**-0,6**	Shear as power law exponent (only shown if shear correction used)
	1	Veer	[°]	**0,1**	Degrees difference over the rotor diameter (shown only if used)
	1	Curtailment index	[]	**0**	See report page "Curtailment assumptions" which rule this refer to
	1	Ref power	[kW]	**296,1**	The power if no curtailment is present
	1	All corrections	[-]	**1,44**	All power curve corrections combined, set to 1 if curtailed
	1	Air density correction	[-]	**1,02**	Correction factor on power due to Air density
	1	Turbulence correction	[-]	**0,97**	Correction factor on power due to TI
	1	Shear correction	[-]	**1,45**	Correction factor on power due to Shear
	1	Veer correction	[-]	**1**	Correction factor on power due to Veer
	1	Temperature	[Deg C]		Curtailment signals added IF USED, might be different from the
	1	Inflow angle	[Degrees]		earlier shown signals, while they can be taken from another source

The columns in result to file output are shown above. Here, they are shown transposed with an explanation for each line (column). After the columns with WT-1, it continues with WT-2 etc. (or selected WT's).
The format is fixed for the first 19 columns per WTG, independent from which corrections applied. If curtailment is included, there can be added more columns per WTG, depending on which curtailment signals used.

NOTE: Signals can be taken from Scaler or METEO objects.
If from Scaler, data can be model signals (from e.g., FlowRes or WAsP-CFD result files) or Meteo signals scaled by the models, depending on settings in Scaler.
If from METEO objects, signals are scaled from Meteo object position and height to WTG position and height, where models for this scaling are available (apart from wind speed/direction, temperature, pressure and turbulence always will be scaled based on simple models).

3.6.13 PARK with Third Party wake model (WakeBlaster)

WakeBlaster was the first external wake model windPRO offer aces to, but probably more will come. The use is limited to time series calculations. Before ver. 3.6 based on precalculated scenarios, from 3.6 also time step by time step calculation based on like different TI or by time step. This is especially relevant for validation calculations, where measured data per time step is available. Then it can be validated how well the wake loss by varying TI is reproduced by the model.

3.6.13.1 About WakeBlaster in windPRO

WakeBlaster is a fast 3D wake model, developed by ProPlanEn[3]. It uses a custom solver of the 3D Reynolds-Averaged Navier Stokes Equations.[4]

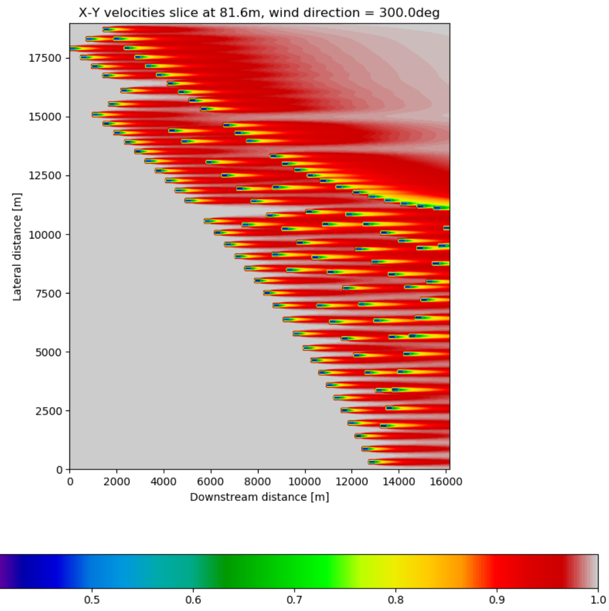


Figure 181 Example of a WakeBlaster CFD simulation.

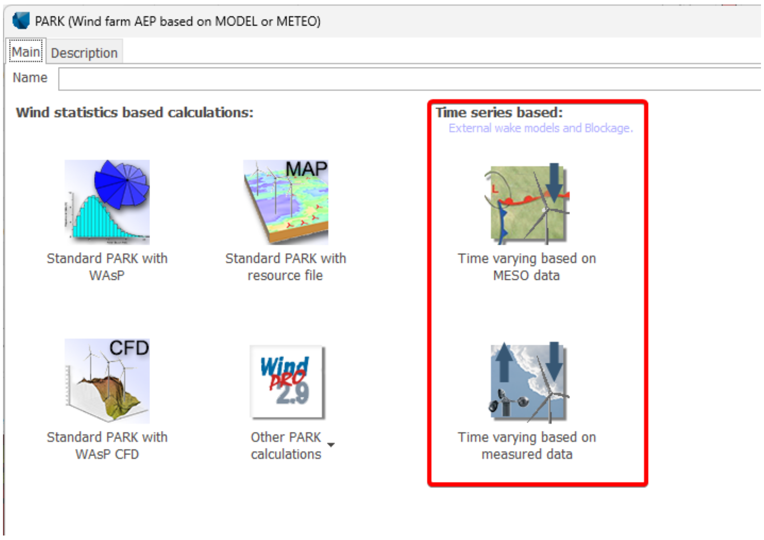
A flow case for Anholt offshore wind farm. Colour-coded as wind speed deficit, relative to free upstream wind speed.

WakeBlaster is implementing a RANS solver that models a complete wind farm, not single turbines. Resolving 3D effects, like wake expansion and wake superposition, results in the replacement of empirical approximations and the reduction of uncertainties. For more information, visit https://proplanen.info/wakeblaster.
WakeBlaster runs on a remote server and requires an API key (see the paragraph below, regarding purchasing and costs).
WakeBlaster users benefit from the capability to run WakeBlaster from windPRO, gaining access to windPRO's advanced handling of meteorological data (by Scaler) and power curve correction options, as well as its reporting features. This makes it easy to compare with other models, as all output is similarly formatted.
WindPRO users benefit from an almost seamless integration of a new state of the art wake model into their existing workflow. It is also possible to use WakeBlaster calculations in, e.g., a performance check module for validation against SCADA data.

3.6.13.2 Setting up the request calculation in windPRO

The first step is to define the layout to be calculated, and to process this in order to generate the necessary files for the WakeBlaster calculation. This is done within the PARK module.
Start PARK module

[3] Wolfgang Schlez, "Virtual Wind Farm Simulation – A Closer Look at the WakeBlaster Project", WindTECH International, Volume 13, No 6, 2017 (https://proplanen.info/wakeblaster).
[4] Philip Bradstock and Wolfgang Schlez, "Theory and Verification of a new 3D RANS model", Wind Energ. Sci. Discuss., https://doi.org/10.5194/wes-2020-33, in review, 2020.



Only the time series-based variants support WakeBlaster calculations in this version.[5]

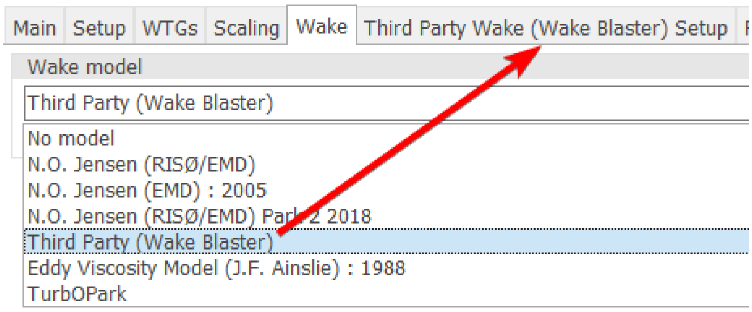


Figure 182 Selection of WakeBlaster model.

At “Setup”, the output specifications can be decided for later use. E.g., by default, result output to file as time series will be aggregated monthly. This can be changed to aggregation level “None”, to get full output resolution for, e.g., use within a performance check module with 10-min resolution SCADA data. At the “Wake” tab, select “WakeBlaster” and a new tab will appear.
Choose WTGs “as usual”.
Note: when running a WakeBlaster calculation on a remote server, the returned results are “locked” to the chosen layout and turbine choice. Any changes in WTGs will require a new WakeBlaster calculation on a remote server. If you later want to calculate with the WakeBlaster result file and SAME layout/turbine type, but different wind data, this is possible if you clone the first calculation, then change the wind data selection in the “Scaling” tab, see below.

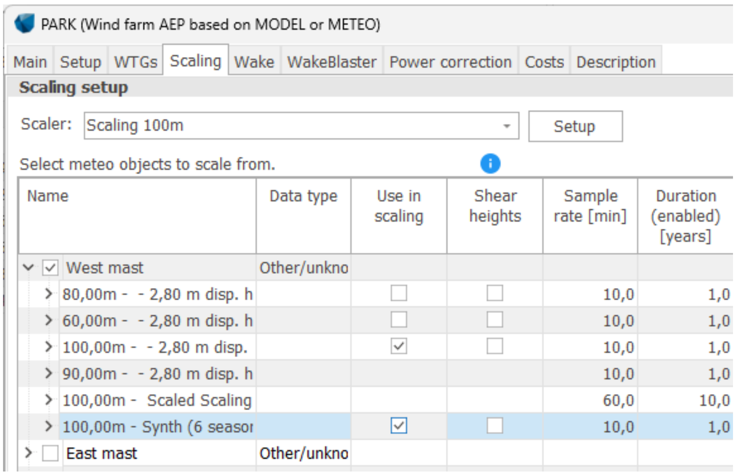


Figure 183 Choosing wind data.

[5] Behind the scenes, the WakeBlaster model is currently operated in a statistical mode, but we will endeavour to change this in a forthcoming release cycle.

Chose the “Scaling” settings, as usual. At least one Meteo dataset must be selected, but more can be selected to reflect how the wind varies over the site. Later, a WakeBlaster calculation based on results from the remote sever calculation can be run by different Meteo selections, without running a new WakeBlaster calculation on the remote server. **This is done by cloning your first WakeBlaster calculation, then editing it in the “Scaling” tab settings.** You will not be able to modify your WTG selections in the cloned calculation, because the WakeBlaster run is for the specific wind farm.

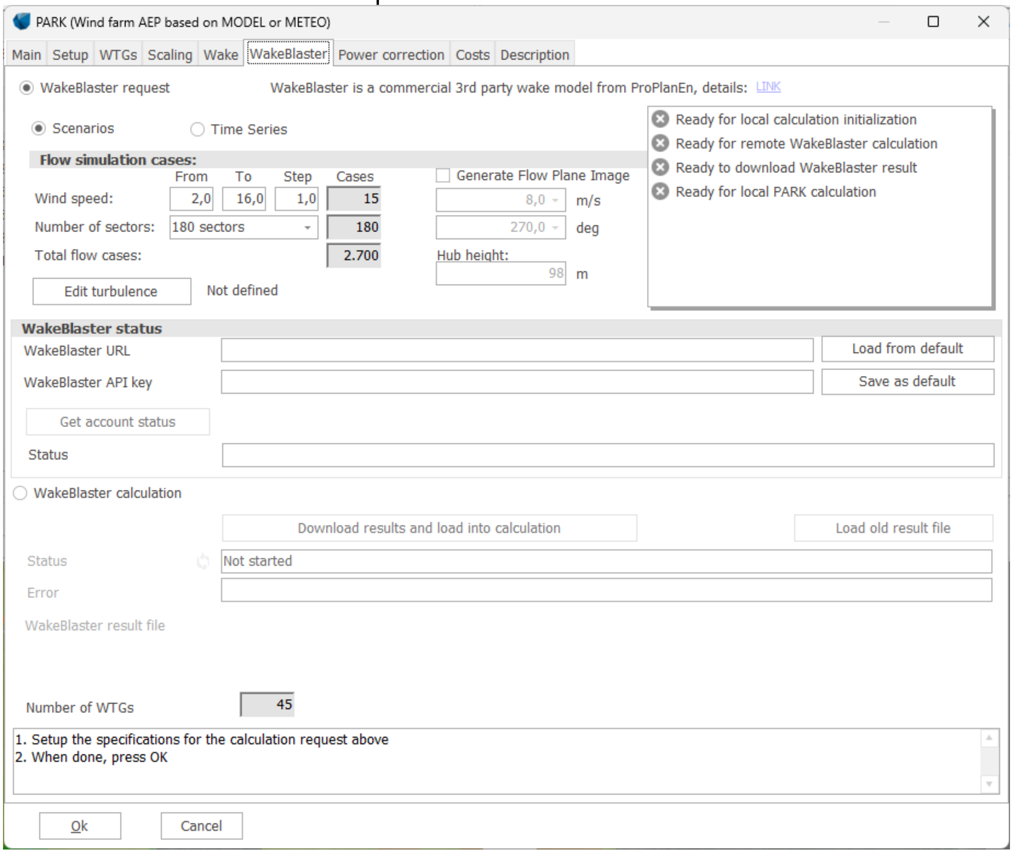


Figure 184 Preparing WakeBlaster calculation.

Choose between scenarios and time step calculation. The time step calculation has the advantage that individual TI by time step can be used and thereby a more accurate calculation is performed. But for long time series it will be an expensive calculation, and thereby mainly recommended for validation calculations, where the focus is to test how well the model handles low versus high TI situations. Typical number of flow cases by scenario calculation is 2700, which correspond to round 4 months of 1-hour values or less than 1 month of 10-min. values.

<u>Preparation for Scenarios:</u>
Set up the flow cases. The minimum span is 2-16 m/s, which will cover all wake loss situations, although this can be expanded in special cases. The recommended step is 1 m/s.
The number of sectors determines how precise a calculation will be. A 2-degree step is high accuracy and means 180 sectors. Less than 72 sectors (5 degrees) cannot be chosen, because it does not make sense to use WakeBlaster for lower wake calculation direction resolution.
You can “Generate Flow Plane image” (costing 100 flow cases) for a specific wind speed, direction, and hub height. This will provide a plot in the report and a picture for viewing/copying - see later example.

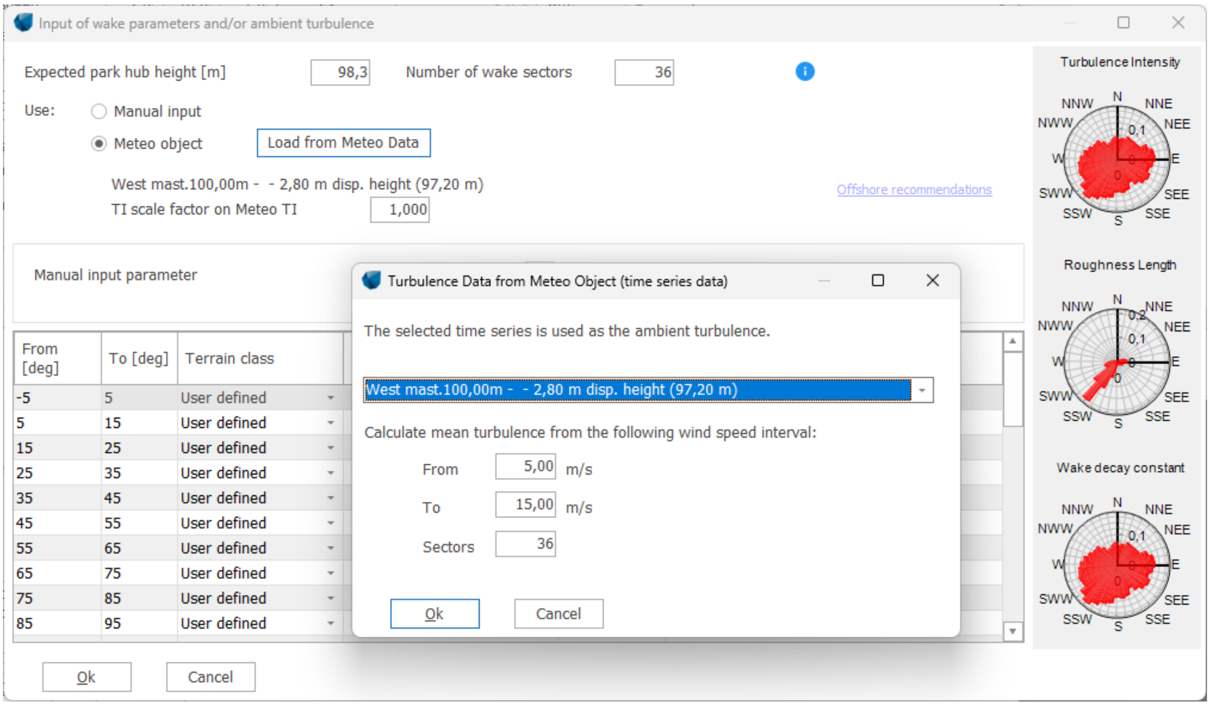


Figure 185 TI setup for WakeBlaster.

Finally, the turbulence must be entered. This can be loaded from a Meteo object, if quality TI data are available. However, please be aware that (like the mesoscale model) TI might not be sufficiently accurate. (The EMD-WRF Europe+ dataset is known to have TI values that are too low, which leads to calculation of wake losses that are too high – but, these TI values can be recalibrated to compensate for this effect). Press “OK” to revert to the “WakeBlaster” tab.

Preparation for Time step calculation:

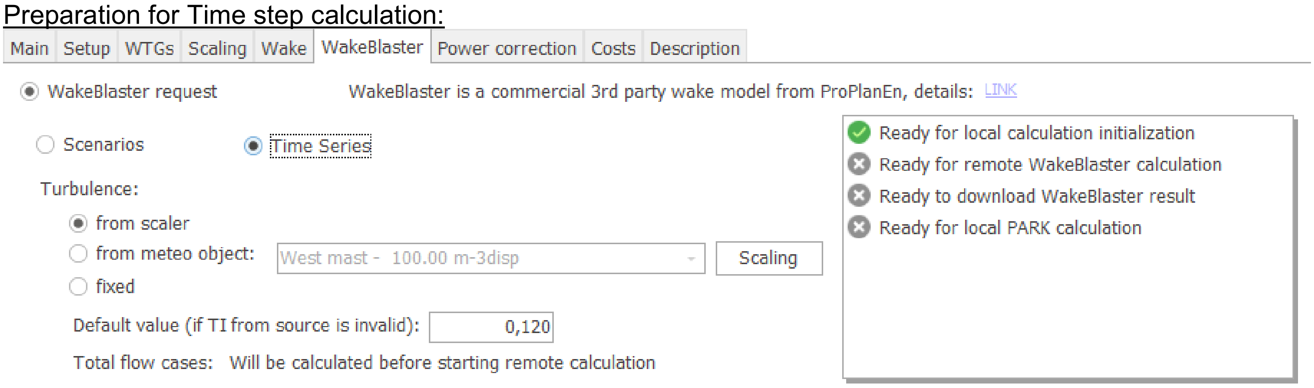


Figure 186 Input for WakeBlaster time step calculation.

The time series containing wind speed and direction data is selected in the Scaling tab. If these data include turbulence, the choice of Turbulence should be “from scaler”. It is also possible to select turbulence data from a different meteo object. The TI data can be scaled. For instance, if the TI data is biased. Finally, a fixed TI can be experimentally chosen, but this voids the whole point of using the time step calculation is to have the TI by time step.

After preparation

Press the “OK” button, and the WakeBlaster input preparation calculation will run. This can take some minutes, depending on the size of the wind farm and the number of meteo positions.

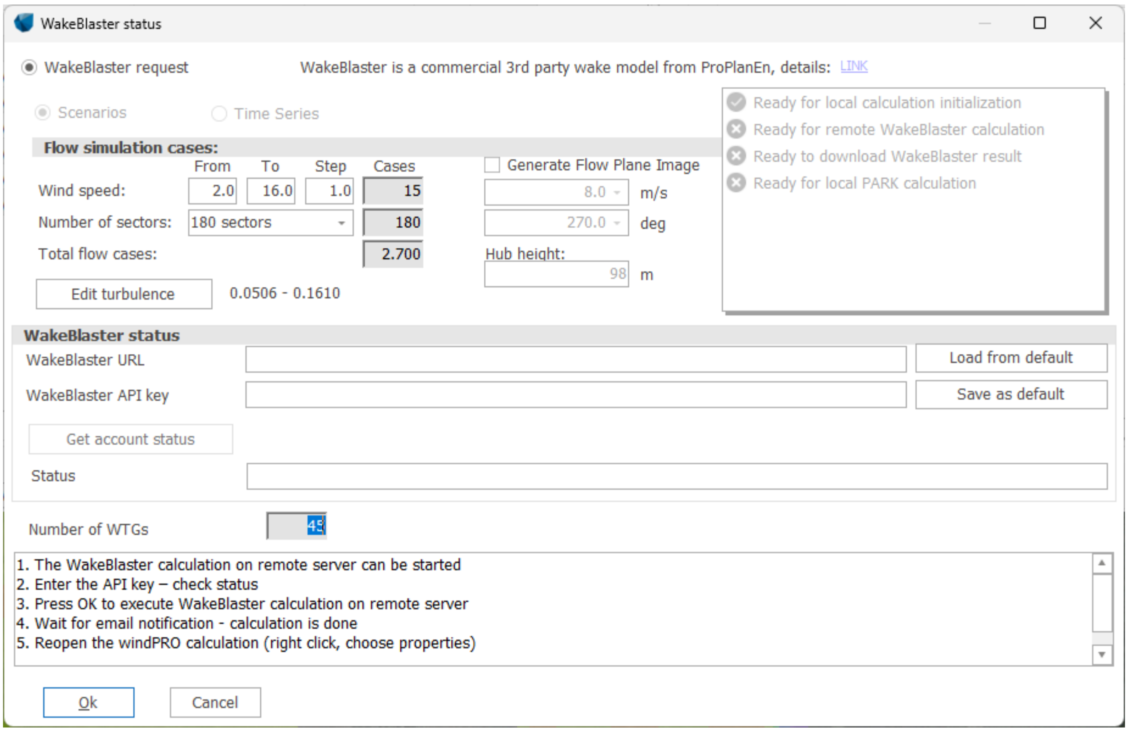


Figure 187 WakeBlaster status appear when ready to start on remote server.
When the request files have been calculated, the “WakeBlaster status” window appears.

3.6.13.3 Starting the WakeBlaster calculation on a remote server

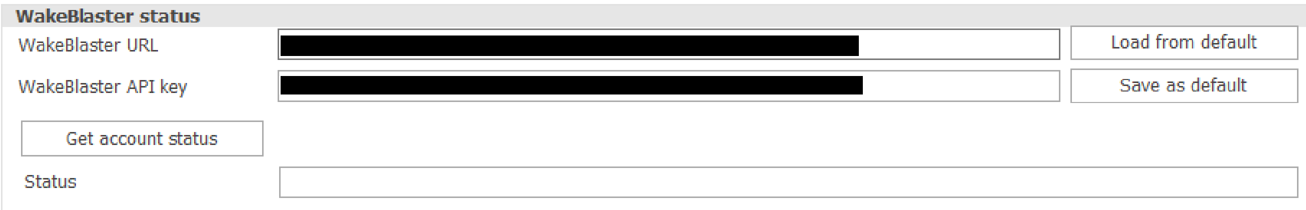
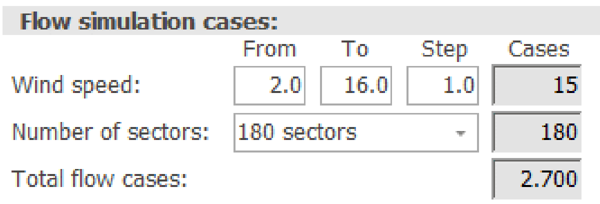


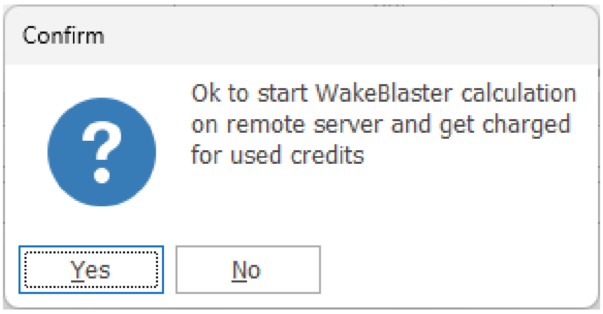
Figure 188 Enter URL and API.

Enter the URL and API key which you received by email when you purchased the WakeBlaster packages[6]. Your monthly inclusive credits will show up in the status when you select: “Get account status”. Additional credit packages will be assigned directly to your account and will show up here as soon as they are activated.
If enough are credits available (see below):



Here, 2,700 flow cases are needed, so it is ok to continue.
Press ”OK”.

[6] Please keep your key safe; it is valid for use within your company, and provides access to your data and flow cases. Flow case credits are non-transferable, and no refund is available for flow case credits that are used without authorisation.



Accept, and the initiated job will be sent to the remote server.

3.6.13.4 Waiting for processing at a remote server

Now wait to receive a confirmation email, stating that the calculation is done:

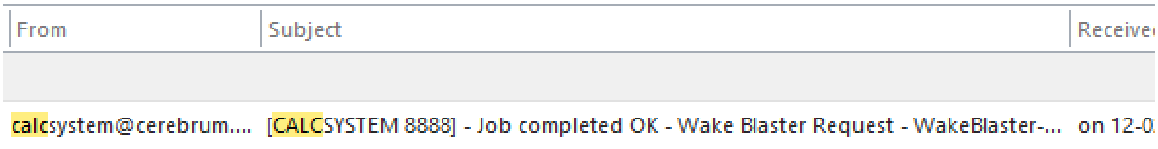


Figure 189 Email notification when result file is ready.

The email will look like this in your mailbox. This process will take from around 10 minutes to more hours depending on the (cost-optimized) server load.[7]

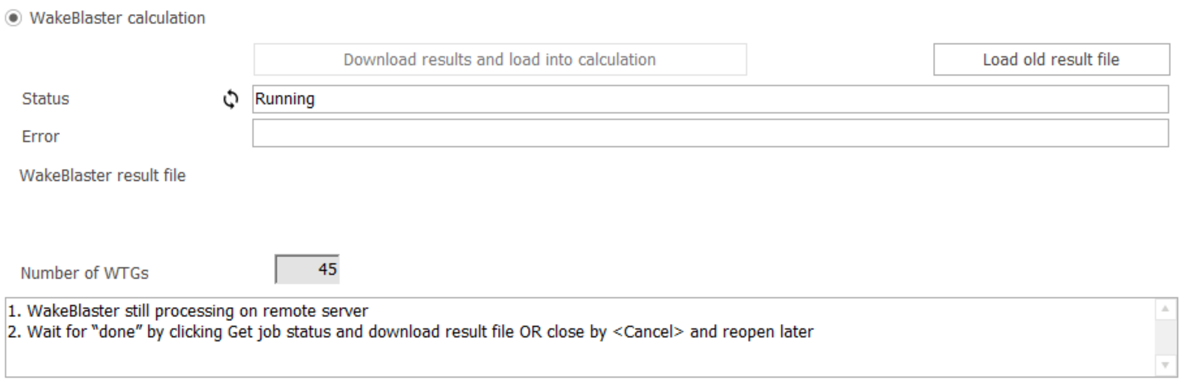


Figure 190 Check calculation status on remote server.

If a calculation takes longer than usual to return a result, you can check the job status. Open the calculation (right click on "calculation" and choose "properties") and select "Get job status". You will receive an update, and potential error messages are displayed. If you cannot identify the cause of an error yourself, please send a copy of the error message to user support. **Select "Cancel" to leave the window –** if you select "OK", a new calculation request will be activated for no reason.
The "Load old result file" gives the opportunity to read a previous downloaded WakeBlaster result file saved locally. To use this for a new WakeBlaster result based file, possible with other wind data, it is important to notice that the WTG configuration must be exact the same as when the WakeBlaster calculation were requested. There will be a check when starting a wake blaster calculation that as well WTG Ct curves as coordinates etc. match. If not, the calculation cannot be performed. The user will be informed about the missing matches.

[7] WakeBlaster is designed, and the available resources are configured, so that the calculations are fast enough to use WakeBlaster in your daily work. If you require a reduced latency and/or faster response-time for a specific application case, please contact us with the details, and we can provide a quote.

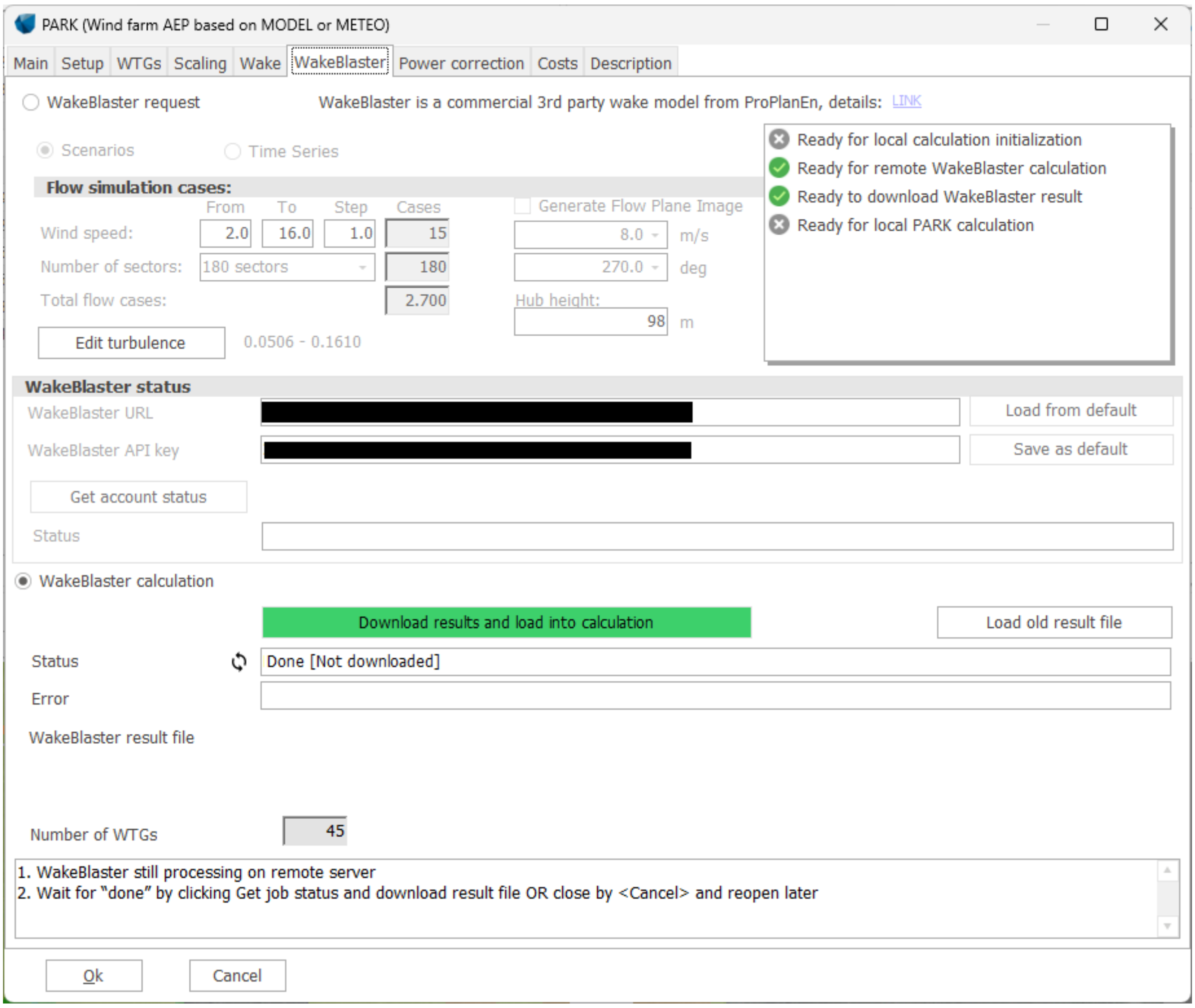


Figure 191 Ready to download WakeBlaster results.

When the calculation is done (you have received the email), open the calculation and download the result file. You can "Show flow plane", if it is included in the calculation: (*here shown for the Anholt project, not similar to the calculation setup shown in all the previous screen shots)*

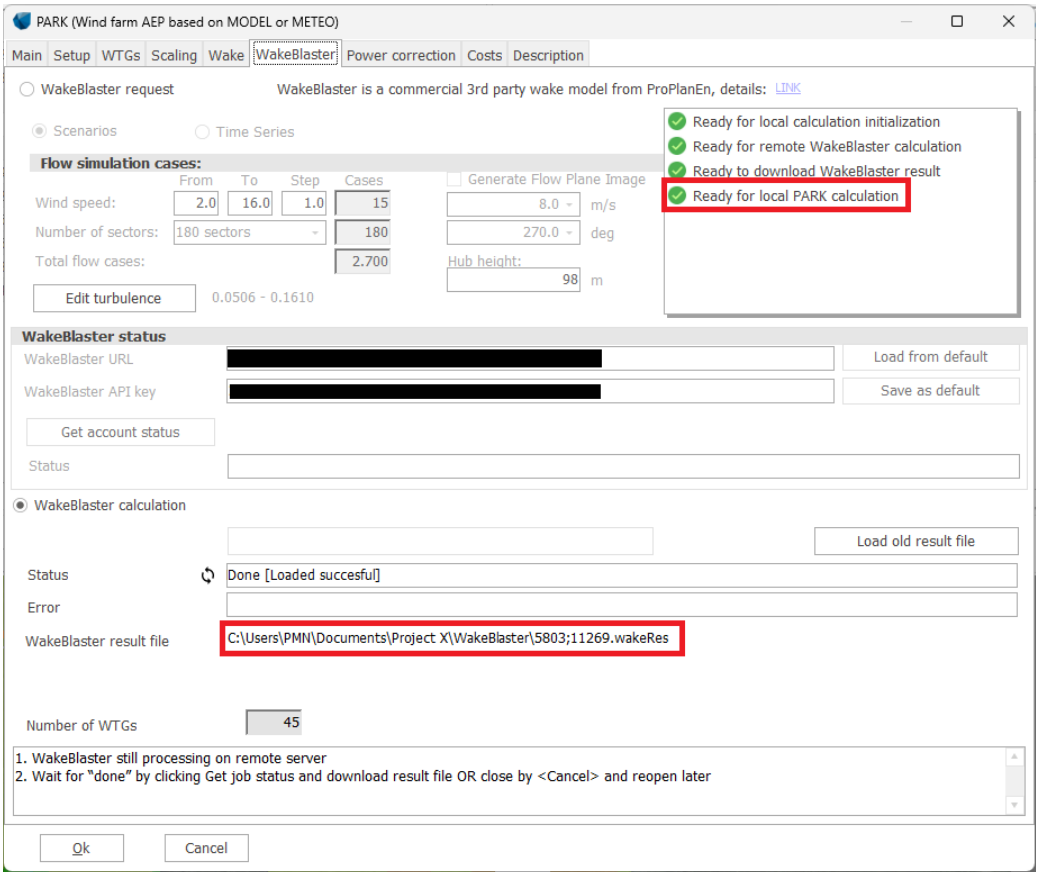
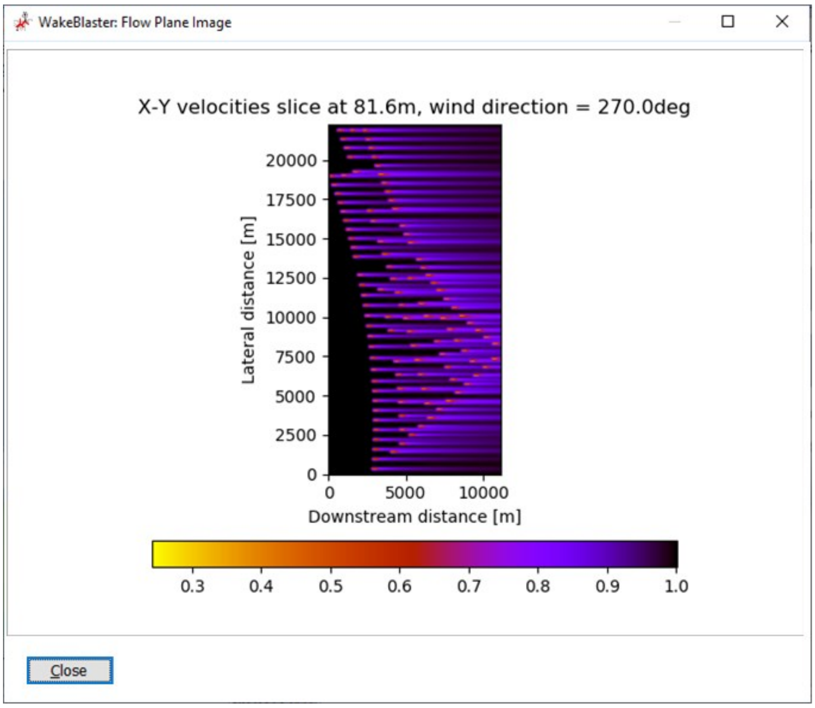


Figure 192 Downloaded WakeBlaster results, ready to calculate.

When downloaded, the highlighted fields changes, and you are ready for performing the WakeBlaster based PARK calculation by pressing OK. If added, you can choose to show Flow plane or Calculation info. Last one should be copied in case there seem to be something wrong with the calculation, and hotline support is needed, then the WakeBlaster team can identify which calculation and thereby hopefully the problem.



3.6.13.5 PARK calculation based on WakeBlaster result file

Now press "OK" and the calculation based on the WakeBlaster result file will run. Note: Meteo data in "Scaling", "Power corrections", and "Setup" (e.g., selection of the aggregation resolution for the time series output), can all be modified before "OK" is selected.

When calculation is done, the reports can be shown/printed and "result to file" data extracted.
A new page option, the "flow plane", will show the above graph in the report, if it is selected at the point of calculation.

3.6.13.6 Evaluation of WakeBlaster results, compared to PARK2

Wake
Wake Model: WakeBlaster, 2.1.3
Reference WTG: 85

Scaler/wind data

Name	EMD Default Measurement Mast Scaler
Terrain scaling	Measured Data Scaling (WAsP Stability / A-Parameter)
Micro terrain flow model	WAsP IBZ from Site Data
Used period	02-01-2013 01:00:00 - 02-07-2015
Meteo object(s)	(1)85 (From PFC), 81,60m - 85
	(2)86 (From PFC), 81,60m - 86
	(3)87 (From PFC), 81,60m - 87
	(4)88 (From PFC), 81,60m - 88
	....
	....
	(108)63 (From PFC), 81,60m - 63
	(109)1 (From PFC), 81,60m - 1
	(110)64 (From PFC), 81,60m - 64
	(111)0 (From PFC), 81,60m - 0
Horizontal interpolation	Take nearest
WAsP version	WAsP 11 Version 11.06.0028

Power correction (All existing WTGs)
Power curve correction according to IEC 61400-12-1 ed. 2

		Min	Max	Avg	Corr. [%]	Neg. corr. [%]	Pos. corr. [%]
Air density							
WTG F10 (53) - 81,60 m	[°C]	-4,8	23,1	9,1			
From air density settings	[hPa]	1002,8	1003,8	1003,3			
Resulting air density	[kg/m³]	1,180	1,302	1,239			
Relative to 15°C at sea level	[%]	96,4	106,3	101,1	0,4	-0,2	0,6
Turbulence							
WTG F10 (53) - 81,60 m	[-]	0,00	0,92	0,07	0,7	-0,7	1,3
Reference turbulence	[-]			0,12			
No shear correction							
No veer correction							

Here, WakeBlaster ver. 2.1.3 is being used and, in this case, free wind for each WTG position. Power curve corrections are available, as for other wake models in windPRO. Here, air density correction adds 0.4% to the calculated AEP and turbulence correction adds 0.7%, compared to using the standard power curve.

Calculated Annual Energy for reference WTGs

Calculated prod. without new WTGs [MWh/y]	GROSS (no loss) Free WTGs [MWh/y]	Wake loss [%]	Specific results Capacity factor [%]	Specific results Mean WTG result [MWh/y]	Full load hours [Hours/year]	Wind speed free [m/s]	wake reduced [m/s]	Actual wind corrected energy [MWh/y]	Goodness Factor [%]
1.868.437,3	1.996.674,1	6,4	53,3	16.832,8	4.676	9,1	8,7	1.793.278,0	96,0

Calculated Annual Energy for each of 111 reference WTGs with total 399,6 MW rated power

The main results are a 6.4% wake loss, calculated for the Anholt offshore wind farm. This is slightly higher than in PARK2, which shows a 6.3% wake loss, with default offshore WDC settings of 0.06 - see similar results, below:

Calculated Annual Energy for reference WTGs

Calculated prod. without new WTGs [MWh/y]	GROSS (no loss) Free WTGs [MWh/y]	Wake loss [%]	Specific results Capacity factor [%]	Specific results Mean WTG result [MWh/y]	Full load hours [Hours/year]	Wind speed free [m/s]	wake reduced [m/s]	Actual wind corrected energy [MWh/y]	Goodness Factor [%]
1.871.544,7	1.996.620,6	6,3	53,4	16.860,8	4.684	9,1	8,8	1.793.278,0	95,8

With EMD's recommended approach for PARK2 (using WDC = 0.8 x TI for offshore), the result is:

Calculated Annual Energy for reference WTGs

Calculated prod. without new WTGs [MWh/y]	GROSS (no loss) Free WTGs [MWh/y]	Wake loss [%]	Specific results Capacity factor [%]	Specific results Mean WTG result [MWh/y]	Full load hours [Hours/year]	Wind speed free [m/s]	wake reduced [m/s]	Actual wind corrected energy [MWh/y]	Goodness Factor [%]
1.853.393,0	1.996.674,1	7,2	52,9	16.697,2	4.638	9,1	8,7	1.793.278,0	96,8

Calculated Annual Energy for each of 111 reference WTGs with total 399,6 MW rated power

Here, there is calculated 7.2% wake loss, somewhat higher than in the two previous examples. The sensitivity to the accuracy of the TI data is high.

The actual production (normalised to 1 year) for the calculation period is 1,763 GWh, which gives the following evaluation of the 3 calculations:

Table 13 WakeBlaster and PARK2 results.

	Measured	PARK2 TI	PARK2 DTU	WakeBlaster
Production [GWh]	1.763	1.853	1.872	1.868
Ratio		0,95	0,94	0,94

The real production at this low-resolution follow up level cannot tell which model performs best. An over-prediction of around 5% can easily be explained by losses and downtime (technical and market regulation), wind data bias, etc.

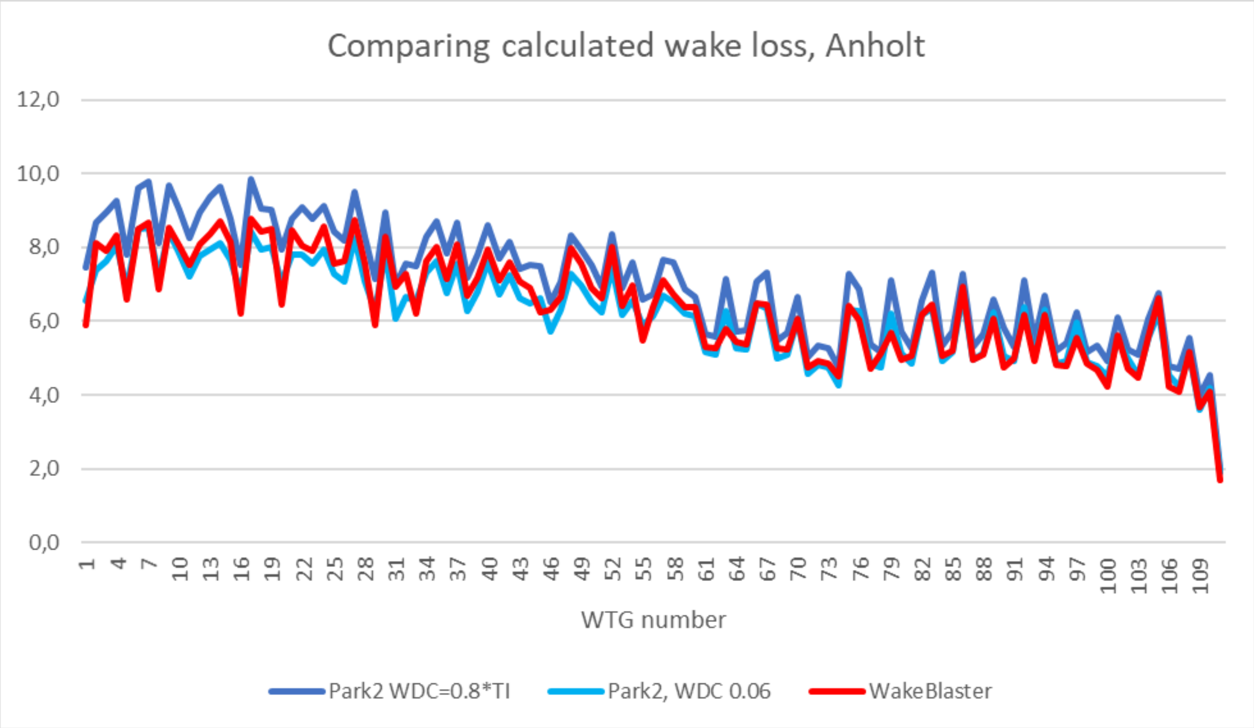


Figure 193 Wake loss by turbine.

A result comparison, by turbine. There is no big difference between the calculated wake losses here, but other detailed tests against measurements show that the WakeBlaster model does make it better than the N.O. Jensen based models in some cases, but not all. In any case, such comparisons are very sensitive to turbine operation issues, and the accuracy of Ct curves, etc. In the OWA (Offshore Wind Accelerator) project, several wake models were compared against operation data for six Danish and UK offshore wind farms. Here, WakeBlaster (and PARK2) also performs well (it is not outperformed by any other wake models). A project result presentation is available. It cannot be concluded that any one wake model is *always* the best but having multiple opinions will always be better than having just one.
Plotting the calculated wake loss based on the time step calculation, with a high directional resolution, illustrates the model differences:

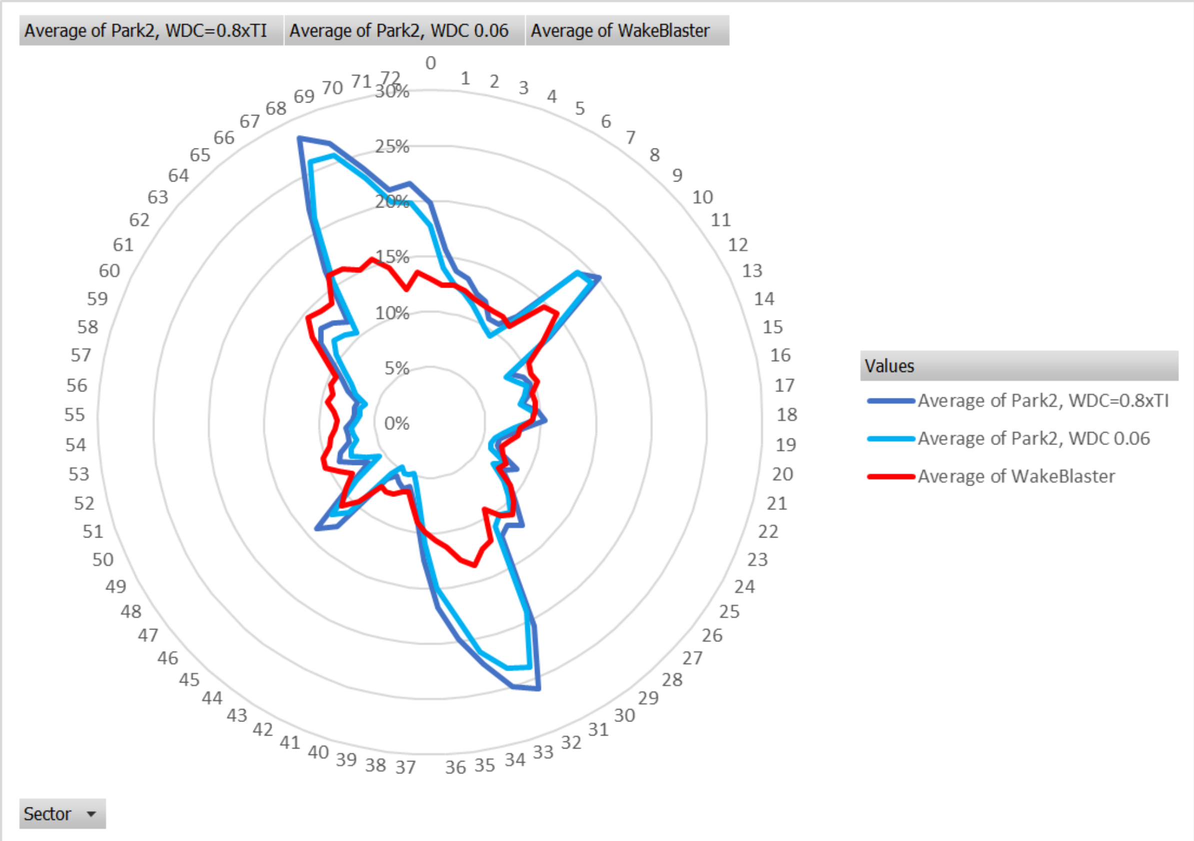


Figure 194 Wake loss by direction, WakeBlaster and PARK2.

Looking at the layout in next figure, when the wind comes along the long rows, PARK2 calculates higher wake losses than WakeBlaster. It is difficult to validate what is most correct while precise direction data are rare. However, from the test for Horns Rev1 (for example), there are indications that PARK2 calculates wake losses that are too high when the wind comes along the rows, compared to when wind comes skew to the rows. All in all, both models end up producing similar overall results.

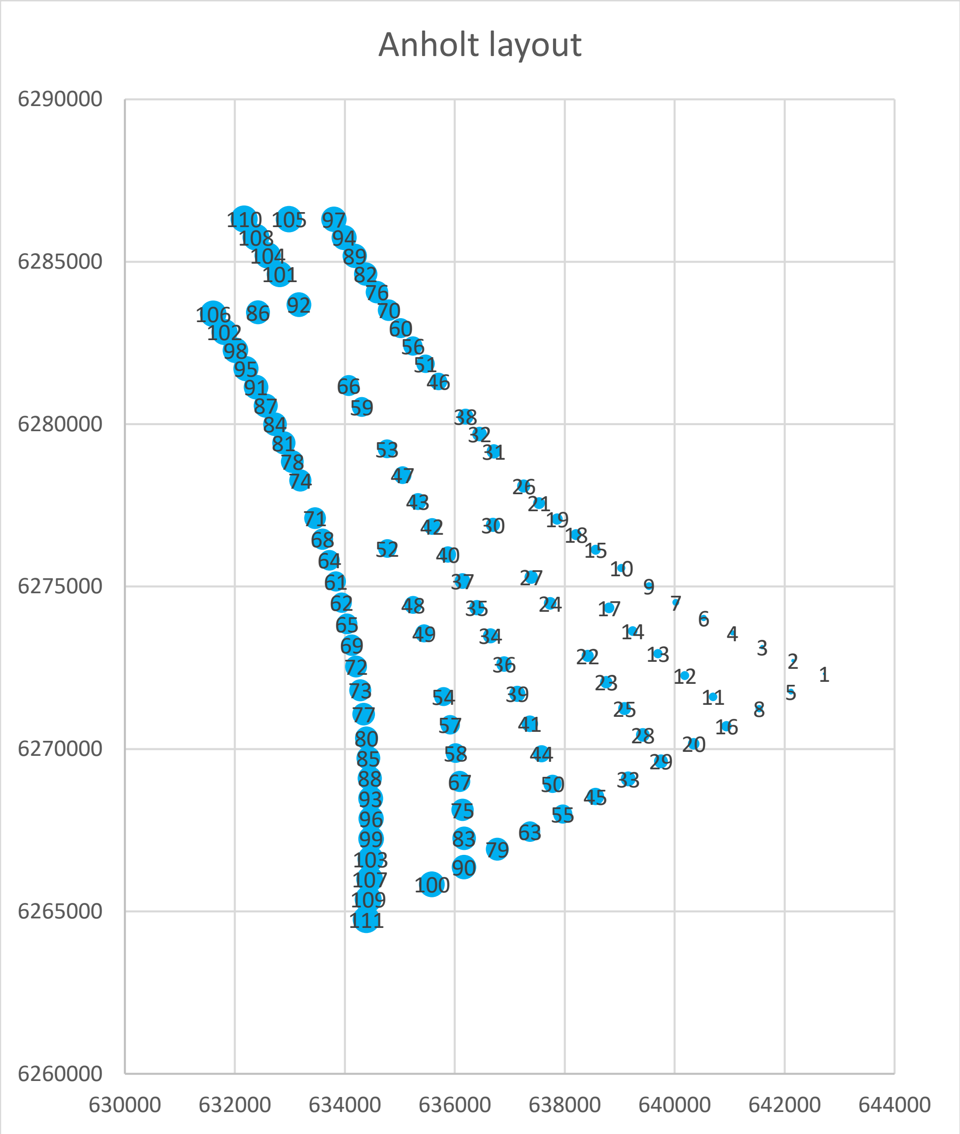


Figure 195 The windfarm layout (Anholt) in the calculation test.

The numbers correspond to those shown in the previous graph.

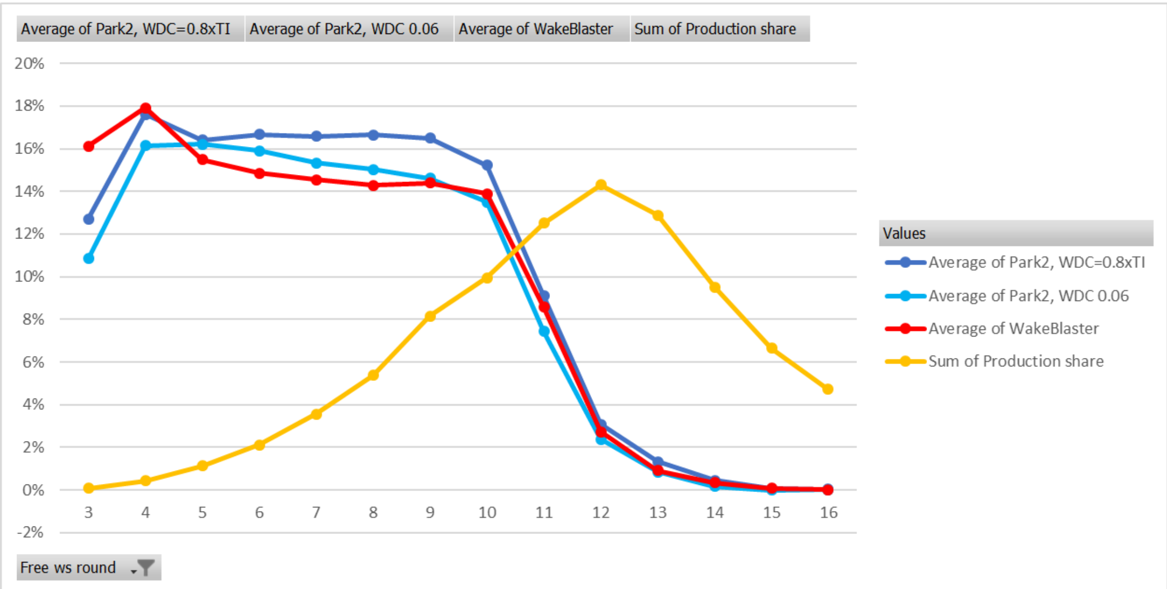


Figure 196 The calculated wake loss by wind speed, WakeBlaster and PARK2.

The calculated wake loss by wind speed. PARK2 calculates more loss from 5 to 10 m/s, whereas WakeBlaster calculates slightly more than PARK2, with DTU default WDC at the higher wind speeds, where there is the most production.

3.6.13.7 Purchasing WakeBlaster credits

Visit https://www.emd-international.com/windpro/cfd/wakeblaster/ for current information on purchasing WakeBlaster credits.

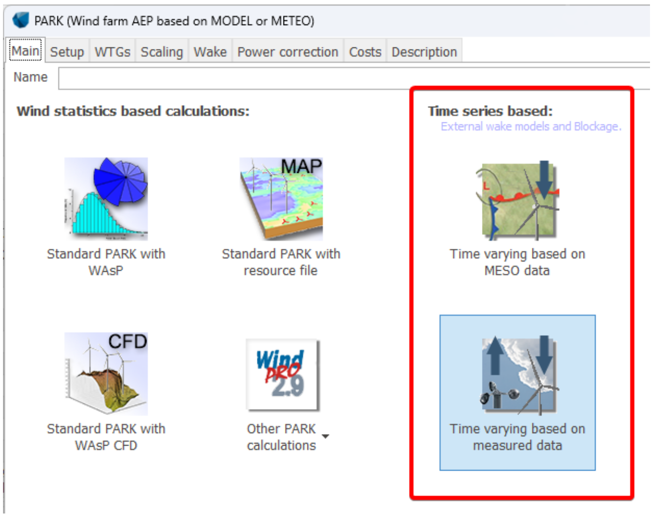
3.6.14 PARK with Third Party wake model (local)

From windPRO 4.1 there is a generalized format to facilitate the use of other *Third Party* wake models in PARK calculations. Like the WakeBlaster implementation, it enables you to run your own wake model outside windPRO.

windPRO will prepare all calculations for you up until the point of applying a wake model. This includes the terrain analysis to calculate the wind speed and direction at each turbine location, thrust curves, and location of turbine and reference locations. This information is written into a wake request file (.wakereq). You or a third-party provider can implement a wake model and run it with this data from windPRO. To finish the calculation in windPRO the result of the wake model needs to be written into a wake result file (.wakeres). You can find the description of the file formats here and examples file here.
The resulting PARK calculation can be used like other PARK calculations in windPRO.

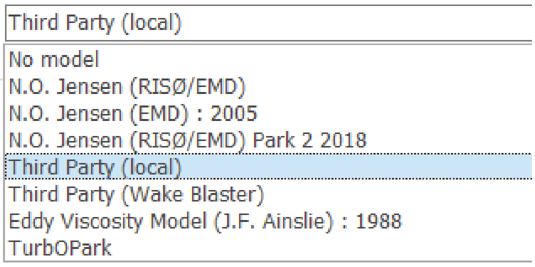
3.6.14.1 Setting up a Third-Party wake calculation

Start a PARK calculation. The *Third Party* wake calculation is only available for time series based calculations.



Like all other time series based PARK calculations you will need to configure the tabs *Setup, WTGs, and Scaling* (see section *3.6.8*).

Under the *Wake* tab you need to select the model *Third Party (local).* This means that the exchange files are generated locally on your computer:



A new tab called *Third Party Wake (local) Setup* will appear where you can set up the calculation for your external wake model. Firstly, there are two radio buttons called *Wake Request* and *Wake Calculation*. This corresponds to two different modes that the calculation is in. In *Wake Request* mode you can change settings in this tab in *Wake Calculation* mode you can load a *wakeres* file.

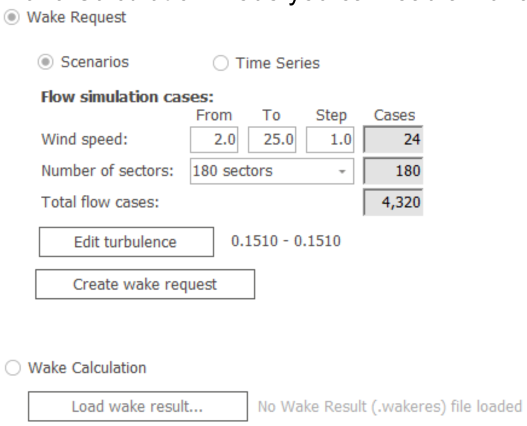
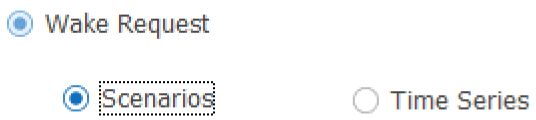


Figure 197 Setup of external wake request

First, you need to decide on the type of wake calculation, whether it's based on scenarios or time series.



For *Scenario*, calculations are performed using wind and direction bins that you can choose. The finer your bins, the more total flow cases will be calculated. windPRO will use the calculated scenarios to interpolate to the data in the time series. Turbulence data is included for a reference location. You can click on edit turbulence to define sector wise turbulence representative for your wind farm.

For *Time Series,* the time series selected in the *Scaling* tab will be used directly. You have multiple ways to setup the output turbulence. You can either use the scaler, data from the meteo object itself (with the possibility to add a simple scaling factor), or a fixed value. Since TI from measurements often does not have the same recovery as wind speed and direction you need to define a default turbulence that will be added when there are no available turbulence data.

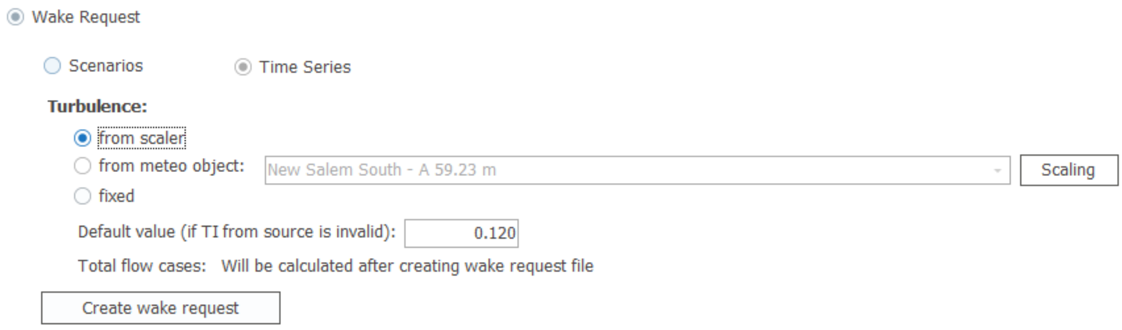


Figure 198 Third Party Wake (local) Setup selections for time series based calculation

Click on *Create wake request*, this will start the terrain analysis to calculate wind speed and direction at all your turbine location and save it in a wake request file (.wakereq). You will be prompted to pick a save location.

It is now up to you to the feed the generated wake request file into your own wake model. This wake model must then return a wake result file (.wakeres) for consumption in windPRO.

3.6.14.2 Using a .wakeres file

To finish the PARK calculation a .wakeres file needs to be loaded into the PARK calculation. To do this you need to select the *Wake Calculation* radio button and point out the .wakeres file.

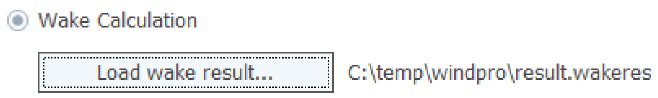


Figure 199 Loading an external wake result

To finish the calculation you click OK as you would for a normal PARK calculation.

The wake calculation will be finalized in windPRO and the usual reports created.

Upon calculation checks are performed to ensure consistency of the wake calculation with the project as it currently is. This ensures that the PARK calculation is correctly reflecting the state of the project at this point, including the position and thrust curve of the turbines, the terrain calculation, and the meteo data used in the calculation.

It is possible to later change settings that do not affect the terrain analysis or thrust curves used, for example the time series aggregation or the air density correction.

3.6.14.3 Implementing an external wake model

windPRO allows you to run a wake model outside windPRO and feed the results back into windPRO. However, you must implement the wake model yourself or get one of your colleagues to do it. Optionally, you can implement wake models from other sources. Examples of freely available models include py_wake from DTU, floris from NREL, and flappy from IWES. Your wake model needs to be able to run with a precalculated terrain analysis where wind speed and wind direction are set per wind turbine. The relevant data need to be read from the .wakereq file and the output needs to be saved in a .wakeres file. Both file formats are zipped files with xml files to contain meta data. The format specifications can be found here: [link]

3.6.15 Project Cost and LCOE calculation

From windPRO 3.6 it is possible to calculate projects costs and Levelized Cost Of Energy (LCOE) for the designed wind farm based on cost functions. The cost functions transform the physical properties of the wind farm to costs using cost formulas and specific costs, typically per MW. The grid and road lengths are automatically calculated based on shortest distance between WTGs within the wind farm.

See detailed description of the cost functions in BASIS manual, chapter 2.18.

NOTE: Only **New WTGs** can be used in the cost calculator.

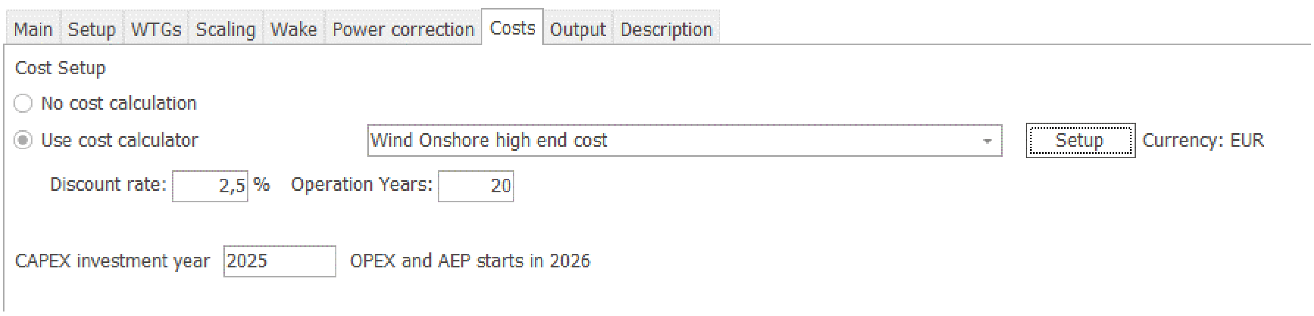
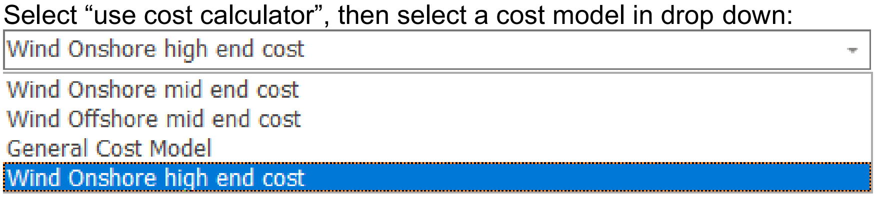


Figure 200 Cost calculator in PARK.

Select "use cost calculator", then select a cost model in drop down:



Then the "Setup" button gives the option to define other cost models.

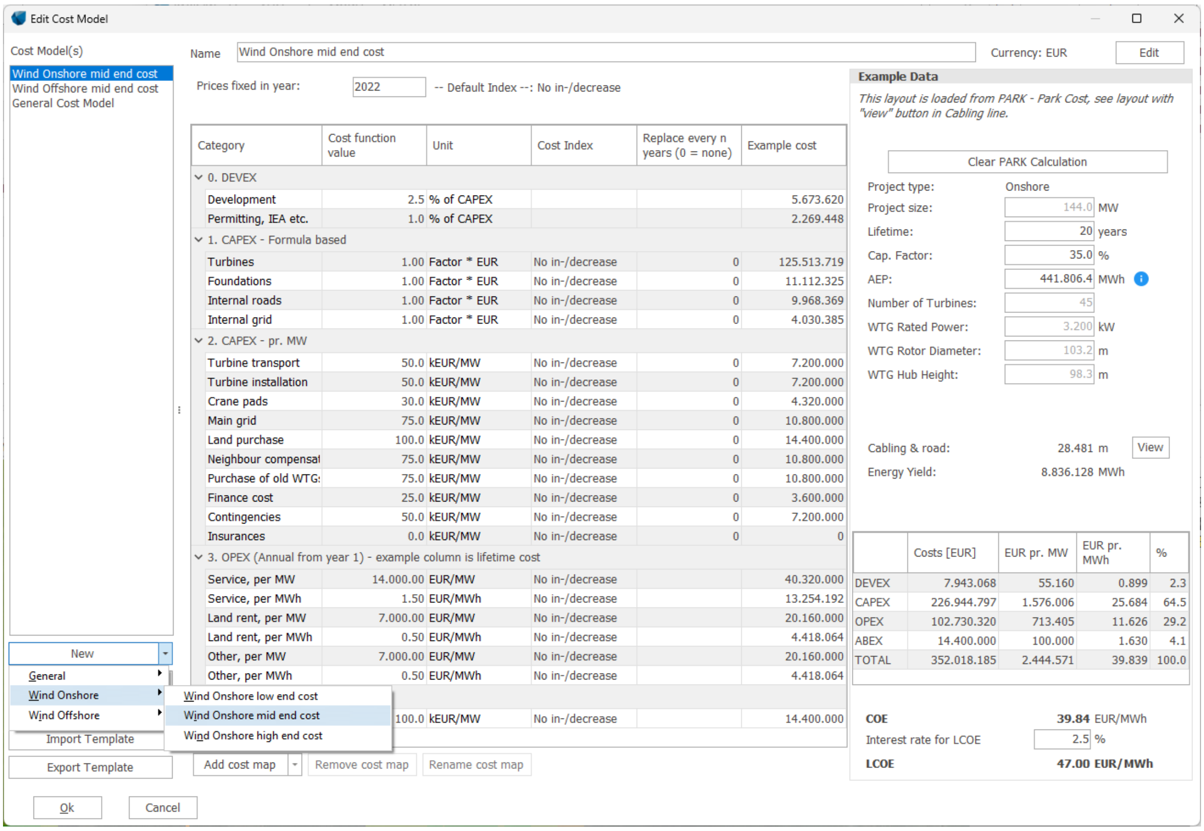


Figure 201 Create new cost models, choose currency, and calibrate costs.

If you already know some of the costs of a component, like the turbine cost, the cost model can be calibrated. See Chapter 2.18.1.2

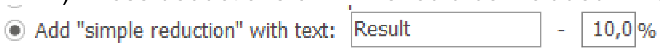
In the Cost Model Setup, several actions can be taken:

Insert a new cost model based on EMD defaults. Here 3 variants, low, mid, high for onshore and offshore are available for typical projects. These should give realistic values based on the designed wind farm, although variations from project to project can be high.

For the AEP, which is very deciding for e.g., LCOE, two important notes:

1) When using the cost function BEFORE a PARK calculation is performed, a rough guess is used (Capacity Factor of 35%). Reopening after a calculation, the calculated values are imported into the "example data" panel in the right-hand side of the window. This will be using the last calculated AEP. So if the wind farm has changed since the last calculation, these changes will not be reflected in the AEP shown in the example. Updating the PARK calculation will also update the example data.

2) Loss deductions of AEP should be included. These are taken from setup tab:



From windPRO 4.0 it is possible to attach cost maps to add known spatial costs depending on soil, ownership, water depths etc. See the BASIS manual section 2.18 for more information about attaching a cost map.

In a PARK calculation the spatial costs are calculated based on the position of New WTGs. Values outside the cost map are assumed to be zero. So, if a WTG's position is not within the cost map, it will have no spatial cost. PARK will warn the user if a turbine is located outside the cost map area.

Results: At the cost function form, tables with costs, specific costs COE and LCOE can be seen. In the report similar results is seen.

3.7 Loss & Uncertainty

The PARK calculation traditionally provides the results assuming all turbines are running “full time” and it provides the AEP results measured at the turbine, which is usually the output before the step-up transformer. Although, in some cases, power curves can represent the output after the step-up transformer. Power curves will also typically include noise reduced operation modes (selected by user). Since windPRO 3.3, curtailment losses and wake losses can be included in the calculated AEP by PARK. This has the advantage that the saved wake losses due to curtailment also are correct calculated. In loss & Uncertainty module, the already included curtailment losses are transferred from PARK similar to wake losses, as a fixed reduction that cannot be edited in L&U. They are also handled different from other losses, described in info box:

Losses are combined to a total loss (shown below) as successive losses using the expression: 1-(1-loss1)*(1-loss2)....
Individual losses in MWh/y are shown for the assumption of no other losses.
Note: all losses are assumed subtracted and the negative signs suppressed.
Pre-calculated losses of wake and curtailment that already accounts for their interaction are summed prior to combination:
Loss_precalc=Loss_wake+Loss_curtailment.

To get the expected AEP sold to grid, as well as grid losses as losses due to turbine availability, curtailments, etc., must be subtracted. This can be done in a PARK calculation as a “lump sum” - a simple percentage reduction. But a far more comprehensive evaluation can be done by importing the PARK results into the LOSS AND UNCERTAINTY evaluation module in windPRO. This partly makes sure all possible losses are judged and partly that there will be specific calculation options helping to get the losses more precisely calculated. An example is the high wind hysteresis, which can be calculated based on the wind distribution and entered controller settings. High wind hysteresis is about how low the wind speed shall go and for how long of a time before a turbine restarts after a high wind, cut-out event.

The uncertainty can also partly be judged, partly calculated, by help from the LOSS AND UNCERTAINTY module. Here are more refined calculation options, like calculation of the uncertainty based on the distance between measurement mast and each turbine.

3.7.1 Introduction, definitions and step-by-step guide

After calculating the expected AEP (Annual Energy Production) with the windPRO PARK module, the next step to bring a wind farm project to a “Bankable” level is to estimate losses and uncertainties. Losses have the recent years become a more and more important part of the AEP estimate, partly because the losses typically are higher for modern wind farm projects, partly because the margin in AEP estimates has been lowered due to larger project sizes, and more tight budgets for wind farm projects. While wind farm investments have increased heavily, the need of knowing the uncertainties similarly has become of huge importance to get the projects financed.

With the windPRO LOSS & UNCERTAINTY module the estimation of expected losses and uncertainties can be performed on a structured basis, with numerous tools for quantifying the individual components quite accurately.

Besides losses and uncertainties, the module also offers a Bias correction part. A Bias is a “known issue”, like model problems (e.g., RIX correction) or wind speed measurement bias, which have not been corrected in the calculation basis.

3.7.1.1 Basic definitions

The basic concept behind the module is:

Calculated GROSS AEP
+/- BIAS correction
<u>- LOSSES</u>
= NET AEP (expected sold energy production) = P50

The expected NET AEP is also named the P50 value, which is the expected outcome of the project. There is a probability of 50% that the outcome will be more than P50 and a probability of 50% that the outcome will be less. This can also be named the “central estimate”. The uncertainty must be judged/calculated to find out how accurate the estimate is, and thereby the risk of getting a lower outcome than expected.

Including the uncertainty, the AEP estimate is assumed to follow a normal distribution. All uncertainty components are assumed independent and, thus, combined as standard deviations, i.e. the square root of summed squares of individual contributions. The individual uncertainty components, judged or calculated, shall be given as 1 std dev (Standard Deviation or simply σ).

If the std dev (hereafter σ) is 10%, this means that the production at a given AEP exceedance level (PXX) for a calculated result can be calculated using the inverse normal distribution as:

P84 = P50 – 1 x Uncertainty (= P50 - 10%, for σ=10% as above)
P90 = P50 – 1,28 x Uncertainty (= P50 - 12,8%, for σ=10% as above)

Below are listed additional coverage factors for other typical exceedance levels (e.g., 75%), all based on the normal distribution.

Prob. (%)	Coverage factor
50	(0,00)
75	0,67
84 *)	1,00
90	1,28
95	1,64
99	2,33

**) For P84,00 the coverage factor is not exactly 1,00 but 0,99. The coverage factor 1,00 corresponds to P84,13 which we round off to P84 here for convenience.*

A special component in the uncertainty evaluation is the year-to-year variability of the wind, which can be included in the calculations. The variability describes how much the annual average wind speed varies from year-to-year for the region. This figure can be calculated in the MCP module based on long term data series, or it can be found in different research projects.
The expected probability of exceedance is calculated for 1, 5 10, 20 years with the variability for the time span in question included in the uncertainty. Contrary to the other uncertainties the variability depends on how many years the forecast covers, referred to as “expected lifetime”. This can be of importance for judgment of the risk of the investment.

3.7.1.2 Understanding the uncertainty concept (Probability of exceedance)

The uncertainty concept is well illustrated by the figure below.

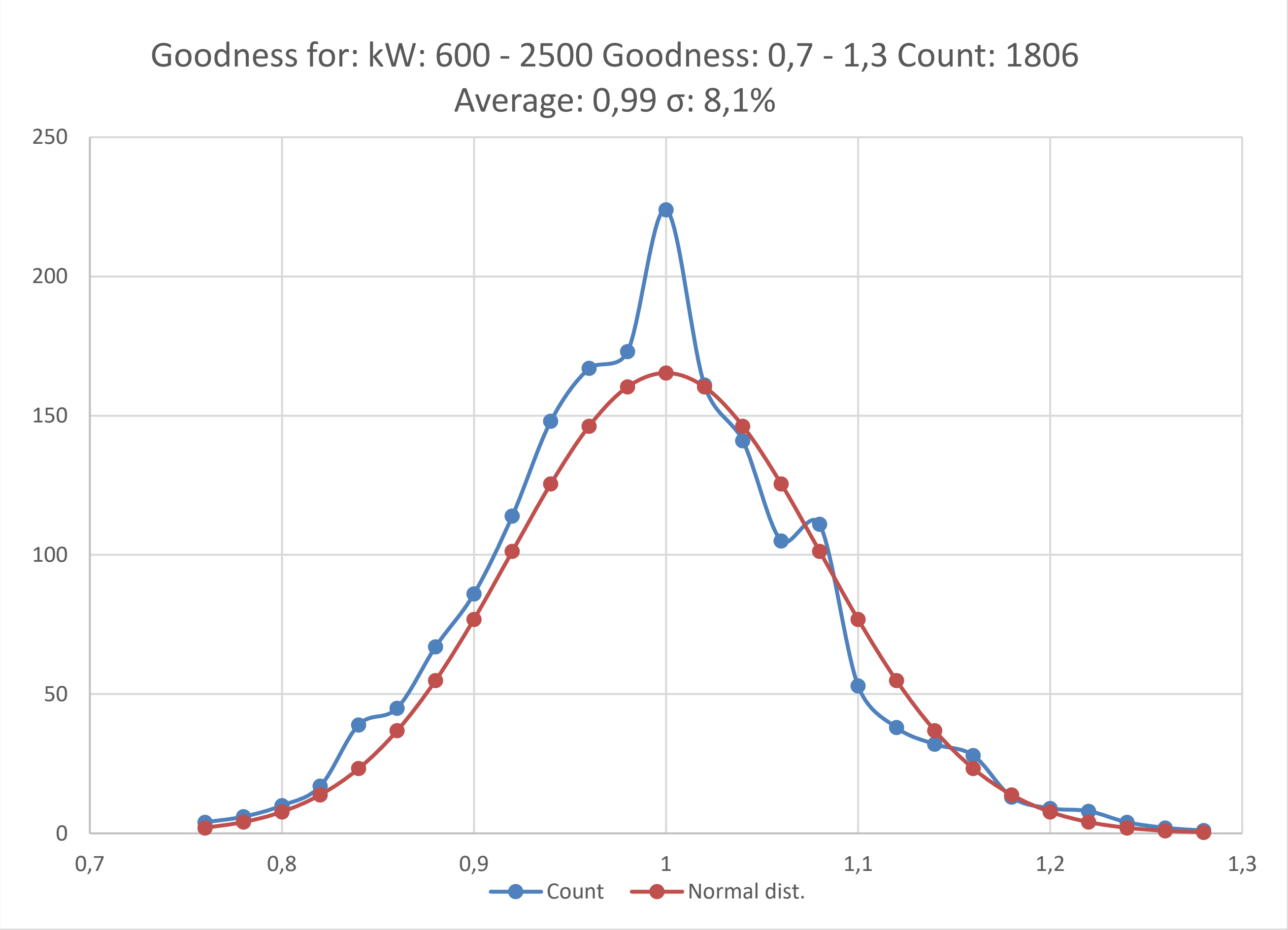


Figure 1 Based on calculations of 1806 wind turbines in Denmark, the count of goodness factor (Actual/calculated AEP corrected with wind energy index) for each turbine shows that the actual results are close to a normal distribution with a σ of 8,1%. In other words the uncertainty for these calculations is 8,1%.

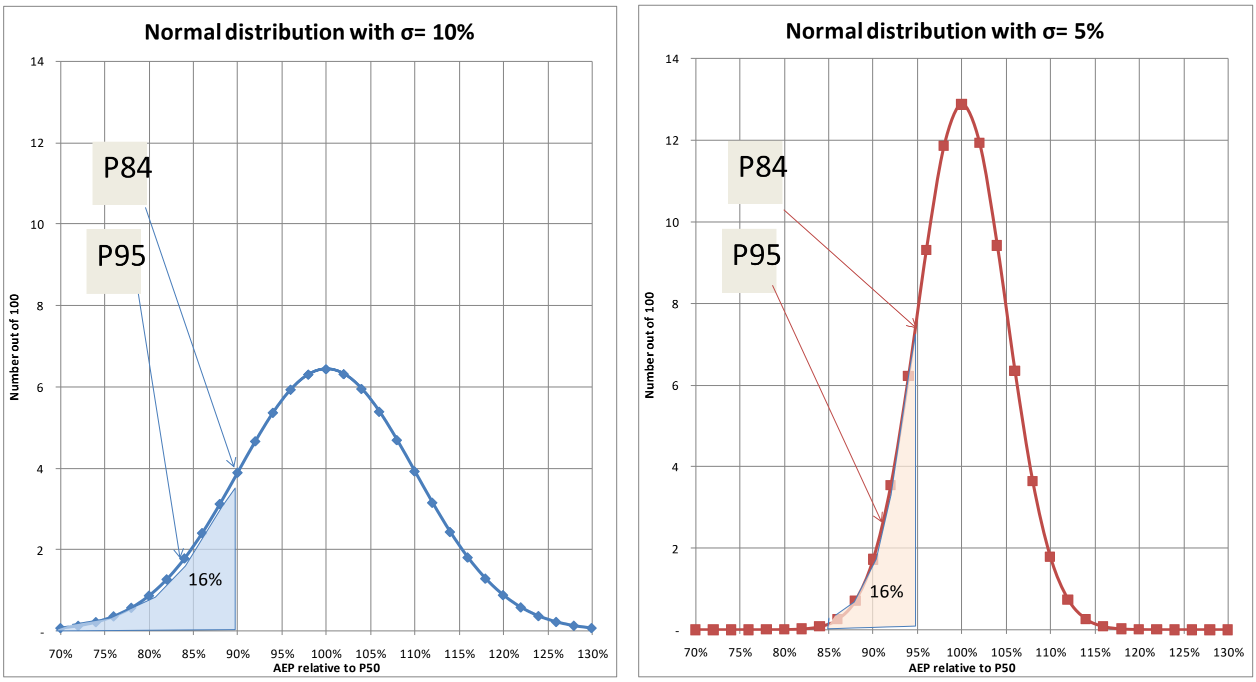


Figure 2 Illustration of the Normal distribution

The normal distribution is defined so that roughly 2/3 (more precisely 68,3%) of all events will be within +/- 1σ and around 32% is outside. In the one tail (e.g., below -1σ), there is around 16%, so there is 16% probability that

the estimate will be below 1σ subtracted from P50, or 84% probability that it will be above (exceed). In other words, the P84 is the value where 84 out of 100 realizations will result in an outcome better than P84. For P95, there is only 5% probability to get an outcome poorer than this exceedance level which is found by subtracting the σ multiplied by 1,64 from the P50. So for σ=10%, the P95 value in the left graph is found where 5% is in the shaded area (P95). This would be found 16,4% below 100%, i.e. at 83,6% on the x-axis.
Similarly, if σ=5%, 5% x 1,64 = 8,2%, so P95 is found at AEP of 100%-8,2% = 91,8% of the P50 on the x-axis.

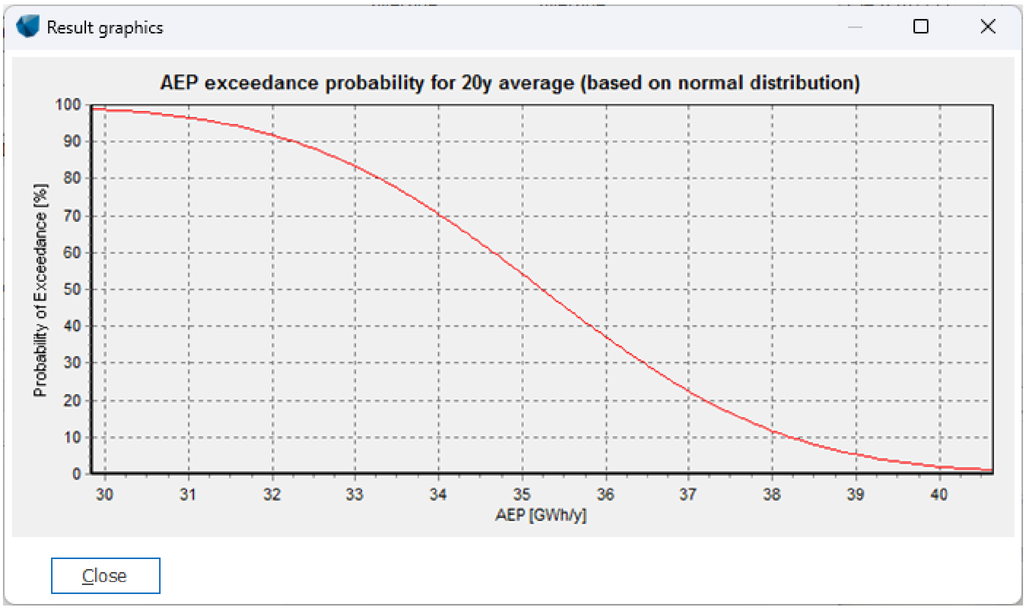


Figure 3 The probability of exceedance graph

The probability of exceedance will normally be shown as a cumulative graph showing the probability of exceedance on the y-axis and the corresponding AEP PXX values on the x-axis.

3.7.1.3 What is included in GROSS value?

The module follows the DNV (Det Norske Veritas) definition as presented at AWEA 2008:

Included in GROSS calculation:
- roughness effects
- topographic effects
- obstacle effects
- air density correction
- (long term correction)
- (wind data correction)

Last two should be included, but it is up to the user to decide what is included. If e.g., a post calibration show that the wind data has been offset, it can be decided to redo PARK calculations with updated wind data or it can be decided to include the offset as a Bias correction of the GROSS.

NOT included in GROSS calculation:
- Wake losses (The PARK result includes wake losses, but these are “taken out” in the loss module so the “real Gross” based on the DNV definition is used as basis for all loss reductions.
- Other losses like availability, grid losses etc., see complete list below.
- Model issues like RIX correction or known power curve bias, will should be included as Bias, not as Losses, because these are considered “known issues” and should thereby be treated as corrections to the calculation results applied before the loss evaluation.
- Curtailments included in PARK calculation are treated similar to wake losses.

The structure of the module set demands to the user keeping track of what has already been compensated in the PARK AEP calculation, and what should be added in the loss, bias and uncertainty evaluation. The only “automized” issue is that the wake losses are taken out of the windPRO PARK AEP calculation (the size of the wake loss is automatically filled in), so the LOSS & UNCERTAINTY module starts from the non-wake loss added wind farm AEP calculation result.

The module has these features:

1. All Bias, loss and uncertainty components can be judged by the user and entered manually.
2. Some of the components can be calculated by the software based on different data sources, typically wind data time series.

The wind data time series are used to divide the expected AEP in time steps, to enable calculation of time, wind speed or wind direction dependent losses. But also links to other windPRO calculations like SHADOW can be used to give an accurate estimate of AEP loss due to flicker stop, or a PARK RIX calculation can be used to perform a RIX bias correction.

3.7.1.4 Loss definitions

The loss definitions in the module follow the below definitions (in *italic* the EMD modifications). Note we have switched group 1 and 2 relative to the original paper so Wake effects occur first and availability second.

Paper, AWEA 2008: Standard Loss Definitions for Wind Resource / Energy Assessments
Prepared by Steve Jones of Global Energy Concepts (DNV)

Standard Loss Category	Recommended Subcategories	Comments
1. Wake Effects	Wake effects, all WTGs	Losses within the turbines which are the subject of the energy assessment. Helimax currently includes wake losses in the gross yield. Losses on the turbines which are the subject of the energy assessment, from identified turbines that are not the subject of the energy assessment, which either already operate or which are expected to operate the entire useful life of the facility being studied. *If the PARK calculation includes existing turbines (which it should), the wake losses from as well internal as external wake effects are included in the wake loss calculation, therefore the EMD has brought the two groups from original document into one.*
1. Wake Effects	Future wake effects	Losses due to additional development in the vicinity of the turbines being studied, but which would occur after commissioning of the turbines being studied.
2. Availability	Turbine	GEC further divides this into routine maintenance, faults, minor components, and major components. AWS Truewind uses a separate factor (Availability Correlation with High Wind Events) that could be buried into this number or categorized with “7. Other” below.
2. Availability	Balance of plant (*Substation)*	Losses due to downtime in components between the turbine main breaker to and including project substation transformer and project-specific transmission line.
2. Availability	Grid	Losses due to downtime of power grid external to the wind power facility.
2. Availability	Other	Other availability losses not accounted for above or in other categories below.
3. Turbine performance	Power curve (can be part of Bias)	Losses due to the turbine not producing to its reference power curve (even with new blades and wind flow within test specifications).
3. Turbine performance	High wind hysteresis	Losses due to shutdown between high-wind cutout and subsequent cut back in.
3. Turbine performance	Wind flow	Losses due to turbulence, off-yaw axis winds, inclined flow, high shear, etc. These represent losses due to differences between turbine power curve test conditions and actual conditions at the site.
3. Turbine performance	Other	Other turbine performance losses not accounted for above.
4. Electrical	Electrical losses	Losses to the point of revenue metering, including, as applicable, transformers, collection wiring, substation, transmission.
4. Electrical	Facility consumption	Losses due to parasitic consumption (heaters, transformer no-load losses, etc.) within the facility. This factor is not intended to cover facility power purchase costs, but does include the reduction of sold energy due to consumption “behind the meter.”
5. Environmental	Performance degradation not due to icing	Losses due to blade degradation over time (which typically gets worse over time, but may be repaired from time to time), and blade soiling (which may be mitigated from time to time with precipitation or blade cleaning).
5. Environmental	Performance degradation due to icing	Losses due to temporary ice accumulation on blades, reducing their aerodynamic performance.

5. Environmental	Shutdown due to icing, lightning, hail, etc.	Losses due to turbine shutdowns (whether by the turbine controller, SCADA system, or by an operator) due to ice accumulation on blades, lightning, hail, and other similar events,
5. Environmental	High and low temperature	Losses due to ambient temperatures outside the turbine's operating range. (Faults due to overheating of components that occur when ambient conditions are within the turbine design envelope would be covered under turbine availability category above.)
5. Environmental	Site access and other force majeure events	Losses due to difficult site access due to, for example, snow, ice, or remote project location. Note that this environmental loss and some other environmental losses may be covered under the availability definition, above. However, these "environmental" losses are intended to cover factors outside the control of turbine manufacturers.
5. Environmental	Tree growth or felling	Losses due to growth of trees in the facility vicinity. This loss may be a gain in certain cases where trees are expected to be felled.
6. Curtailment	Wind sector management	Losses due to commanded shutdown of closely spaced turbines to reduce physical loads on the turbines.
6. Curtailment	Grid curtailment and ramp-rate	Losses due to limitations on the grid external to the wind power facility, both due to limitations on the amount of power delivered at a given time, as well as limitations on the rate of change of power deliveries.
6. Curtailment	Power purchase agreement curtailment	Losses due to the power purchaser electing to not take power generated by the facility.
6. Curtailment	Environmental, Noise	Losses due to shutdowns or altered operations to reduce noise and shadow impacts, and for bird or bat mitigation. This would include use of a low-noise power curve vs. a standard one from time to time. *For Noise and flicker, there are in windPRO access to detailed calculation options. Therefore EMD has expanded this with more groups, same for Birds and Bats, which can be set based on "free of choice" parameters like date interval, hour interval etc.*
6. Curtailment	Environmental, Flicker	
6. Curtailment	Environmental, Birds	
6. Curtailment	Environmental, Bats	
6. Curtailment	Temperature Derating	Losses due to the turbine needing to throttle at rated power at certain temperature ranges and elevations. Calculated in time-varying PARK.
6. Curtailment	Other curtailment	
7. Other		This would cover anything that doesn't fit into the above six main categories.

3.7.2 Step-by-step guide

- Establish a PARK calculation (see Energy, Section 3.3.5), <u>BUT note the following:</u>
  If more Site Data Objects or turbine types are used, group these in separate layers before calculation.
  If RIX Bias correction should be included, make the RIX calculation in PARK
  If calculation of time dependent losses etc. makes sure you have a proper time series with required data. The WTI generator in Meteo analyzer tool may be used to establish this. Include temperature if high/low temperature shut down is expected. Include turbulence or gust if high wind hysteresis loss is expected.
- Start LOSS & UNCERTAINTY module
- Load PARK calculation
- You may attach a wind data time series from Meteo object or WTI file
- Input needed parameters in Bias, Loss and Uncertainty tab sheets
- Where "Edit" buttons are available, start detailed calculations – you might need to go back to "Main" to reselect the wind data to more a or less detailed series.
- When all inputs are established, review at "result" tab and start calculation for generating report by OK.

3.7.3 Basic data for calculations

A PARK calculation is the basis. From this all relevant data on AEP for each turbine, wake loss, elevation, hub height etc. are loaded. In addition, sensitivity is calculated. The sensitivity defines the transfer from changes in wind speed to changes in AEP for each turbine by recalculation of the PARK with a small change in wind speed. It is worth to notice that if a RIX bias calculation is wanted, the PARK calculation loaded must hold a RIX calculation. Similarly, if a flicker stop loss calculation is wanted, there must be a shadow calculation for exactly the same wind farm configuration as in the loaded park calculation. For Noise loss calculation it must be noted that if the PARK calculation already includes turbines in noise reduced mode, no additional Noise loss should be entered. If it is a wish to present the loss due to noise in the loss calculation, the PARK calculation must be based on no noise reduced turbines, and the noise reduced modes must then be implemented in the loss module. We are aware of this is somewhat “tricky” and the handling of noise loss calculation will be improved further in the future. If for example the noise reduced mode only occurs during e.g., night hours, the Loss&Uncertainty module is very convenient to use, as the calculation setup allows limiting the noise reduced mode to specific hours or wind directions.

In addition, following data can be used:

Climate data as time series: Either by link to a Meteo object time series or to a .WTI file (Wind TIme variation file that can be established from the Meteo analyzer or selected from the windPRO Data\Standards\ folder). From windPRO 3.3 selection of datasets for different loss calculation parts can be selected individual for each loss calculation type.

Power curve uncertainty can be specified detailed in the WTG catalogue and used from uncertainty module, but also simpler approaches for this calculation are available if no detailed data are available for the turbine.

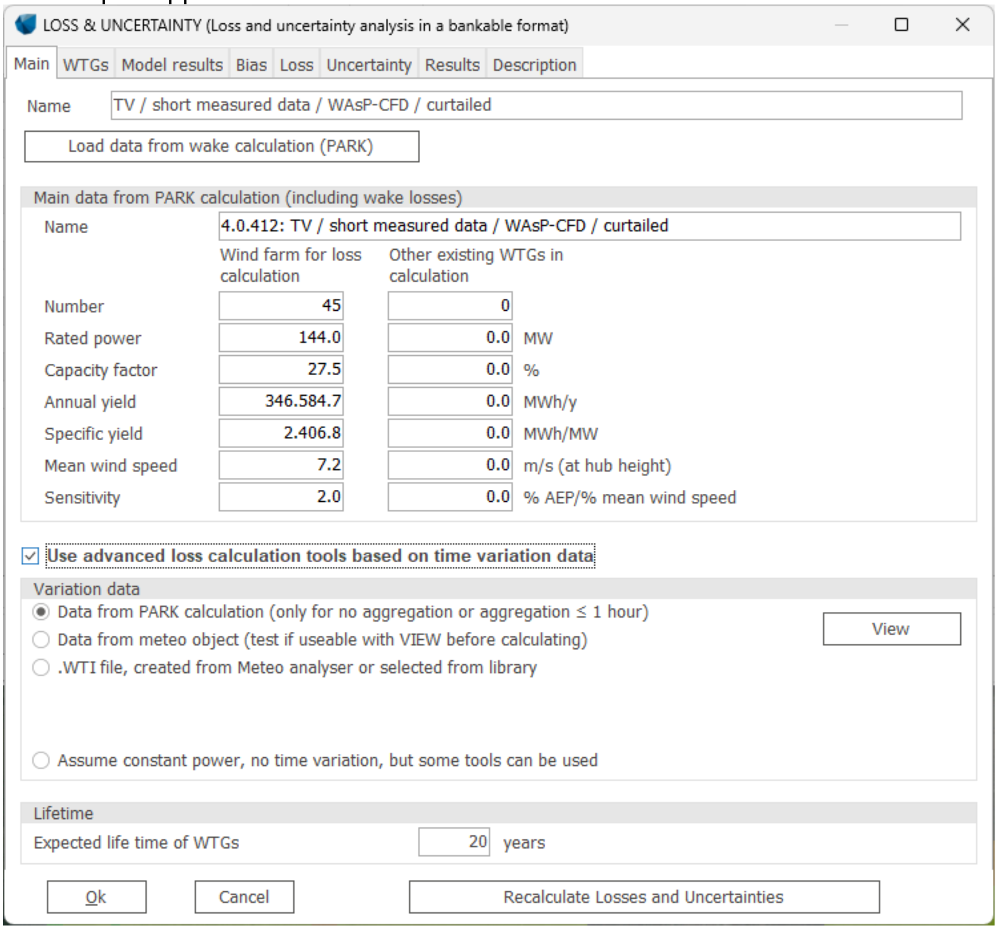


Figure 4 The Main tab where PARK calculation is loaded.

When loading a PARK calculation, it can be decided if existing turbines included in PARK shall be included in the loss & uncertainty evaluation. Further it is possible only to include the existing turbines if these are flagged “treat as PARK WTG” (property on existing WTG objects).
This tab shows the main results from the PARK calculation and the calculated sensitivity for propagation of changes in wind speed to changes in AEP (AEP%/ws%).

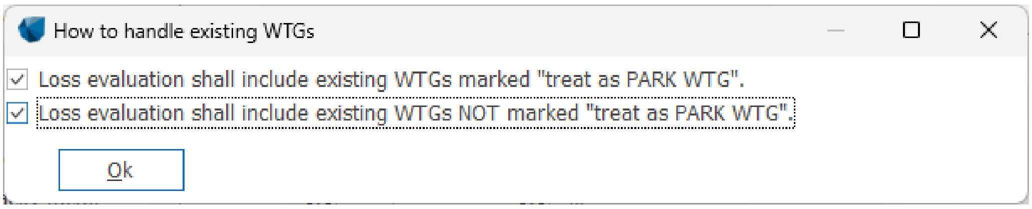


Figure 202 Decide how to handle existing WTGs.

Checking the “Use advanced loss calculation tools…” gives access to add time varying data or to assume constant power. The last option is used if no time varying data are available, but the user still wants to calculate flicker or temperature loss assuming constant AEP in each time step.
With the time step PARK calculation concept, it is obvious to use a time step PARK calculation as input. This must although in the Setup be set to non-averaged output or hourly averaged. Default is monthly. The time step PARK calculation should be long term representative, meaning being calculated based on e.g., 1 or 3 y LT scaled data or e.g., 10 or 20y calibrated mesoscale data.

The expected lifetime only influences the uncertainty contribution from the variability of the wind. All other calculations are based on annual averages. The uncertainty component coming from the year to year variability decreases with the number of years and will thereby be lower the longer the lifetime (part of the variability is averaged out).

3.7.3.1 Climate data

Several loss calculations are based on climate data including also temperature data. Of high importance is that the climate data represent a typical year. A time series averaged over several years will not hold the information of the dynamic behavior that is of high importance for the expected shut down situations of the wind turbines. However, calculations can be performed based on more than 1 year of data in a Meteo object.

In a Meteo object, a dataset of one or more years of data can be established from more years of data by disabling data, so that one or more representative year(s) is enabled. If the data series merely holds a ½ year or 1½ year, the calculation will be seasonally biased. This should be avoided. But no matter how long (or short) period of data the Meteo object used hold, it is important to remark that the calculations always will assume these data as long term representative and scale the calculations to annual values.

A specific way to establish exact 1 year of data prepared for such analysis is found in the Meteo analyzer. Here you can generate exactly 1 year of data with a specific temporal resolution (data can be down or up sampled) based on one or more time series in Meteo objects. See further details in the chapter on time varying data from Meteo analyzer.

Climate data can be selected individually for each loss calculation type. It the best (most precise) wind variation time series e.g., not have temperature information, a temperature loss calculation (shut down at low/high temperature) can be calculated based on e.g., Merra data which includes both wind and temperature. It is although important that wind data **must exist** in the meteo object used in each specific calculation, while it is concurrent wind and e.g., temperature, that decides the loss.

3.7.3.2 Model results

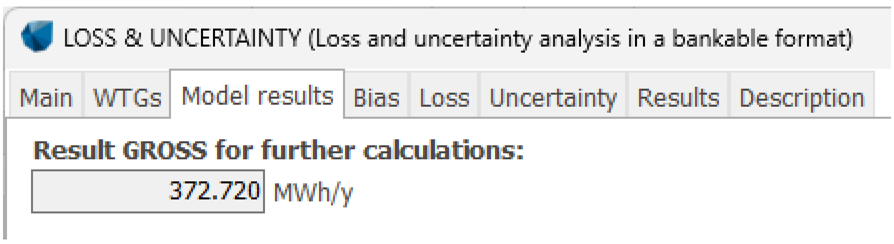


Figure 5 At the Model results calculated Gross is shown.

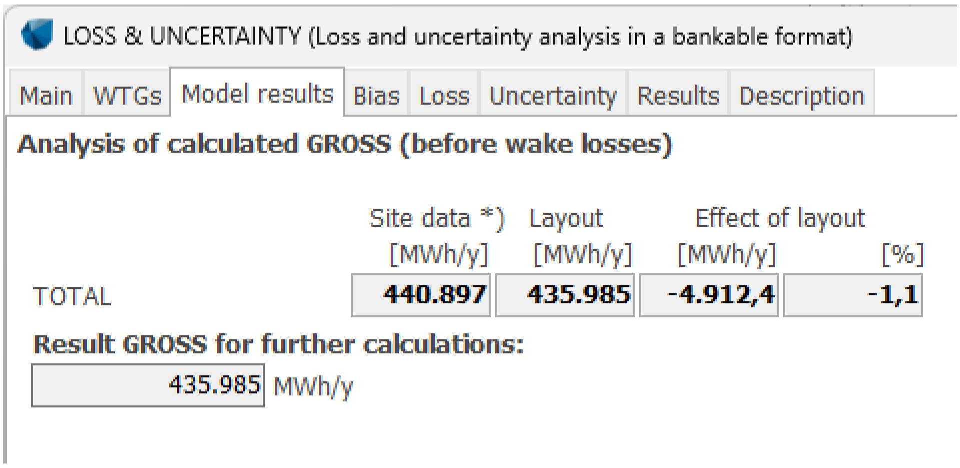


Figure 203 For "Standard" PARK also model modifications shown.

Depending on which PARK variant is loaded, there can be more details shown on Model results, e.g., the effect of the layout. This can give an idea of how large model corrections are applied. The software calculates the AEP if all turbines are positioned at the position(s) of the Site Data Object(s) – if more than one Site Data Objects, the turbines "belonging" to a specific Site Data Object is moved to this object and calculated. This is compared to the actual calculation with the turbines at their "real positions" (the Layout). Thereby it can be seen how much the model transforms data based on roughness, orography and local obstacles. The higher the effect of the layout, the higher the risks are of errors in calculations if the model does not perform accurately. In other words, the more measurement masts the calculation is based on, the lower the effect of the layout, or the lower complexity of terrain/roughness, the lower the effect of the layout.

Note the results here are EXCLUDING wake losses and curtailment losses included in PARK; these are simply taken out of the calculation and transferred automatically to the LOSS sheet where belong according to the DNV standard definitions.

3.7.3.3 General concept for input of data in bias, loss and uncertainty sheets

In general, there can only be entered one value for a loss/bias/uncertainty to represent the entire wind farm. But if a calculation module is available (i.e. an "Edit" tickbox), values can be entered in a more flexible way:

- Individually for each turbine
- For all turbines on a specific layer (in Maps&Objects)
- For all turbines

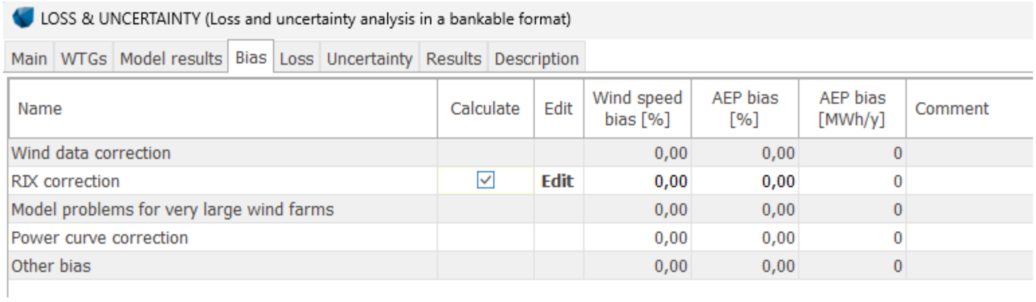
This means that if there is a need for specific data on half of the turbines and other values on the other half, it would be a very good idea to place these two groups in different layers in the project setup. A lot of individual input can then be avoided. An example could be if a wind farm is established with 2 or 3 different wind turbine types or if e.g., one group is more exposed (on a ridge) than another group and therefore needs a lower cut out wind speed value.

Input of data for an individual turbine or for all turbines in a layer is simply selected by clicking with the mouse on the individual turbine or on the specific layer. The input will then be assigned to the selected turbine or group.

3.7.4 Bias

Bias is a correction for "known issues", like e.g., the RIX (Ruggednes IndeX) modifications of wind speeds in complex terrain introduced by RISØ, or e.g., power curve correction, where those are known to be too pessimistic or optimistic based on experience or evaluation by the HP method. Also wind measurements can have a known bias. For example, specific anemometers are known to have a systematic error, or post calibration could show an error, in both cases it is more convenient to include these corrections as biases than by reanalysing all the wind data behind the calculations. It is important is that bias corrections only are included once, either in the data basis of the PARK calculation or as a bias in the LOSS & UNCERTAINTY module. An advantage by having bias corrections in the LOSS & UNCERTAINTY module is that it will be clearly documented, and easy to change if new information appears at a later stage.

A bias can be entered as a simple correction in percent either on wind speed or in percent on AEP. If entered as wind speed percentage, this quantity is converted to percent on AEP using the sensitivity AEP%/WS% (WS=Wind Speed). The AEP percentage is then multiplied with calculated GROSS and added (or subtracted) to GROSS before loss subtraction. Remember that a bias can have a positive or negative value - so do remember the sign.



LOSS & UNCERTAINTY (Loss and uncertainty analysis in a bankable format)

Main | WTGs | Model results | Bias | Loss | Uncertainty | Results | Description

Name	Calculate	Edit	Wind speed bias [%]	AEP bias [%]	AEP bias [MWh/y]	Comment
Wind data correction			0,00	0,00	0	
RIX correction	☑	Edit	0,00	0,00	0	
Model problems for very large wind farms			0,00	0,00	0	
Power curve correction			0,00	0,00	0	
Other bias			0,00	0,00	0	

Figure 6 The input form for Bias.

As seen above five different predefined bias input lines are available. If PARK calculation includes a RIX calculation, but NO correction, there will be a “calculate” tick box option for this (see next chapter for details). If PARK calculation includes RIX correction, this is not treated as a bias in Loss&Uncertainty. However, there will be an information in the comment box how much RIX correction was included from the PARK calculation.

3.7.4.1.1 Wind speed correction

If the wind data is known to have a bias, which has not already been corrected in the wind data used for the PARK calculation, the correction should be included here.
Wind data bias can have many reasons and is probably the most frequent reason for biased calculation results. But it can be very difficult to discover such a wind speed bias. The best method to avoid wind bias is to have more wind data sources for the site/region. Existing turbines with available production figures present near the site is also a valuable source of validation of the wind data level.
If local wind measurement equipment is used, the wind data correction can simply be due to known offset related to the equipment used. Often this will be corrected for at previous stage in calculations, if so it SHALL NOT be entered as a bias, the correction would then be double. But it is a good idea to write a comment if corrections are performed before PARK calculation, or if any validation of the wind speed level is made.
The correction can be entered as a modification on wind speed or AEP, remember to include the sign (- if it is a reduction) of the bias, because corrections can go in either directions.

3.7.4.1.2 RIX correction

For details, see 12.3.2. If a RIX correction proposal is made via another tool than windPRO, or it just is a rough user estimate, the correction can be entered here. But it will then ONLY be as a common correction that will be the same for all turbines. So if RIX correction is issues always make a PARK calculation with RIX and use the correction calculation tool described in “RIX correction calculation”.

3.7.4.1.3 Model problems for very large wind farms

This topic is less relevant today, where comprehensive tests on large wind farms show the wake models handles these reasonable well, see e.g., http://iopscience.iop.org/article/10.1088/1742-6596/524/1/012162/pdf. It seems the problem issue previous seen more are related to low turbulence, which require use of lower WDC in PARK calculation. The right choice of WDC seem to solve this. But if it is assumed that the PARK calculation not includes the full expected wake losses, a bias expectation can be entered.

3.7.4.1.4 Power curve correction

If it is known that a power curve is too optimistic or pessimistic, a simple correction should be entered here.

3.7.4.1.5 Other

Any other issues that the user knows is a bias in the calculation should be compensated here.

3.7.4.2 RIX correction calculation

For the RIX correction a calculation module is established. The main source for the implementation is:

EWEC06 paper:
IMPROVING WAsP PREDICTIONS IN (TOO) COMPLEX TERRAIN
By Niels G. Mortensen, Anthony J. Bowen and Ioannis Antoniou
Wind Energy Department, Risø National Laboratory

This paper describes why complex terrain with steepness > 30-40% violates the WAsP model calculation method, and how calculation accuracy can be improved by applying the RIX correction method.

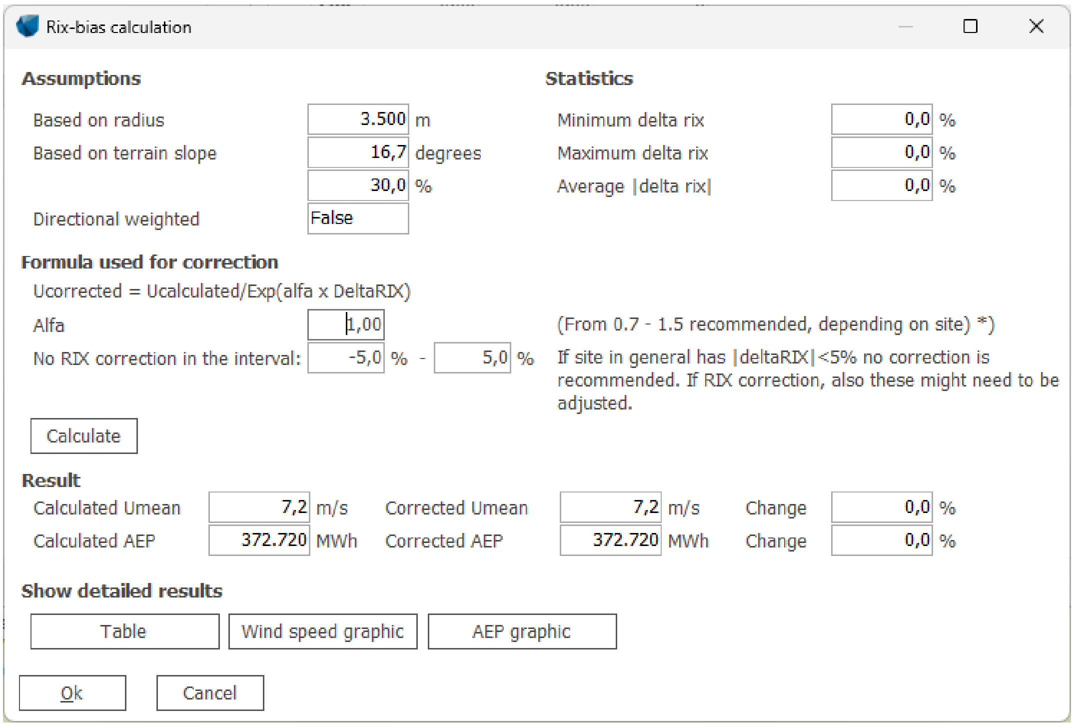


Figure 7 Input of details for the RIX correction calculation and main results.

The basic formula is: $U_m = U_p \times \exp(-\alpha \times \Delta RIX)$, where U_p is the predicted wind speed using WAsP and U_m (measured) is the corrected wind speed. The parameter α is found empirically (e.g., via cross prediction tool in Meteo analyzer in windPRO) and ΔRIX is calculated by windPRO in a park calculation based on the elevation data at the site. The key issue is to estimate the α value and to decide the radius and slope threshold for the ΔRIX calculation. Given these the RIX correction is simple math. The calculation tool finds the appropriate (given α and ΔRIX) correction of the wind speed at each WTG position and converts this to an AEP modification based on the AEP%/ws% sensitivity for each WTG position. The calculated modification will be stored individually on each WTG.

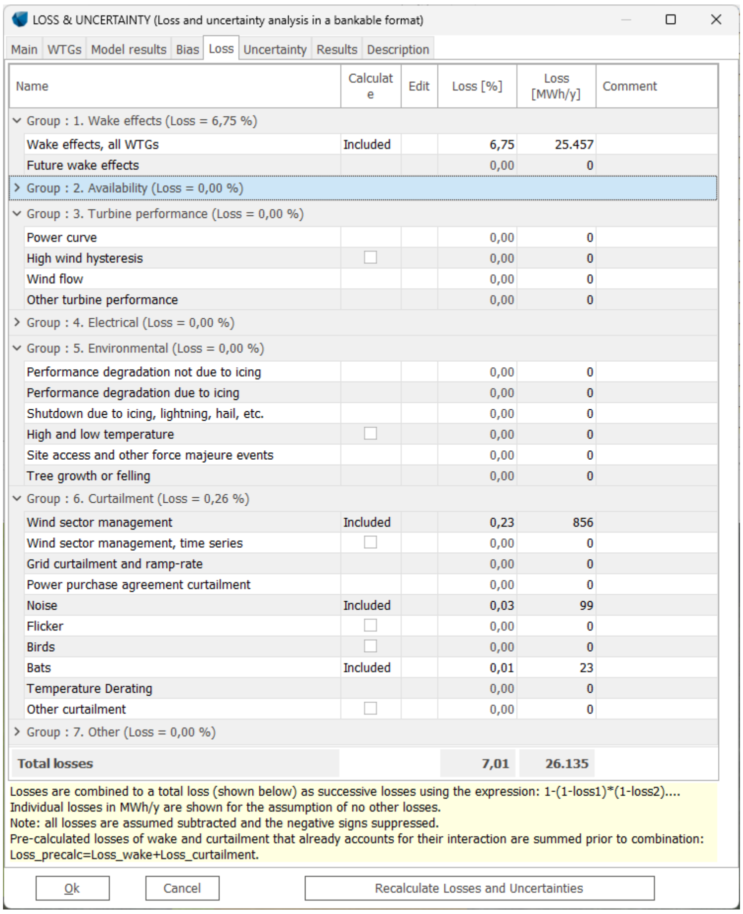
3.7.5 Loss

Loss is the AEP that should be produced based on the available wind and the turbine power curve, but never reach the “sales metering”. Partly due to physical losses such as grid losses, partly due to wake losses, where turbines take wind from each other and partly due to reductions in turbine operation, e.g., due to shut down at low temperatures or availability losses when out of order.

The seven loss main groups defined by DNV are listed in the Intro chapter. Here is how the general calculation runs.

For each turbine a given loss component is converted to efficiency, i.e. a 3% loss is converted to 100%-3% = 97% efficiency. This is done turbine by turbine. The efficiencies from each component are then multiplied and a resulting efficiency found. This is multiplied with the GROSS AEP after Bias correction, if any. Then the NET AEP = P50 is the result of the loss reduction.

Pre-calculated losses, Wake and Curtailment, included in PARK calculation, that already account for their interaction, are summed prior to combination.


LOSS & UNCERTAINTY (Loss and uncertainty analysis in a bankable format)

Main | WTGs | Model results | Bias | Loss | Uncertainty | Results | Description

Name	Calculate	Edit	Loss [%]	Loss [MWh/y]	Comment
Group : 1. Wake effects (Loss = 6,75 %)					
Wake effects, all WTGs	Included		6,75	25.457	
Future wake effects			0,00	0	
Group : 2. Availability (Loss = 0,00 %)					
Group : 3. Turbine performance (Loss = 0,00 %)					
Power curve			0,00	0	
High wind hysteresis	☐		0,00	0	
Wind flow			0,00	0	
Other turbine performance			0,00	0	
Group : 4. Electrical (Loss = 0,00 %)					
Group : 5. Environmental (Loss = 0,00 %)					
Performance degradation not due to icing			0,00	0	
Performance degradation due to icing			0,00	0	
Shutdown due to icing, lightning, hail, etc.			0,00	0	
High and low temperature	☐		0,00	0	
Site access and other force majeure events			0,00	0	
Tree growth or felling			0,00	0	
Group : 6. Curtailment (Loss = 0,26 %)					
Wind sector management	Included		0,23	856	
Wind sector management, time series	☐		0,00	0	
Grid curtailment and ramp-rate			0,00	0	
Power purchase agreement curtailment			0,00	0	
Noise	Included		0,03	99	
Flicker	☐		0,00	0	
Birds	☐		0,00	0	
Bats	Included		0,01	23	
Temperature Derating			0,00	0	
Other curtailment	☐		0,00	0	
Group : 7. Other (Loss = 0,00 %)					
Total losses			**7,01**	**26.135**	

Losses are combined to a total loss (shown below) as successive losses using the expression: 1-(1-loss1)*(1-loss2)....
Individual losses in MWh/y are shown for the assumption of no other losses.
Note: all losses are assumed subtracted and the negative signs suppressed.
Pre-calculated losses of wake and curtailment that already accounts for their interaction are summed prior to combination:
Loss_precalc=Loss_wake+Loss_curtailment.

Ok | Cancel | Recalculate Losses and Uncertainties

Figure 8 The loss input screen.

The loss input screen holds seven main groups that can be expanded for input of the relevant loss estimates. Some input lines hold a “Calculate” option. When checked, the edit button opens a form for detailed calculation of the loss due to the specific component.

For the losses that can be calculated by the module, a more detailed description of calculation method follows. For all components a comment can be added. This is an important part of the loss evaluation. In the report all lines with comments will be shown, so the user can see the background for the evaluation even if no loss is assumed due to the specific component.

Besides what can be calculated, it is of high importance to emphasize that two loss components always should be included:

1. Turbine availability, typically 2-5%, depending on service arrangement and turbine quality.
2. Grid losses (can be calculated with eGRID module), will typically be 1-3% depending on distance to meter point, and if e.g., staff house consumption should be included. Note that the power curves used in PARK-calculation are measured at the low voltage side of the turbine transformer, so the turbine transformer losses should always be included; this alone is typically between 0.5 - 1%.

3.7.5.1 High wind hysteresis

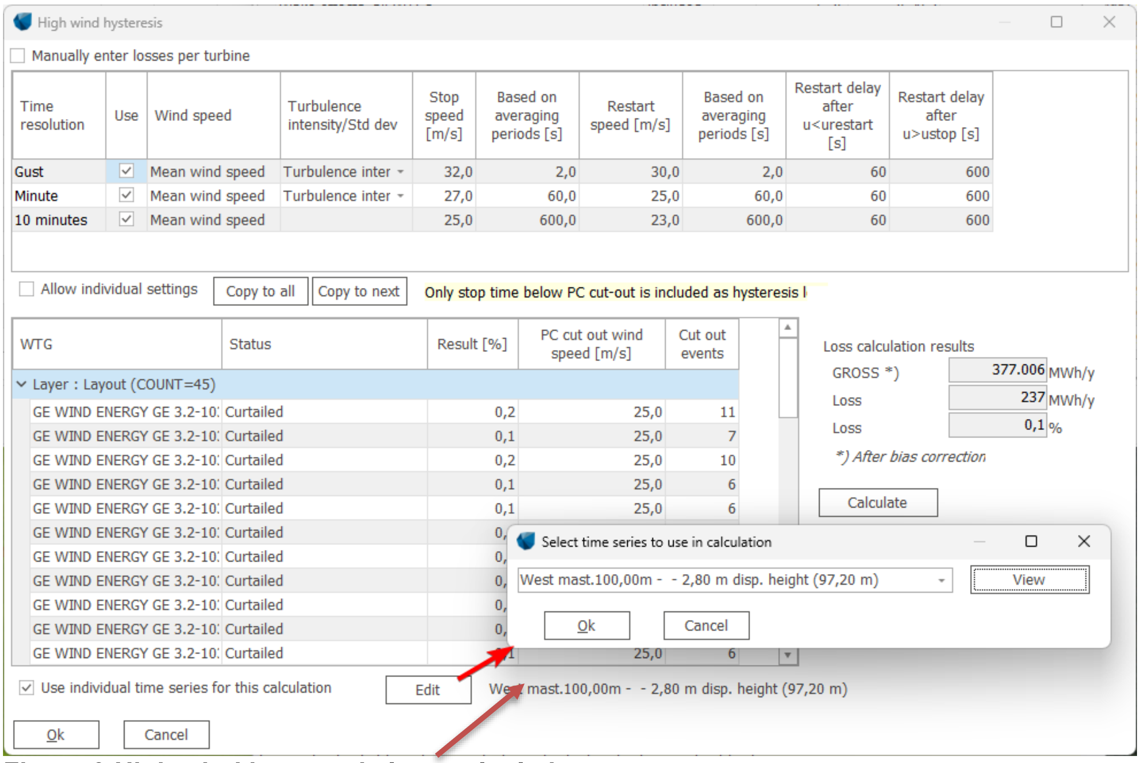


Figure 9 High wind hysteresis loss calculation.

Note the feature for adding a separate time series for this specific calculation. The data used for distributing the production in time (e.g., a time varying PARK calculation), might not hold the needed data for this specific calculation type. For the High wind hysteresis, the turbulence is of importance for redistribution of 10-min data to minute and gust data. Therefore, an alternative time series might be needed.

High wind hysteresis loss is where the turbine is stopped below the cut-out wind speed. All stop time above cut out wind speed (defined in power curve) are already corrected for in AEP calculation. But high wind speed shutdown events can cause significant fatigue loading. Therefore, to prevent repeated start up and shut down of the turbine when winds are close to the shutdown threshold, hysteresis is commonly introduced into the turbine control algorithm. Thereby losses in relation to AEP calculation are introduced. The setup of the stop/start procedure must be confirmed by the turbine manufacturer. This is individual from turbine type to turbine type but is sometimes also set individually from site to site.

The threshold for stop and restart of the turbine can be defined on different time resolution parameters: “Gust”, “Minute” or “10 minutes values”. The latter is the standard mean wind speed as defined in the wind data selected on the main tab (a meteo object or a wti file). The “Gust” values may be estimated from measurements using the max of each 10-minute interval (often logged as “maximum mean wind speed”). However, the averaging period of such estimates is unknown. The IEC61400-1 standard for turbine design requires 3-second averages to be used for gust estimates. So instead of maximum 10-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 the peak factor dependent on the averaging time t for which the conversion is required (defined in the article BELJAARS, The Influence of Sampling and Filtering on Measured Wind Gusts, 1987)
The same equation is used for the “Minute” parameter, allowing to define the stop and restart threshold on an averaging period of 1 or 3 minutes for example.

Once the time resolution is selected the values of the threshold for stop wind speed and restart wind speed (with their respective averaging periods must be defined).
“Restart delay after u<urestart” is a safety margin in time to prevent the turbine restarting too rapidly if the wind shortly after increases again.
“Restart delay after u>ustop” ensures that the wind has decreased steadily below the restart speed before it really starts again. This prevents the turbine to to restart too shortly (and may be unnecessarily) again.

Note that if all three “Time resolution” parameters are selected, they must all be fulfilled for a WTG to “restart” in windPRO’s calculation of the hysteresis loss. But a WTG will stop if any of the stop criteria is fulfilled.

Calculation:

windPRO runs through the time series, find the events that triggers cut-out and logs the period the turbines would have to stop until restart criteria are fulfilled.
The loss is calculated and normalized to a full year.

3.7.5.2 Degradation losses due to Icing

This loss is not yet established as a calculation feature, but there are made a quite comprehensive work in relation to this. Based on meso scale modeling with focus on Icing calculations, the needed output can be established. A comprehensive validation of the results has been made, see EMD-WRF On-Demand ICING - Wiki-WindPRO for further details. It is e.g., possible to calculate an icing loss map with expected AEP loss for a specific site, see example below.

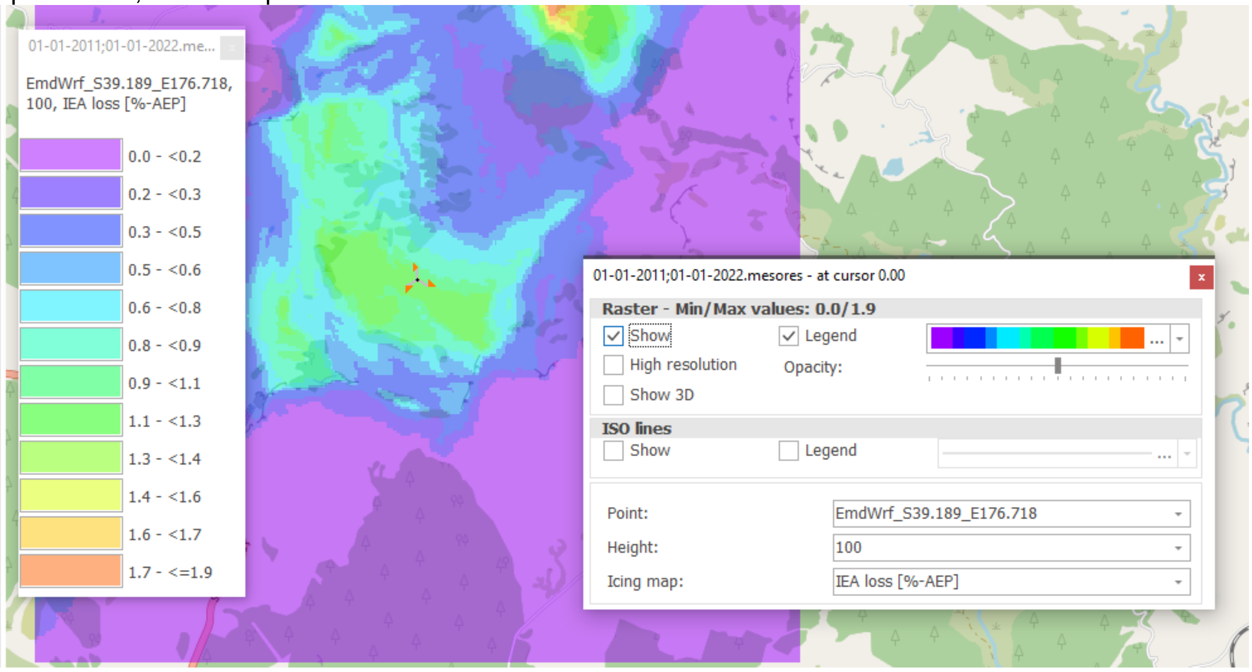


Figure 204 Example of calculated icing loss with EMD WrfOnDemand.

See also manual Chapter 4 Cluster Services.

3.7.5.3 High and low temperature

AEP is calculated for each time step in the climate data time series based on a scaling of the wind speed to the calculated average wind speed for each turbine. The AEP results based on this method is then scaled so the annual sum equals the main calculation result.
Based on entered shut down threshold temperatures, the AEP calculated for each time step is summed for all time steps outside the temperature threshold values. The AEP loss sum is then converted to a loss percentage that is saved for each WTG.

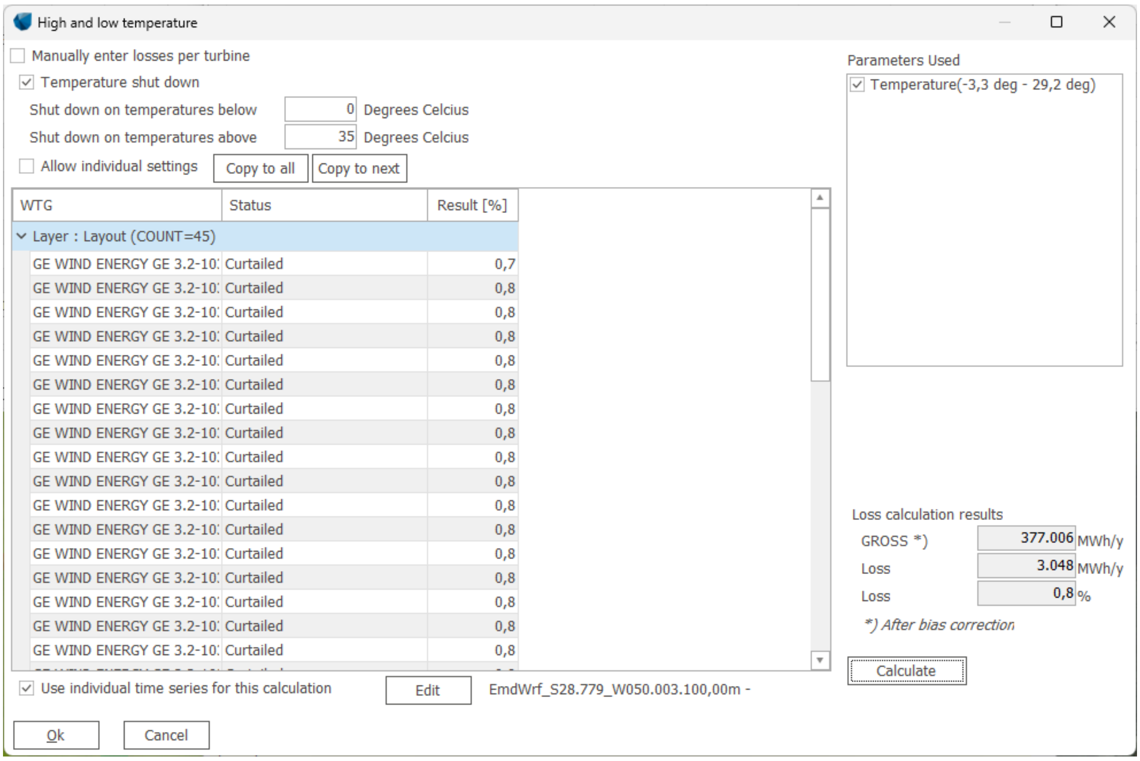


Figure 10 The loss due to high/low temperature is calculated.

In the example above it is seen that the time series with temperature vary in the range from -3.6 to 26.7 degrees. The setting for temperature shut down is below -0 and above +35 deg. C (this is set low just to illustrate the calculation). The loss is calculated to 0.8% based on an AEP calculation for each time step, where the time steps with temperatures outside operation range is summed and included as a loss. The loss calculation for each turbine is shown, in this example it is almost same for all turbines while only one time series can be handled.

Note the temperature is taken from mesoscale model data in this example, see bottom of form.

3.7.5.4 Wind sector management

Wind sector management is stop of turbines when the wind comes from specific directions within specific wind speed intervals, to prevent damage of neighboring turbines due to wake added turbulence due to dense spacing. From windPRO 3.2 it is possible to perform this calculation within the PARK calculation. This will then be loaded into Loss & Uncertainty and treated like wake losses, as pre-calculated loss. It will although still be possible to input sector management settings and calculate losses direct in L&U module if not calculated in PARK.

This is quite complicated to input, while it is individual from turbine to turbine. Below is seen an example where all turbines in the East group have the same settings. But to input this realistically, there must be an individual input for each turbine based on e.g., a Site Compliance calculation. By mouse click at one specific turbine (highlighting this), the settings in the field above will only relate to this specific turbine. For a large wind farm this work is quite troublesome. Therefore, it is possible partly to import from a file. These data could have been established within the Site Compliance analyses.

The" right" way from windPRO 3.2 onwards will be to include sector management in the PARK calculation. Then curtailment settings can be taken from WTG objects. The curtailments will decrease wake losses, and the resulting curtailment and wake loss are transferred and handled correctly in L&U module.

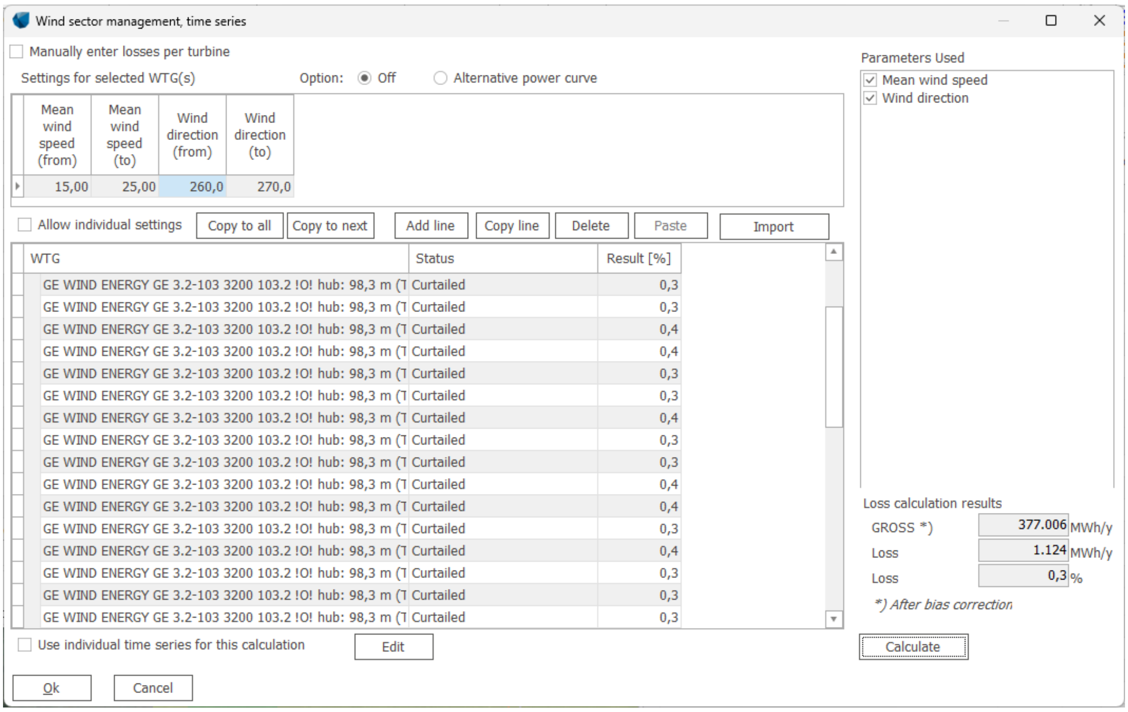


Figure 11 Wind sector management, flexible input options.

For wind sector management there are two variants:

- Based on wind statistic calculation
- Based on time step calculation

Only one of these should be used.

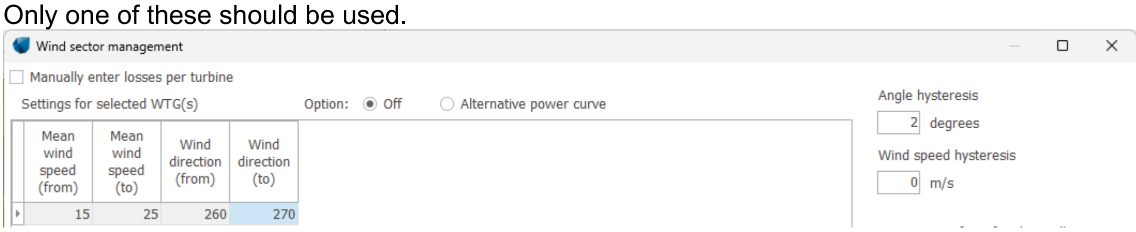
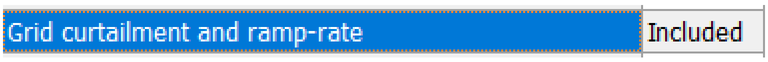


Figure 205 Statistic based wind sector management.

For the statistic-based sector management there is an option to set a hysteresis. This works so: In a 2-degree hysteresis, there are calculated loss 2 degrees outside the specified interval at each "side". But only the half of this loss is included. In that way is simulated if e.g., the wind direction gradually changes from 178 degrees to 180 degrees there is no stop before 180 degrees is reached. But after stop at 180 degrees, and the wind direction rotates back, the turbine is first back in operation when the direction is below 178 degrees. This feature is not included in time step based, but the user can just manually set the angle according to above example to 179 degrees, and almost same result will be seen.

3.7.5.5 Grid curtailment and ramp-rate



In case of included grid curtailment loss in PARK calculation, this will just appear in the list as information. The Gross result transferred from PARK to Loss & Uncertainty module will be without the grid curtailment and applied as a loss afterwards. This is due to the grid curtailment being calculated independently from wakes and WTG curtailments. If grid curtailment is not included in PARK calculation, a value can be entered. This can aside from limitations in grid capacity also hold losses due to restrictions on how fast the power delivery are allowed to change, ramp-rate.

3.7.5.6 Power purchase agreement curtailment

If the power purchaser not always can take all production. This can be a quite complex calculation with several market regulation mechanisms.

3.7.5.7 Noise

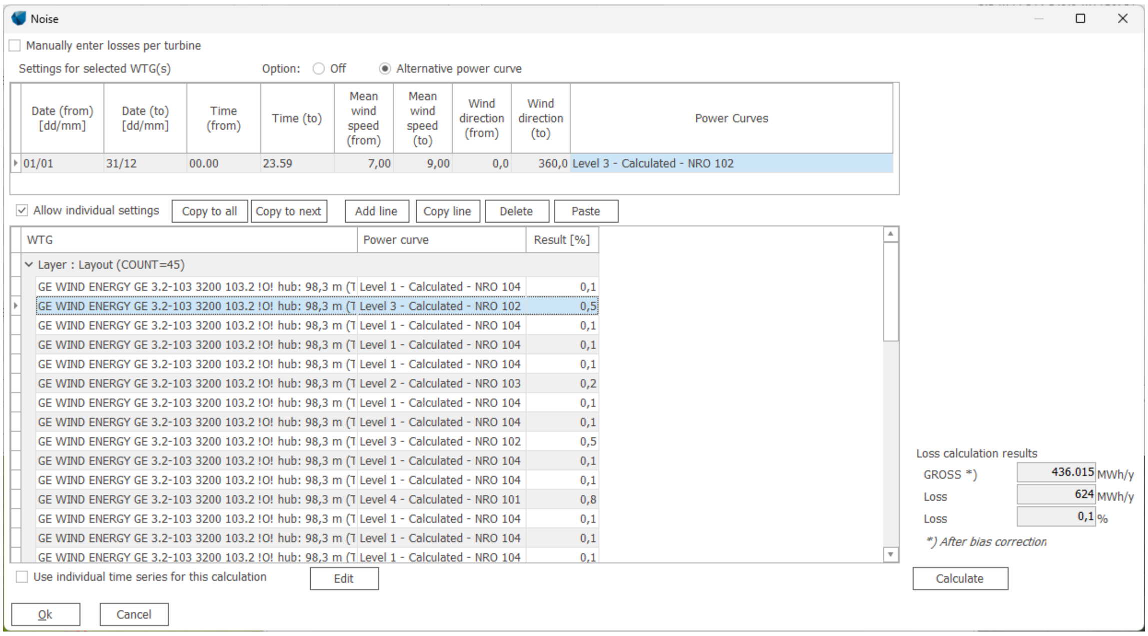


Figure 12 Input for noise loss.

Some turbines might run in noise reduced mode, maybe only within specific time of day, maybe only at certain wind directions (or combinations). Besides time and direction interval, the noise reduced power curve (or no power curve meaning full stop), can be selected. A tricky issue here is if the PARK calculation already is calculated with noise reduced power curves. In this case, there shall not be entered noise loss. So to include the noise reduced mode loss correctly, the PARK calculation must be without noise reduction, and the noise reduced modes selected here. In future version, there will be an option to treat noise reduction the same way as wake reduction, meaning the software first takes out the effect of noise reduction, and transfers the loss, where it is automatically set up. This will also include L_{den} calculations, where different settings for day, evening and night will be required. Note in the power curve selection field, there will be information telling with which power curve each turbine has been calculated.

3.7.5.8 Flicker

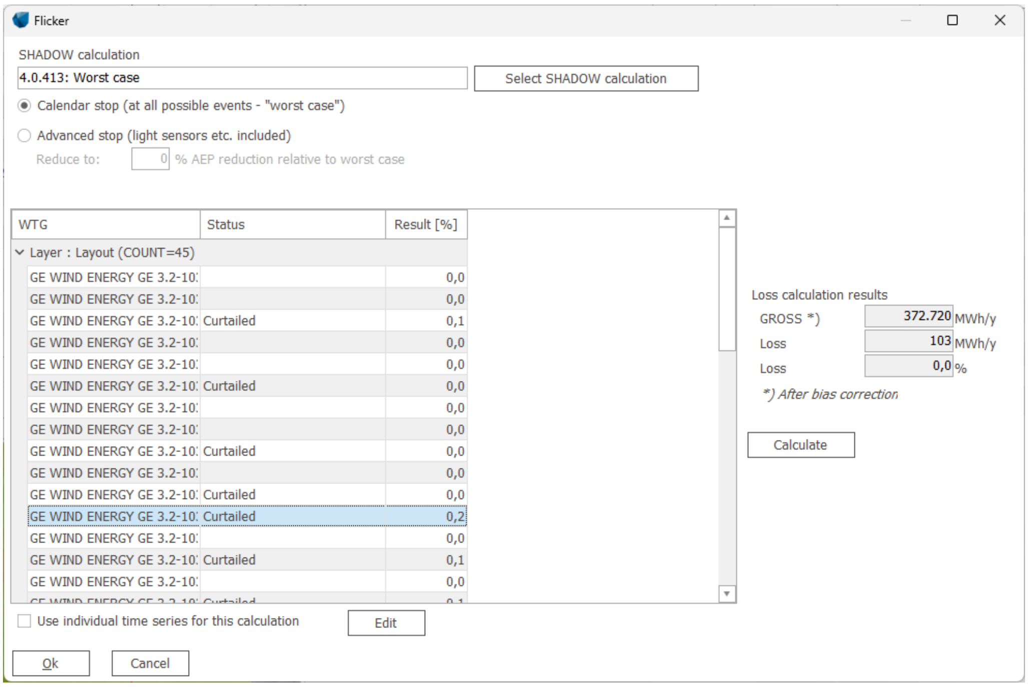


Figure 13 Setup of input for shadow flicker stops loss calculation.

Loss due to stop caused by flicker at neighbors is simple to performed. A Shadow calculation for exact the same wind farm layout as PARK calculation is based on, must be loaded. Then time step by time step it is checked if there is flicker at a neighbor and the loss due to stop within flicker time is calculated. The calculation is based on the turbine running in “calendar mode”, meaning all possible events of giving flicker is included (worst case calculation). If a more advanced flicker reduction mode is implemented, the stops will be less, and a simple reduction due to this can be entered – typically around 50%.

3.7.5.9 Bat

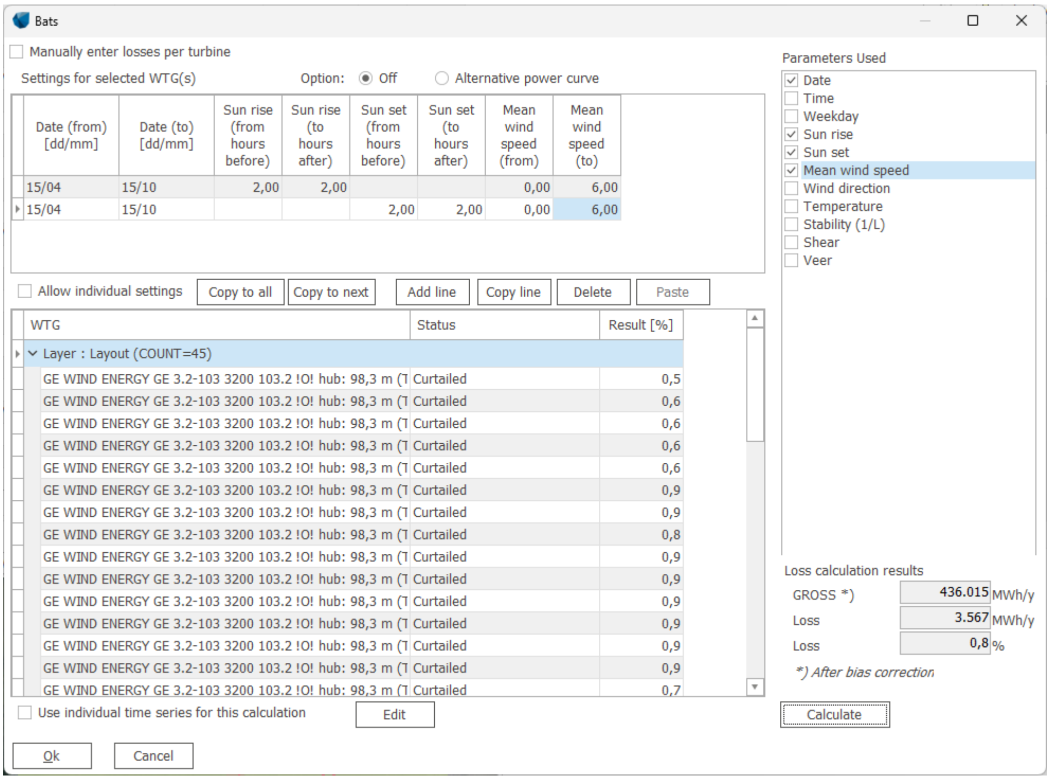


Figure 206 Setup of Bat stop loss calculation.

A special feature for calculating Bat curtailment, sunrise and sunset can be included. But note that two separate lines must be included, while conditions in one line is AND, and therefore like 2 hours before and after sunrise/set would not work if entered in the same line. The AND would eliminate the two options.

The shown setup above illustrates how a curtailment calculation is set up based on:
From 15-04-yyyy to 15-10-yyyy, 2 hours before and after as well sun set as sun rise, the turbine will be stopped if wind speed is below 6 m/s.

Note the calculation is performed based on the time varying dataset that is chosen in the setup at the main page. This should always include ONE FULL YEAR. So it is if e.g., a .wti file is generated from the Meteo analyzer. But if more years, it will still work, although note the year will be ignored, it only looks at the dates and assume same stop period each year.

Note also the wind speed checked against is SCALED to the calculated wind speed at the turbines in hub height. If the regulations refer to e.g., 10m height wind speed, the user must modify the limits, e.g., if stop demanded below 4 m/s at 10 m height, a stop below 6 m/s in turbine hub height (e.g., 80m), must be used. Example: (look in manual for details, search for “Shear”)

Shear	0,2
Height	Wmean calculated
10	**4,0**
20	4,5
30	4,9
40	5,2
50	5,5
60	5,7
70	5,8

80	6,0
90	6,1
100	6,3
110	6,4
120	6,5

The table show the wind speeds at different heights, by a typical shear of 0.2. Here having 6 m/s in 80m height. An often-seen problem although is that the authorities that set the criteria's, forget to mention for which height. Then most often it is just assumed it is for hub height.

Note if a field is entered with no value having "-" in the field, it mean "all included". If eg. Sunrise (from hours before) is set to "-" it takes all the hours before sunrise into the calculation. (From midnight).

The data for when sunrise – sunset appears is calculated based on geometry from the site center position (same formulas as used in the Shadow flicker calculation without a horizon angle threshold.)

3.7.5.10 **Other**

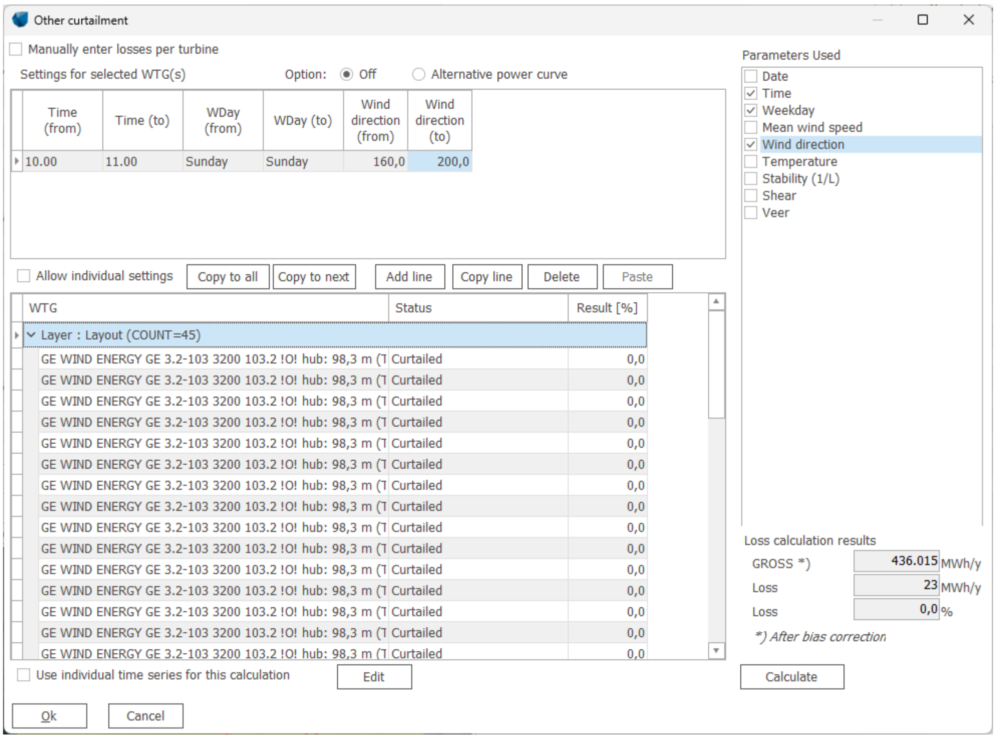


Figure 14 "Other" gives large flexibility for loss calculation depending on any parameter combination.

Using "Other" any parameters available in Meteo object or .WTI file can be used for setting up any parameter combination. In the example above, stop for the one group of turbines is every Sunday between 10:00 – 11:00 if wind direction is between 160 and 200 degrees. This could be when wind blowing towards the Church within church time.

3.7.5.11 Manual entering losses by turbine

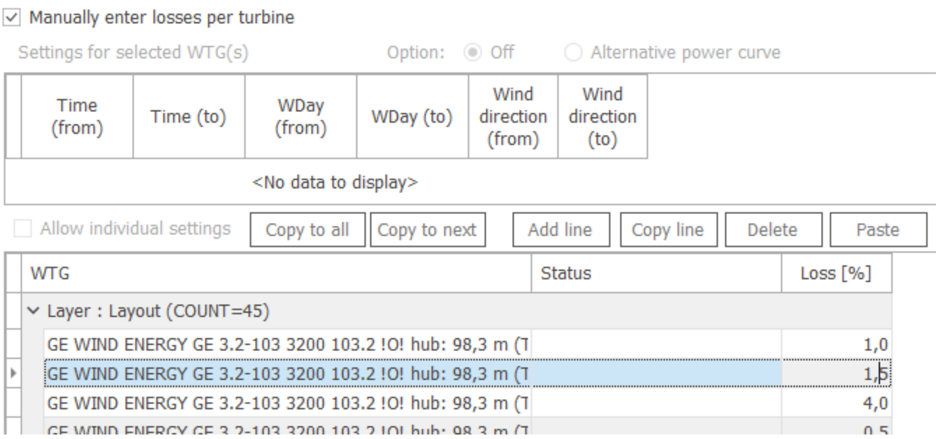


Figure 207 Checking "Manually", individual loss per turbine is entered.

For the loss types where calculation features are available, it is possible to enter losses by turbine manually. This is relevant if calculated by other tools, e.g., Icing loss calculation.

3.7.6 Uncertainty

Uncertainties are grouped in 5 groups,

A. Wind data
B. Wind MODEL
C. Power Conversion
D. Bias
E. Loss

Each of those groups must be judged, and as for bias and loss, some groups have calculation features which will be described in separate chapters. In later versions, more calculation features will be implemented.

Before going to the calculation features, the Wind data group will be explained, while this is one of the more important ones.

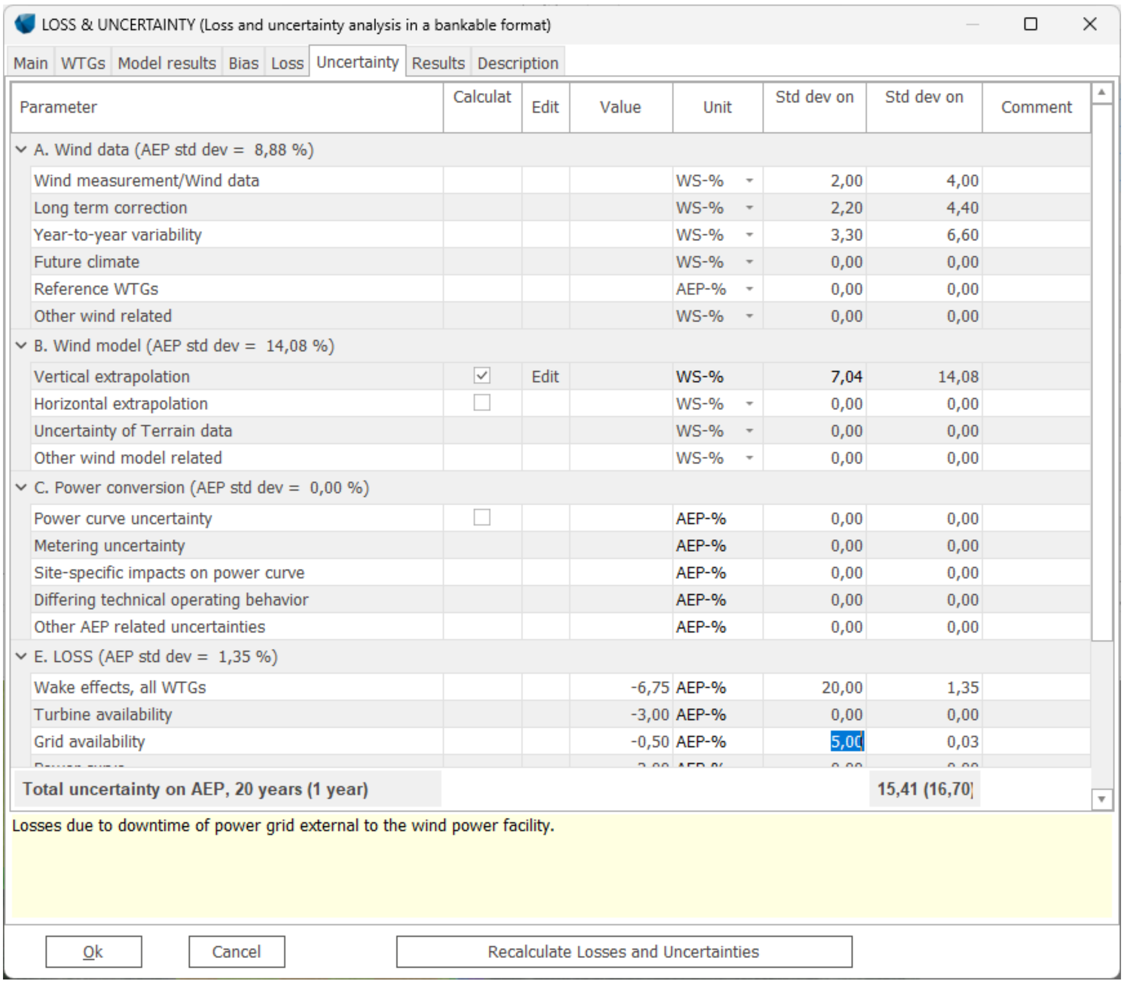


Figure 15 The five uncertainty groups A-E.

For category E all lines with a loss entry is shown.

3.7.6.1 Wind data uncertainty

Wind data can be used in the PARK calculation in different ways:

- Measurements on site, typically along with a long-term correction.
- A wind statistic for the region, possibly verified/calibrated based on performance from existing turbines in the region.
- A wind resource map, based on a model, like mesoscale model, CFD model or WAsP model – behind the wind resource map there will be wind data, that can be based several different sources.

To judge the quality of the wind data is probably the most essential part of the uncertainty evaluation. If turbines with longer operation period (>1y) exists in the region, a test calculation with the used wind data is one of the best ways to reduce uncertainty of the wind data basis. It is essential that the production from these turbines is properly long term corrected and cleaned for availability problems. If the actual cleaned production from those can be reproduced accurately, the uncertainty on the wind data can be assumed small.

If only local measurements are available, the uncertainty depends much on measurement equipment, mast configuration, sensor calibration and quality. Long term correction is normally a must, but here additional uncertainties are introduced, while the long term sources often are of poor quality, and might even be trended, if e.g., trees has grown up around the reference mast of if it is modeled data there might be trends due to changes in the data basis for the model. Such trends should NOT be considered just as an uncertainty, but should be corrected for up front or included as bias correction.

Even with high quality data, the wind measurement uncertainty should not be assumed lower than 2% on wind speed - an “upper limit” is difficult to give. If it is a low wind site, the wind speed uncertainty converted to AEP uncertainty can be as high as 3 times the wind speed uncertainty, while it at a high wind site only will be 1,5 times the wind speed uncertainty.

A specific source of uncertainty is the position on the measurement mast. If the mast location is in a hilly environment, it is crucial that the position is correct, and that the elevation information around the mast is accurate. It is often seen that measurement masts are placed on a small hill top. If the elevation data are rough, the little hilltop is not included in the data and an error is introduced when cleaning the data based on orography. This is not an uncertainty but an error that must be handled by establishing the elevation data round the mast in a correct way. Photomontage tool should be used to verify that the elevation data round the mast is correctly established. If the mast position is uncertain, this should be included in uncertainty, for instance in “Other wind related”.

Long term expectations might be the component within the wind data group with highest uncertainty. It is therefore important to understand how the composition of this part should be established.

In the input forms, there are 3 different input fields related to this topic:

- Long term correction
- Year–to-year variability
- Future climate

3.7.6.2 Long term correction

Here the uncertainty based on the facts used in the long-term correction, typically performed with the MCP module shall be entered. From 3.2 there are implemented an uncertainty calculation, the “Klintø model” which is based on studies of many data series, finding which parameters decides the uncertainty. See details in MCP chapter.

3.7.6.3 Year-to-year variability

The figure entered here is decides how the 1,5,10, 20 year uncertainty is calculated. It tells how much the wind varies from year to year in the specific region. A typical value is **around 6% on wind speed,** but several sources are available at the Internet giving more specific regional variations. In the MCP module, the variability is calculated based on the long term reference used. The variability entered is used for the 1-year calculated uncertainty, while the 5 year then is the σ_{1y}/sqrt(5) etc. So the 20y variability uncertainty is the σ_{1y}/sqrt(20). E.g., for σ_{1y} = 6%: 6%/sqrt(20) = 1,3% (on wind speed, which converts to AEP% depending on wind speed level). It is important to be aware of that the variability tells about the fluctuations within few years, not the very long term variations seen in e.g., Northern Europe described by the NAO index (North Atlantic Oscillations). This is handled separately in the “future climate” input field.

3.7.6.4 Future climate

E.g., in Northern Europe, we have seen large variations during the 30 year 1980-2009 of modern turbine operation in Denmark. While 1986-95 (10y) were 8% above long term average measured in AEP, 1996-2006 (11y) were 5% below long term average. This illustrates well that 10 year for sure is too short a period to use as long term, and that there are climate variations that no one can predict. So far it seems that the variations in wind climate are not related direct to global warming etc. The slow variations have been seen for 150 years (e.g., by the North Atlantic Oscillation); going up and down, but not trending towards more or less wind. Prediction the future 20y wind is a hard task that no one really can do. So to assume an uncertainty around 1-3% on wind speed due to future climatic variations seems appropriate – at least for Northern Europe – other parts in the world have similar variations, some has not. This should be studied region by region.

3.7.6.5 Reference WTGs

Option to account for calibration of wind based on reference WTGs.

3.7.6.6 Model uncertainty

3.7.6.6.1 Vertical extrapolation

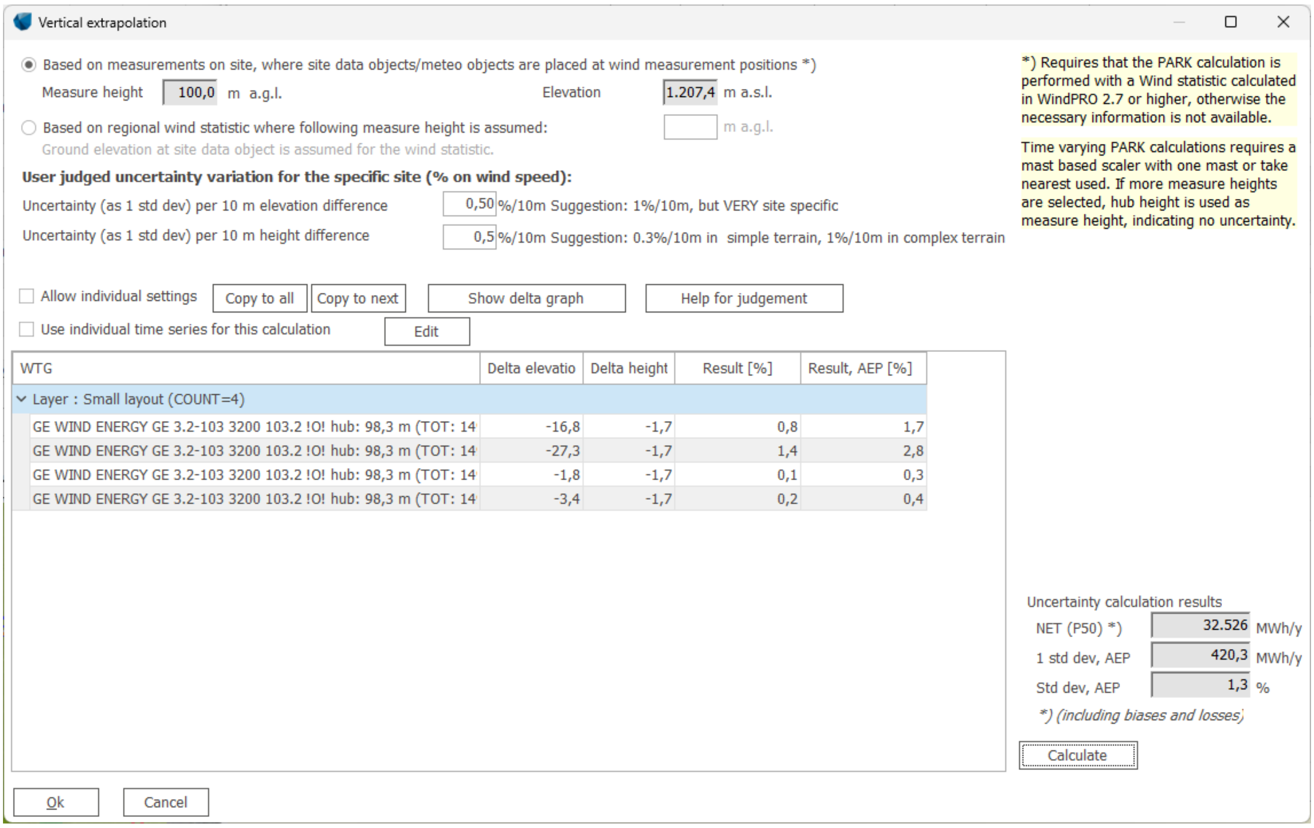


Figure 16 Input for vertical extrapolation uncertainty calculation.

The vertical extrapolation uncertainty is divided into the uncertainty due to elevation (above sea level) difference and difference between mast height and turbine height (above ground level).
The proposals given for the uncertainty is based on different studies, but can be very site dependent. The best way to get a reasonable basis for the judgment is if there are more masts at the site, the cross prediction accuracy can give an idea on the uncertainty.

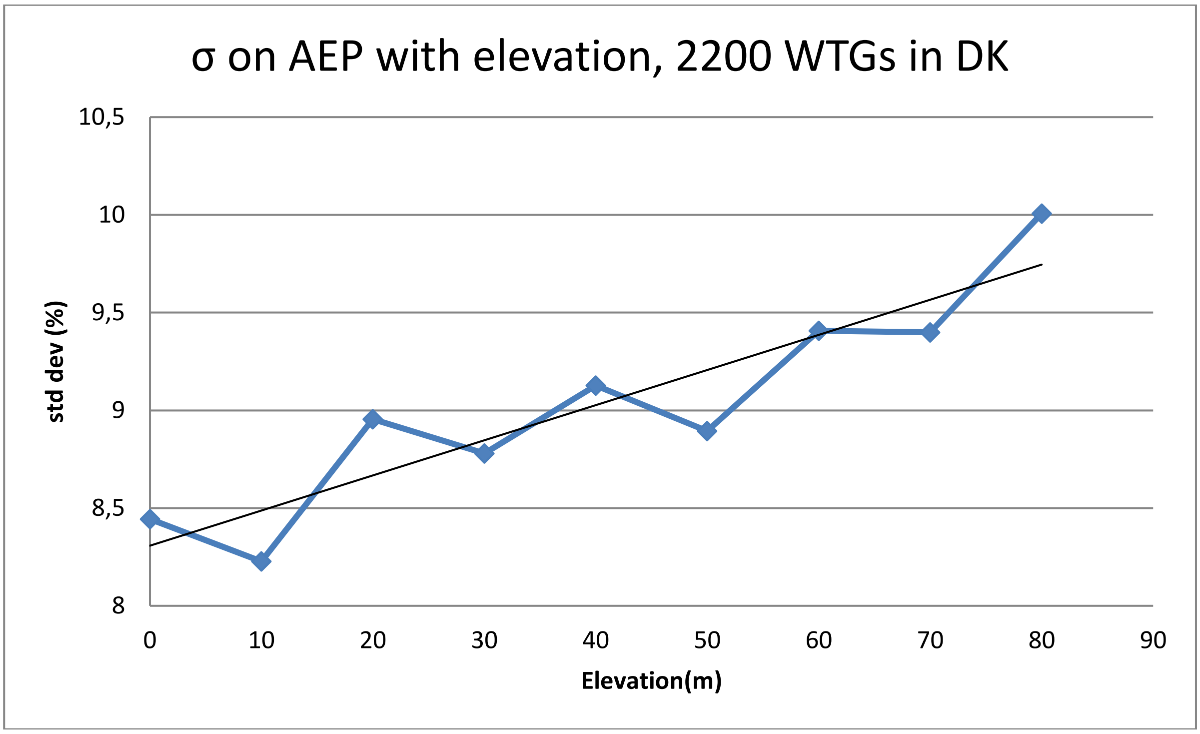


Figure 17 A large number of calculations in Denmark suggest a linear relationship between uncertainty and increased elevation in non-complex terrain.

For the DK example above, it is important to emphasize that it is actually the absolute elevation that is shown. But in the Danish landscape the elevation difference is linked to the absolute elevation as the typical data basis is based at low elevation. Therefore, the figure indicates an increased uncertainty with increased elevation difference. Several other studies come up with similar findings. If the terrain is very complex, a RIX correction might have been performed. In this case the elevation difference uncertainty will be lowered.

The recommendations written in the input fields are intended to give an idea for input of uncertainty, but as terrain types vary very much from site to site, also the uncertainties vary similarly much. The best way is always to have more measurement mast at site and use the cross prediction tool in Meteo Analyzer to help give more precise indications of the uncertainty of the wind model.

3.7.6.6.2 Horizontal extrapolation

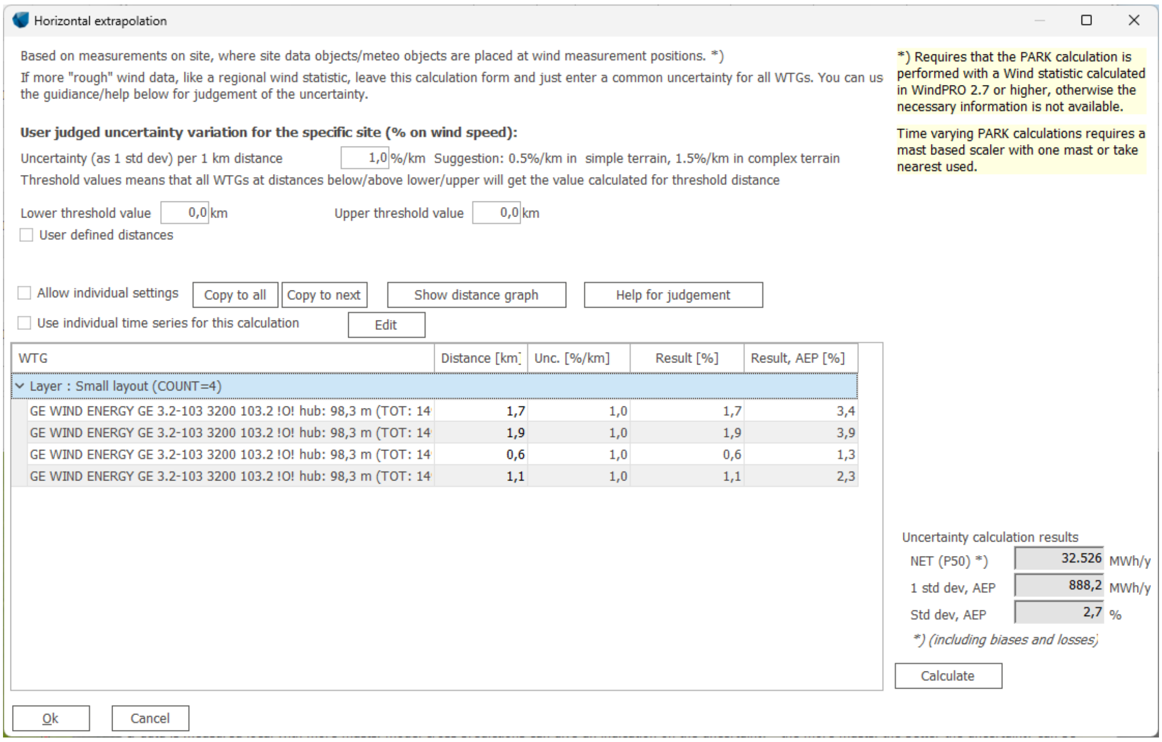


Figure 18 Input for horizontal extrapolation uncertainty calculation.

This calculation is similar to the vertical extrapolation. The critical issue is to judge the distance dependency of the uncertainty. An upper threshold value will normally be reasonable to use, while the uncertainty does not just continue to increase with distance. As for the vertical uncertainty, cross prediction based on more masts will be the best way to establish a basis for the judgments of uncertainty versus distance.

3.7.6.7 Uncertainty of terrain data

Makes it possible to account for partly the complexity of the terrain, partly the quality of the terrain data.

3.7.6.8 Power conversion uncertainty

Power curve uncertainty will often be found in the reports from power curve measurements. But please note that these will typically give very high uncertainty estimates, which might not be fair. Often power curves are measured on more turbines of the same type at different locations and the manufactures then perform their best judgments/averaging of more measurements to reduce their risk. This will reduce the uncertainty. A simple input can be given as illustrated above like a detailed input requiring input in the WTG Catalogue can be used. It is our hope to get the uncertainty included for the most power curves in future, but it will probably take some time before these are available – at least the structures are ready now.

3.7.6.8.1 Power curve uncertainty

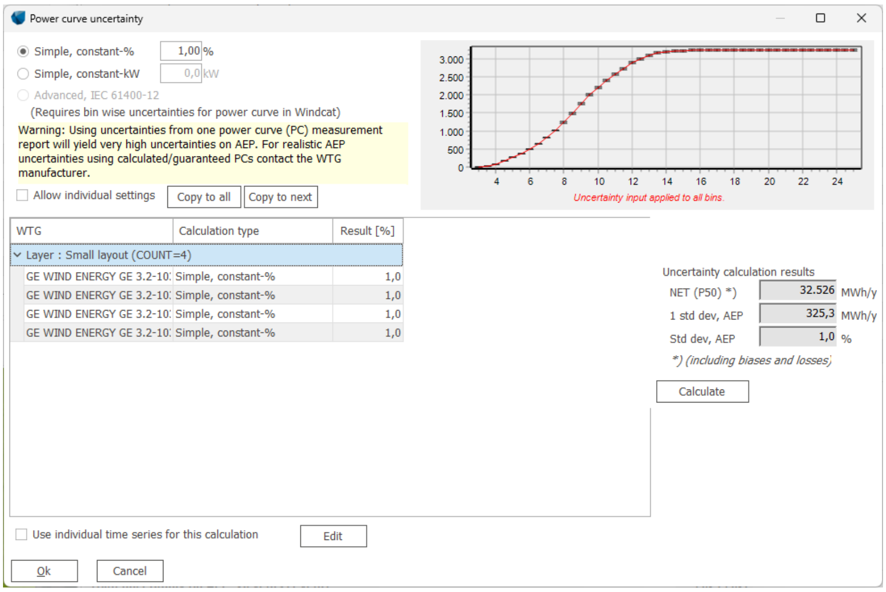


Figure 19 Input for power curve uncertainty calculation.

3.7.6.9 Bias uncertainty

For each bias component the user attributes a value, the uncertainty on this value can (and should) be set as well. Note that the entered uncertainty estimate is multiplied by the bias value, so if e.g., a bias is set to 5% with an uncertainty of 10% on that value, the resulting uncertainty is 0,5% on AEP resulting from that component.

3.7.6.10 Loss uncertainty

For each loss component included with a value, the uncertainty should also be set by the user. Note that the estimate is multiplied with the loss value-. A loss of e.g., 5% with an uncertainty of 10%, results in an uncertainty on AEP of 0,5% due to that loss component.

3.7.7 Results

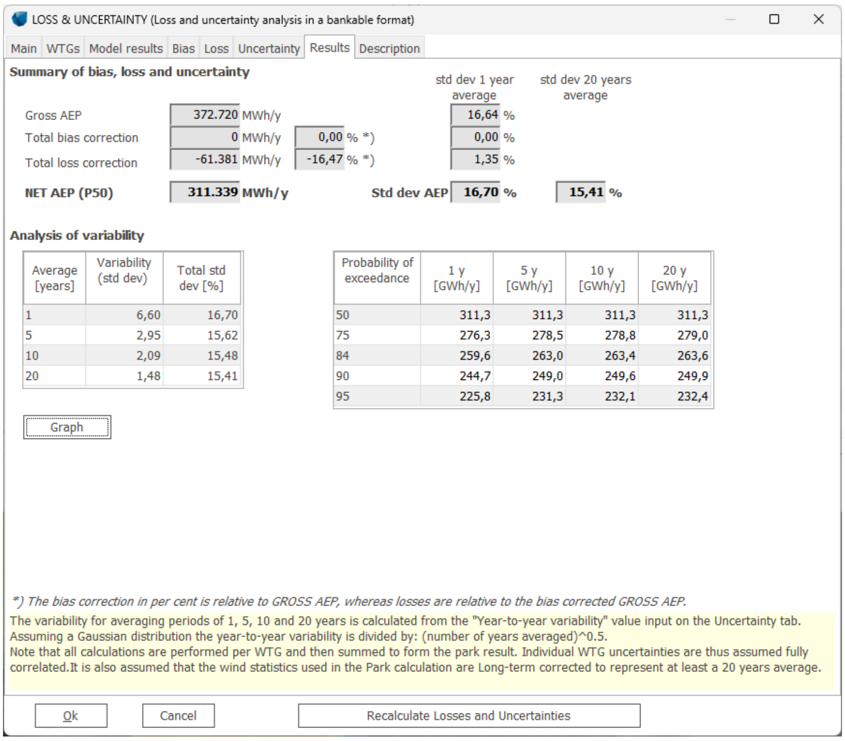


Figure 20 Evaluation of results.

On the Results sheet to the lower right presents results for 1, 5, 10 and 20 years of averaging (i.e. life time) and at several probabilities of exceedance values (50%, 75%, 84%, 90% and 95%).

3.7.7.1 Sum of WTG P-values differ from PARK P-values

If and only if the total loss (in percent) of each WTG and the total park loss are identical the WTG P50s will sum up to the PARK P50.

However, if some WTGs have significantly different losses (usually due to wake effects) the sum of the WTG P50s will NOT add up to the PARK P50.

But why is it necessary to have both methods then?
Because we need consistency across P50, P90 etc. – and the WTG P90s will never add up to the PARK P90 as they are the result of a non-linear statistical model. Hence, either the calculation of P50, P90 etc. is done on a park level OR on WTG level – what is correct depends on if the project is sold/developed as a whole or individual WTGs.

3.7.8 Calculation and print

3.7.8.1 Main result

Project:
Aparados da Serra basic project

Description:
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pmn / pmn@emd.dk
Calculated:
01/09/2023 20.49/4.0.413

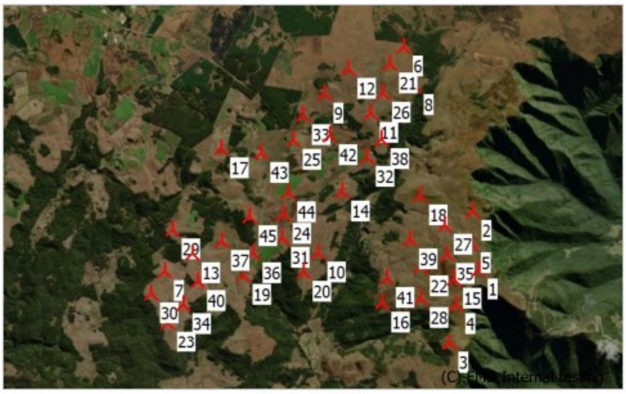
Loss & Uncertainty - Main result

Calculation: TV / short measured data / WAsP-CFD / curtailed

Main data for PARK

PARK calculation 4.0.412: TV / short measured data / WAsP-CFD / curtailed

Count	45
Rated power	144,0 MW
Mean wind speed	7,2 m/s at hub height
Sensitivity	2,0 %AEP / %Mean Wind Speed
Expected lifetime	20 Years



Scale: 125.000

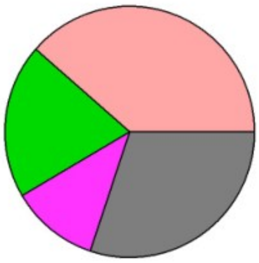
RESULTS

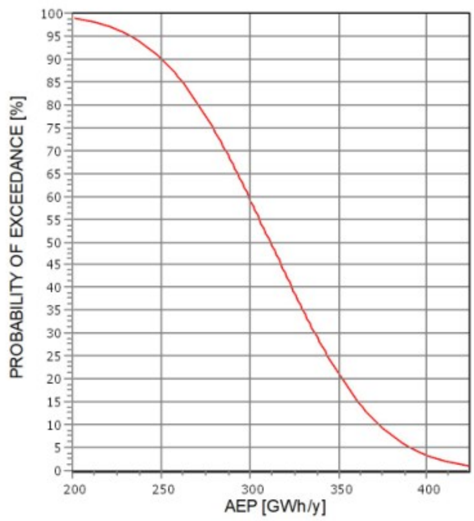
		P50	P84	P90
NET AEP	**[GWh/y]**	**311,3**	**263,6**	**249,9**
Capacity factor	[%]	24,7	20,9	19,8
Full load hours	[h/y]	2.162	1.831	1.735

Result details

	P50		Uncertainty
GROSS AEP *)	372,7 GWh/y		15,4 %
Bias correction	0,0 GWh/y	0,0 %	0,0 %
Loss correction	-61,4 GWh/y	-16,5 %	1,4 %
Wake loss		-6,8 %	
Other losses		-10,4 %	
NET AEP	**311,3 GWh/y**		**15,4 %**

Loss: 16,5 %





Uncertainty: 15,4 %

*) Calculated Annual Energy Production before any bias or loss corrections
Assumptions: Uncertainty and percentiles (PXX values) are calculated for the expected lifetime

windPRO 4.0.413 by EMD International A/S, Tel. +45 69 16 48 50, www.emd-international.com, support@emd.dk 01/09/2023 20.50 / 1

Figure 21 The printout of main result gives an overview of all results as a table and as graphics.

3.7.8.2 Assumptions and results

Project:
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Calculated:
01/09/2023 20.49/4.0.413

EMD International

Loss & Uncertainty - Assumptions and results

Calculation: TV / short measured data / WAsP-CFD / curtailed

ASSUMPTIONS

LOSS

		Method *)	Loss [%]	Loss [GWh/y]	Std dev**) [%]	Comment
1.	Wake effects					
	Wake effects, all WTGs	Calculation	6,8	25,2	20,0	
2.	Availability					
	Turbine availability	Estimate	3,0	11,2	0,0	
	Grid availability	Estimate	0,5	1,9	5,0	
3.	Turbine performance					
	Power curve	Estimate	2,0	7,5	0,0	
4.	Electrical					No input
5.	Environmental					No input
6.	Curtailment					
	Wind sector management	Calculation	0,2	0,8	0,0	
	Noise	Calculation	0,0	0,1	0,0	
	Flicker	Calculation	0,0	0,1	0,0	
	Bats	Calculation	0,0	0,0	0,0	
	Other curtailment	Estimate	5,0	18,6	0,0	
7.	Other					No input
	LOSS, total		**16,5**	**61,4**	**1,4**	

UNCERTAINTY

		Method *)	Std dev, wind speed [%]	Std dev, AEP [%]	Comment
A.	Wind data				
	Wind measurement/Wind data	Estimate	2,0	4,0	
	Long term correction	Estimate	2,2	4,4	
	Year-to-year variability	Estimate	3,3	6,6	
	Future climate				
	Reference WTGs				
	Other wind related				
B.	Wind model				
	Vertical extrapolation	Calculation	7,0	14,1	
	Horizontal extrapolation				
	Uncertainty of Terrain data				
	Other wind model related				
C.	Power conversion				
	Power curve uncertainty				
	Metering uncertainty				
	Site-specific impacts on power curve				
	Differing technical operating behavior				
	Other AEP related uncertainties				
D.	BIAS, total uncertainty			0,0	
E.	LOSS, total uncertainty			1,4	
	UNCERTAINTY, total (1y average)			16,7	
	UNCERTAINTY, total (20y average)			**15,4**	

VARIABILITY

Years	Variability (std dev) [%]	Total std dev [%]
1	6,60	16,7
5	2,95	15,6
10	2,09	15,5
20	1,48	**15,4**

RESULTS

AEP versus exceedance level / time horizon

PXX [%]	1 y [MWh/y]	5 y [MWh/y]	10 y [MWh/y]	20 y [MWh/y]
50	311.339	311.339	311.339	311.339
75	276.272	278.535	278.829	278.977
84	259.637	262.974	263.407	263.625
90	244.711	249.011	249.569	249.851
95	225.823	231.342	232.059	232.420

Figure 22 Second report page collect all input data on 1-2 pages. Also the detailed result matrix will be shown at the bottom of this page (not shown here).

3.7.8.3 WTG results

Project:
Aparados da Serra basic project

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Calculated:
01/09/2023 20.49/4.0.413

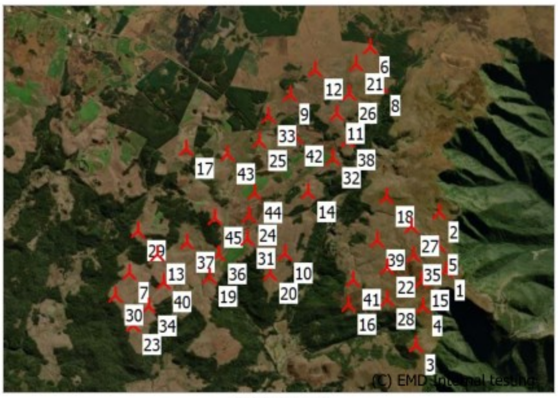
EMD International

Loss & Uncertainty - WTG results

Calculation: TV / short measured data / WAsP-CFD / curtailed

Main data for PARK

PARK calculation 4.0.412: TV / short measured data / WAsP-CFD / curtailed
Count 45
Expected lifetime 20 Years
Mean wind speed 7,2 m/s at hub height
Rated power 144,0 MW
Sensitivity 2,0 %AEP / %Mean Wind Speed



Scale: 125.000

Expected AEP per WTG including bias, loss and uncertainty evaluation

	Description	Calculated GROSS*)	Bias	Loss	Unc.	20 years averaging P50 **)	P84	P90
		[MWh/y]	[%]	[%]	[%]	[MWh/y]	[MWh/y]	[MWh/y]
	PARK	**372.719,5**	**0,0**	**16,5**	**15,4**	**311.338,9**	**263.625,3**	**249.850,6**
1	GE WIND ENERGY GE 3.2-103 3200 103.2 !O! hub: 98,3 m (TOT: 149,9 m) (1075)	9.561,4	0,0	17,1	13,4	7.922,8	6.870,2	6.566,3
2	GE WIND ENERGY GE 3.2-103 3200 103.2 !O! hub: 98,3 m (TOT: 149,9 m) (1078)	9.032,3	0,0	14,5	13,9	7.725,1	6.654,4	6.345,3
3	GE WIND ENERGY GE 3.2-103 3200 103.2 !O! hub: 98,3 m (TOT: 149,9 m) (1079)	9.298,7	0,0	13,2	13,7	8.071,5	6.969,9	6.651,9
4	GE WIND ENERGY GE 3.2-103 3200 103.2 !O! hub: 98,3 m (TOT: 149,9 m) (1081)	8.477,6	0,0	15,9	12,8	7.129,7	6.220,1	5.957,5
5	GE WIND ENERGY GE 3.2-103 3200 103.2 !O! hub: 98,3 m (TOT: 149,9 m) (1082)	8.795,1	0,0	17,2	14,1	7.283,0	6.264,2	5.970,1

Figure 23 This page show results turbine by turbine, thereby the needed details for projects sold turbine by turbine are available.

3.7.8.4 Detailed results

For each "calculation option" a separate report is available. These describe the calculation setup and partly the data basis. Only one sample is given below. These reports can be quite detailed.

Project:
Aparados da Serra basic project

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01/09/2023 20.49/4.0.413

EMD International

Loss & Uncertainty -

Calculation: TV / short measured data / WAsP-CFD / curtailed

Calculated losses due to shadow (flicker) loss.

Used SHADOW calculation: 4.0.413: Worst case

Assumptions:
Calendar stop (at all possible events - "worst case")

Result

WTG	Calculated AEP GROSS [MWh]	Loss [MWh]	Percent of AEP [%]
GE WIND ENERGY GE 3.2-103 3200 103.2 !O! hub: 98,3 m (TOT: 149,9 m) (1075)	9.561,4	0,0	0,00
GE WIND ENERGY GE 3.2-103 3200 103.2 !O! hub: 98,3 m (TOT: 149,9 m) (1078)	9.032,3	0,0	0,00
GE WIND ENERGY GE 3.2-103 3200 103.2 !O! hub: 98,3 m (TOT: 149,9 m) (1079)	9.298,7	5,4	0,06
GE WIND ENERGY GE 3.2-103 3200 103.2 !O! hub: 98,3 m (TOT: 149,9 m) (1081)	8.477,6	0,0	0,00
GE WIND ENERGY GE 3.2-103 3200 103.2 !O! hub: 98,3 m (TOT: 149,9 m) (1082)	8.795,1	0,0	0,00
GE WIND ENERGY GE 3.2-103 3200 103.2 !O! hub: 98,3 m (TOT: 149,9 m) (1083)	8.353,3	2,3	0,03
GE WIND ENERGY GE 3.2-103 3200 103.2 !O! hub: 98,3 m (TOT: 149,9 m) (1085)	8.344,2	0,0	0,00
GE WIND ENERGY GE 3.2-103 3200 103.2 !O! hub: 98,3 m (TOT: 149,9 m) (1086)	8.843,7	0,0	0,00
GE WIND ENERGY GE 3.2-103 3200 103.2 !O! hub: 98,3 m (TOT: 149,9 m) (1087)	8.892,5	2,4	0,03
GE WIND ENERGY GE 3.2-103 3200 103.2 !O! hub: 98,3 m (TOT: 149,9 m) (1089)	8.383,8	0,0	0,00
GE WIND ENERGY GE 3.2-103 3200 103.2 !O! hub: 98,3 m (TOT: 149,9 m) (1090)	8.545,7	3,8	0,05
GE WIND ENERGY GE 3.2-103 3200 103.2 !O! hub: 98,3 m (TOT: 149,9 m) (1092)	8.862,8	15,5	0,17
GE WIND ENERGY GE 3.2-103 3200 103.2 !O! hub: 98,3 m (TOT: 149,9 m) (1093)	8.289,3	0,0	0,00

Figure 24 Flicker stop loss is shown with losses for for each turbine can be seen.

3.8 Appendix: Wake model tests and validations

3.8.1 Test of calculated wake loss on varying wind farm sizes

A good way to compare wake models (verification) is to see how the calculated wake loss changes by wind farm size.
Here we show a calculation setup, with a square layout with 7 RD spacing based on a large WTG, the Vestas 8 MW V164 with 100m hub height offshore. Then from 3 x 3 up to 31 x 31 rows (961 WTGs) are tested. This will reveal how the different models compare.

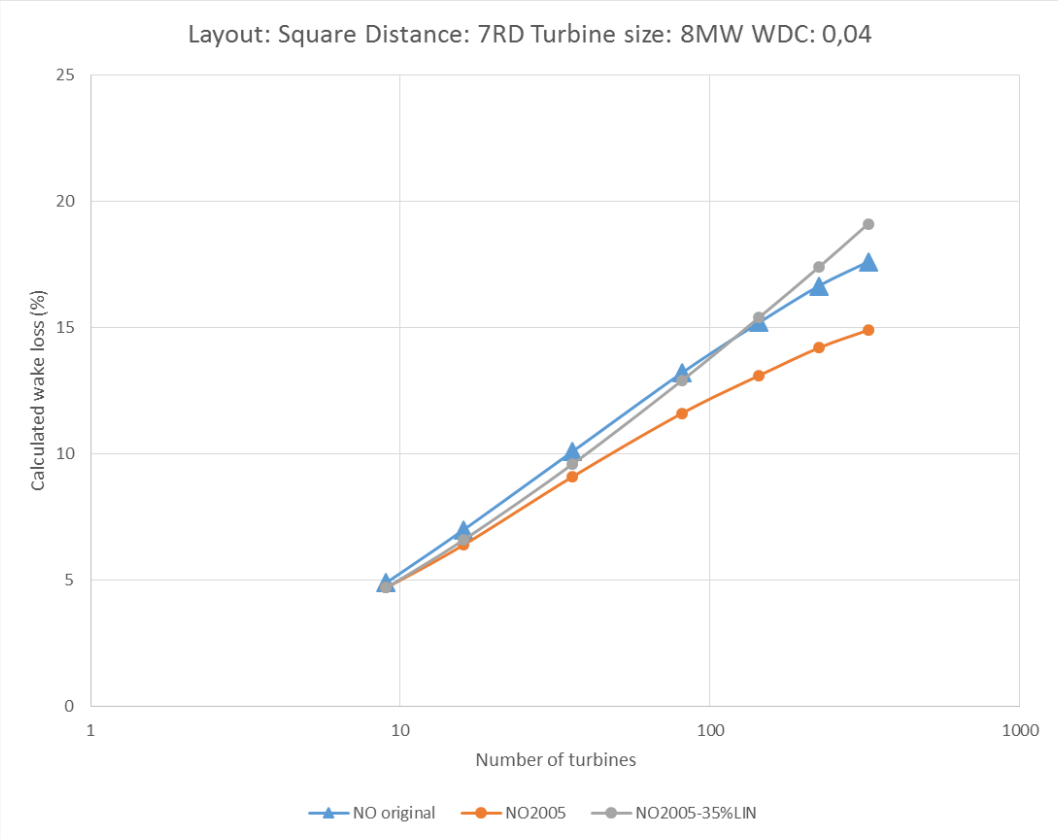


Figure 208. The development of calculated wake loss by wind farm size. NO2005 test.

Using a logarithmic x-axis, the calculated wake loss increases almost linearly with wind farm size when spacing is kept constant.

For small wind farms (< 20 turbines), the three variants calculate almost identical results. The deviations increase as project size increases.

By the time the project reaches 100 turbines, the NO2005 calculates around 2% more AEP than the original N.O. Jensen model. At 250 turbines, this increases to 3%, showing some issues with this model variant for large wind farms.

Using a linear weight of 35% in the NO2005 combination model, brings the result closer to the original N.O. Jensen model and AEP deviations are less than +/- 1%. Mirror wake is used in NO2005 in the figure above.

3.8.1.1 Extended test including PARK2, WakeBlaster and Ainslie DAC.

In earlier windPRO versions (< 3.0) the NO2005 was the only wake model for time step calculations. Now multiple wake models can be used for time step calculations.

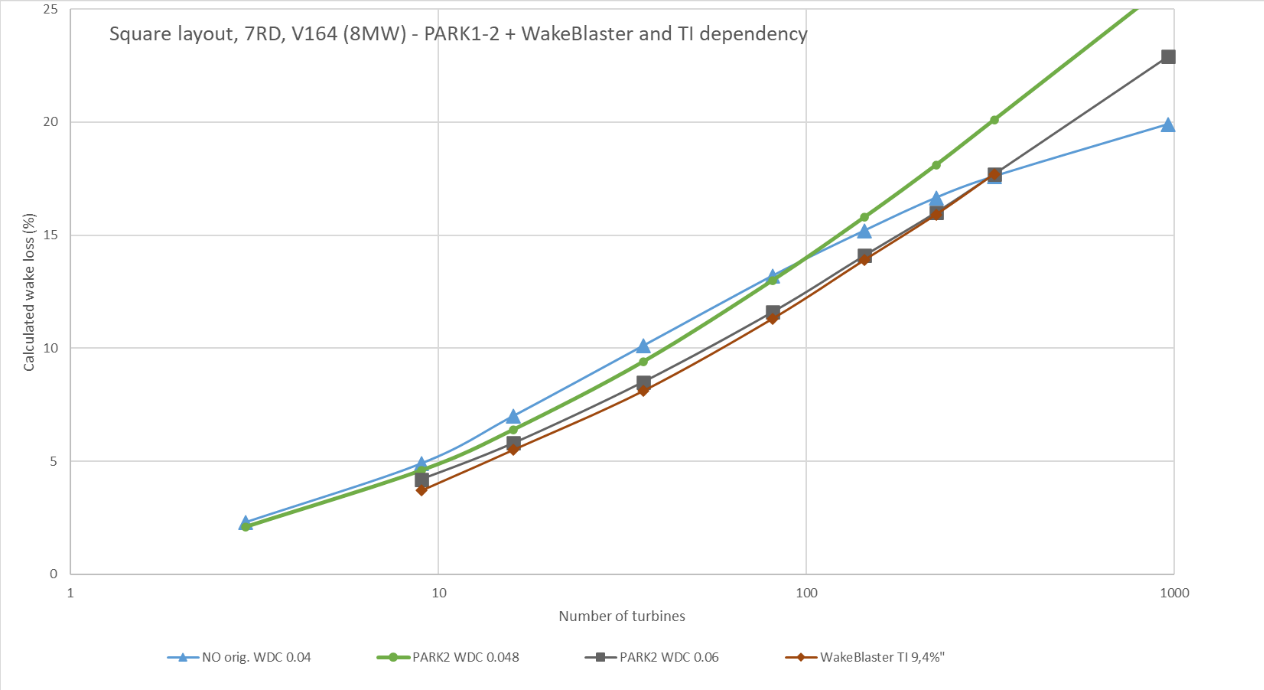


Figure 209 Park 1&2 and WakeBlaster test by wind farm size.

Increasing wind farm size from 3 to 961 WTGs and calculating wake losses for the same layout, is illustrated above for the N.O. Jensen variants + WakeBlaster. A very good agreement is seen. The impact of the WDC choice is seen for PARK2, where the WDC 0.06 (DTU recommendation for offshore) is compared to the lower 0.048 (low TI site). The low TI site shows around 1 percentage point higher calculated wake losses for medium size and 2-3 percentage points higher wake losses for large wind farm sizes. The original N.O. Jensen (PARK1) does have a slight "saturation" with very large wind farm sizes. This has been seen as a problem, which did require some deep array correction for very large wind farms, e.g., the Zafarana wind park in Egypt with 700 WTGs, but this is also seen at e.g., Horns Rev area, where PARK2 handles the wake loss calculation better than PARK1. PARK2 and WakeBlaster almost fully agree in the test. Here WakeBlaster is run with slightly higher TI which explains why it calculates slightly lower wake loss than PARK2.
PARK1&2 almost agree for up to 100 WTGs, which is good as PARK1 has been the most used and recognized wake model in the most recent 30+ years.

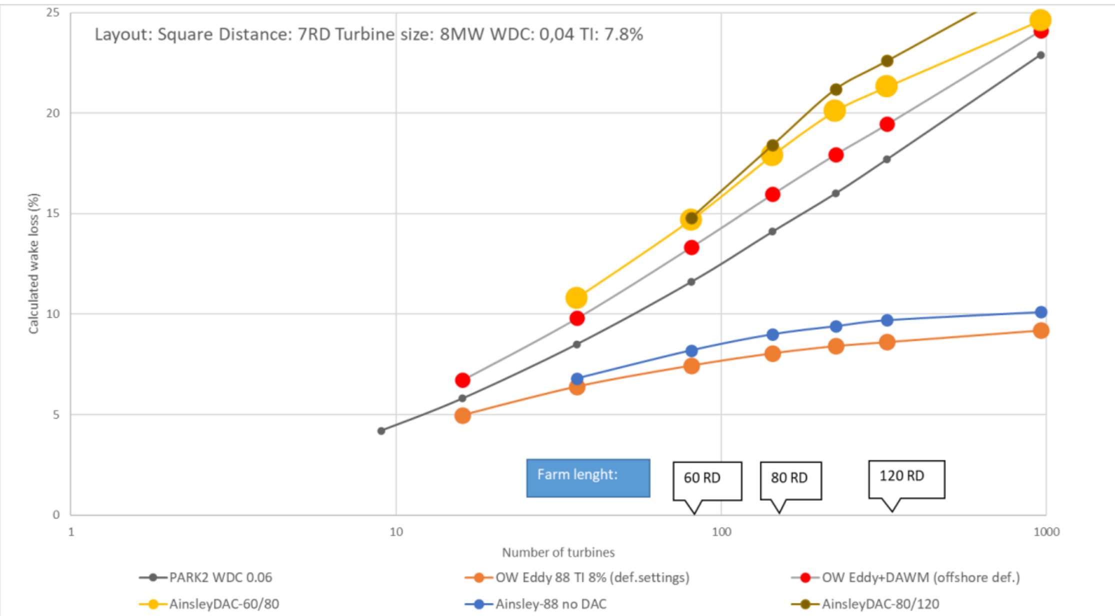


Figure 210 Ainslie in Open Wind and windPRO test by wind farm size.

Above, the new windPRO Ainslie 1988 and DAC implementation is compared to Openwind from UL similar models. This leaves no doubt that the Ainslie as a "stand alone" won't work, even just for 6 x 6 row wind farm; it needs a deep array correction model.

The windPRO and Openwind implementations agree well, although a little higher wake loss is calculated by windPRO. However, there are many parameter options both in windPRO and in Openwind, so the differences are just a matter of default choices. Later validation examples for Horns Rev wind farms and other show that the higher calculated wake loss by Ainslie 1988 is related to the large WTG size (8MW) used in this example. For smaller turbines 2-3 MW, there are better agreements also with PARK2.

For the very large wind farms, the recovery zone settings make a difference in the windPRO Ainslie 1988 implementation. In the chart above there are two series of Ainslie with DAC using different recovery zone settings: “Ainslie DAC-60/80” and “Ainslie DAC-80/120”. It can be observed that the flattening of wake losses as the wind farm size increases gets delayed when increasing the recovery zone from 60/80 RD to 80/120 RD. Where and if this flattening of wake loss shall occur, no recommendations are given.

Some of the tests presented in this chapter will illustrate how the deep array settings perform. This manual chapter concludes that deep array effects are actually more a question of using the correct turbulence. But still, for tuning wake models for post construction evaluations, the so-called deep array effects still can be relevant. Especially if using the Ainslie model as a “stand alone” there is a high underestimation of the wake reductions in the “deep” arrays.

3.8.2 Single row versus multiple row wind farms

A special problem to pay attention to is the single row vs multiple row projects. For single row projects, the wake models tend to estimate too high wake losses for backrow turbines. The simple explanation is that undisturbed wind is fed in from the sides along the row, reducing the actual wake loss. In actuality, it is typically seen that the backrow turbines have similar losses to the second-row turbines, while the wake models instead increase the wake losses with the number of upwind turbines. An example is illustrated below:

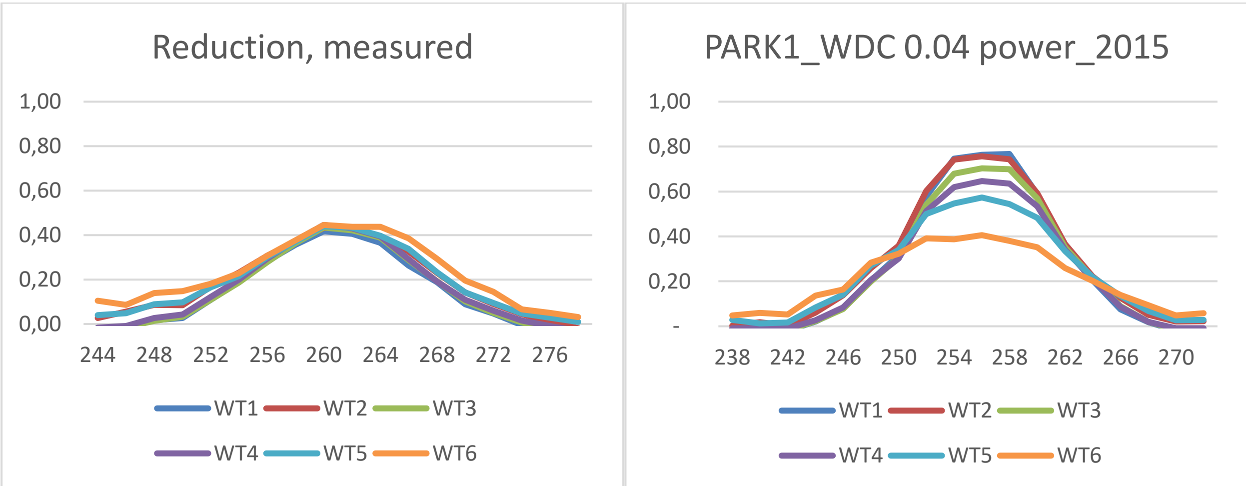


Figure 211 Measured left, calculated reductions by PARK1 (org. N.O. Jensen) right. (by direction).

WTG 6 is the upwind turbine, with just one wake turbine in front (WTG7). X-axis shows direction (degrees). Note the measurements show almost the same reductions (Power%) for all six wake-affected turbines. Calculations show essentially larger decreases in centre angles and by a number of upwind turbines.

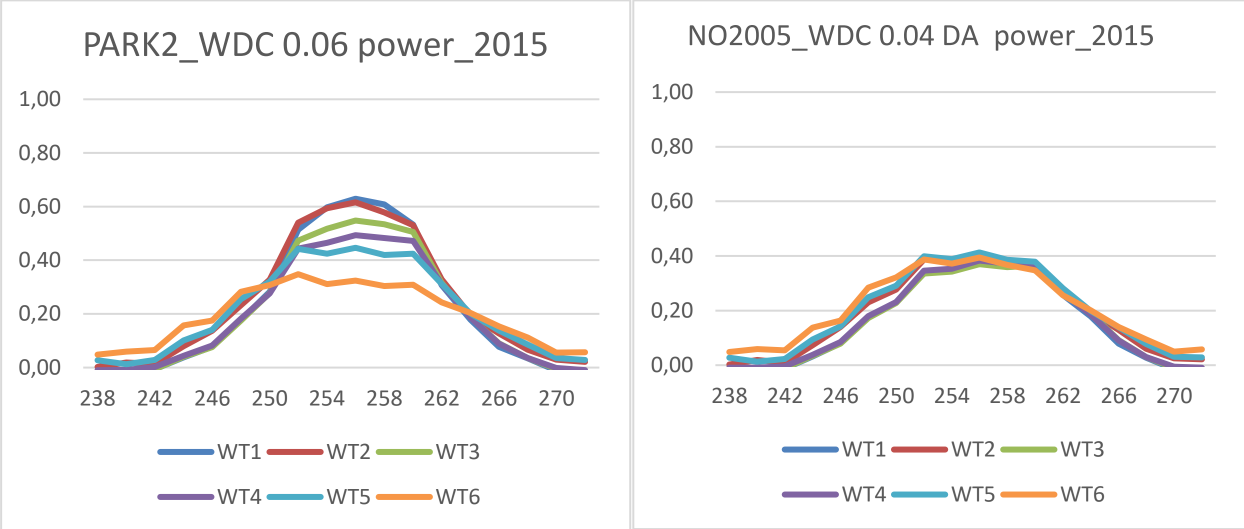
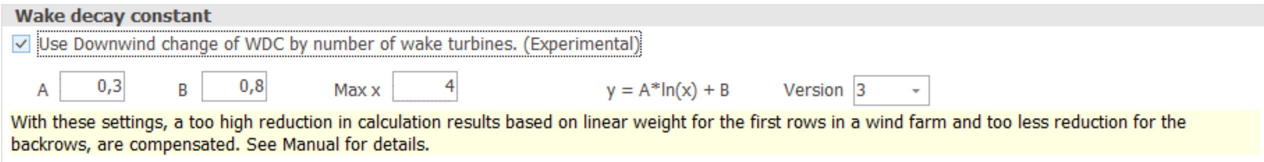


Figure 212 Calculated reductions by PARK2 left and by NO2005 with DA, right.

With PARK2 it looks better, but the only real way to solve the single row calculation problem in this example is to increase WDC by number of upwind turbines using the deep array settings in NO2005.
In the calibrated version above to the right, the WDC change for upwind turbines are set as follows:



This result in the following:

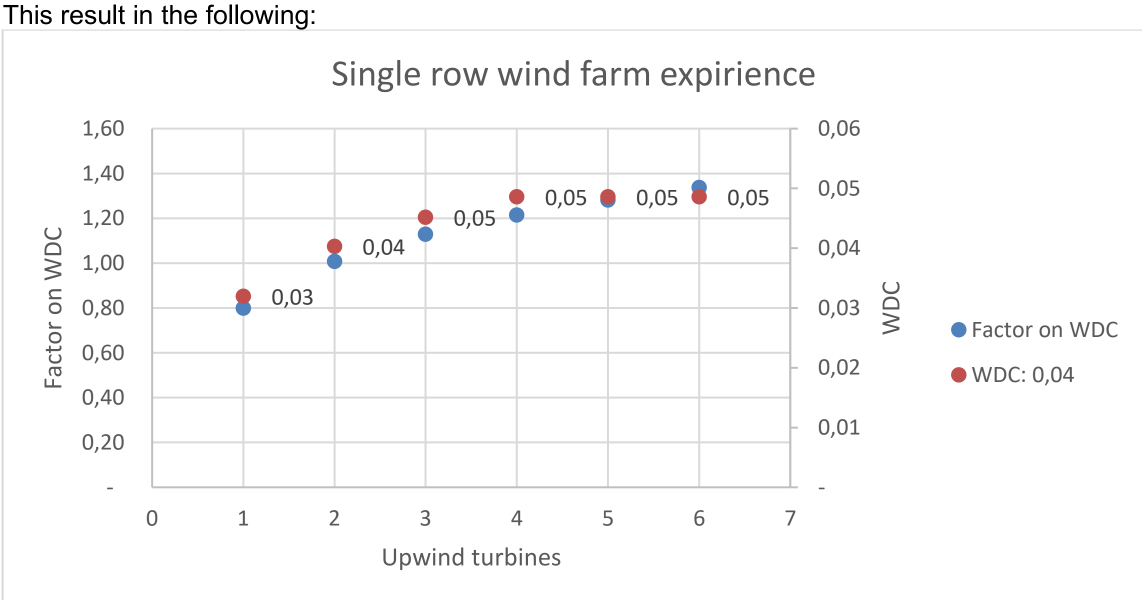


Figure 213 Factor on WDC and thereby increased WDC by number of upwind turbines.

As seen, the WDC with "base" set to 0.04 will convert to 0.03 for the first wake turbine, gradually increasing to 0.5, which is the upper limit after four upwind turbines. This work for single row projects (offshore for the mentioned values), where numerous other single row projects have been tested.

3.8.3 Horns Rev area, Danish Offshore project

The Horns Rev area at the Danish West coast is a good test case as there are three large offshore projects with many operational years for the first two areas and with large 8 MW turbines for the last project, HR3. This makes it possible to test for long-term operation, wind farm area interaction and large turbines.

3.8.3.1 Verification for Horns Rev area, wind statistic based, new Ainslie DAC focus

For the statistical based calculations, the focus is on comparing models (verification), not validation.

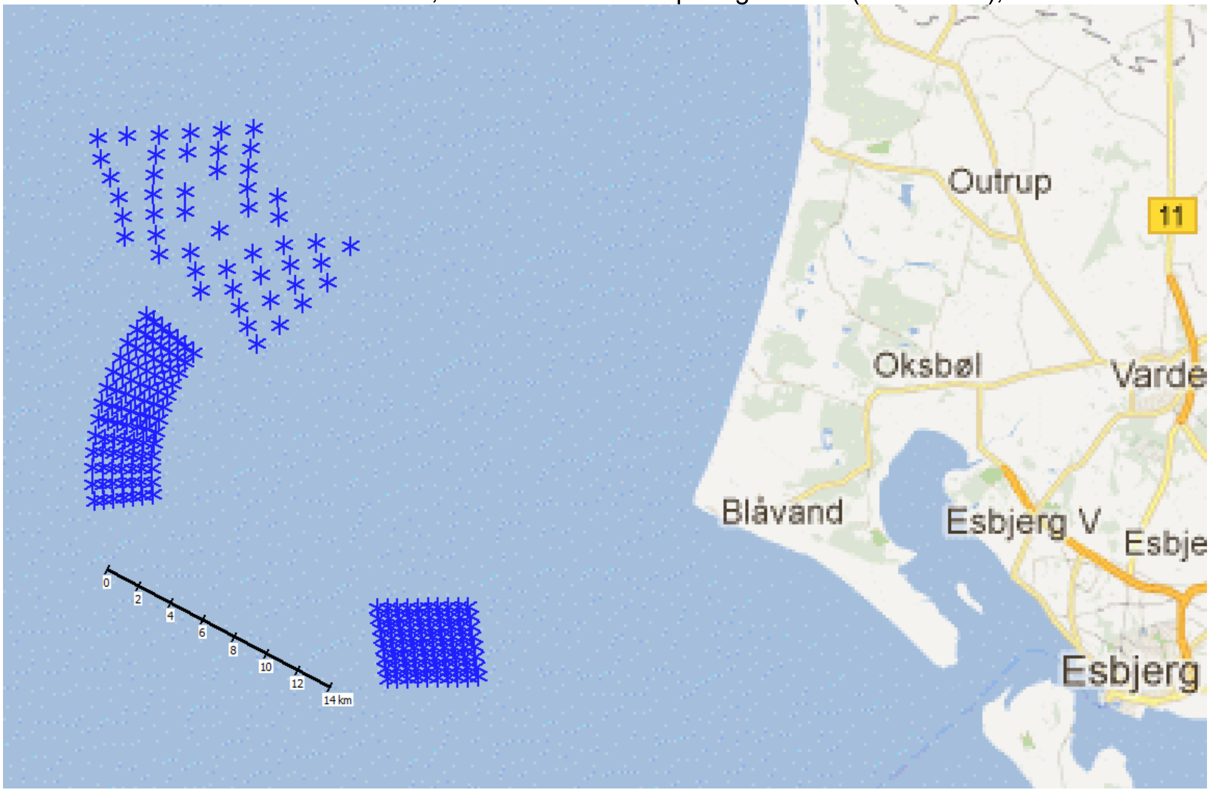


Figure 214 Map of Horns Rev area, HR1 south, HR2 mid and HR3 north.

At Horns Rev there are three wind farms making this area suitable for testing single wind farm calculations with different turbine sizes and different layout configurations.

The Turbulence Intensity (TI) in this area is around 7.5%, which is relatively high for an offshore site. The TI at the site is found from multiple measurement masts in the area combined with mesoscale data and is valid for the wind speed interval of 5-15 m/s. This is the wind speed interval where wakes dominate.

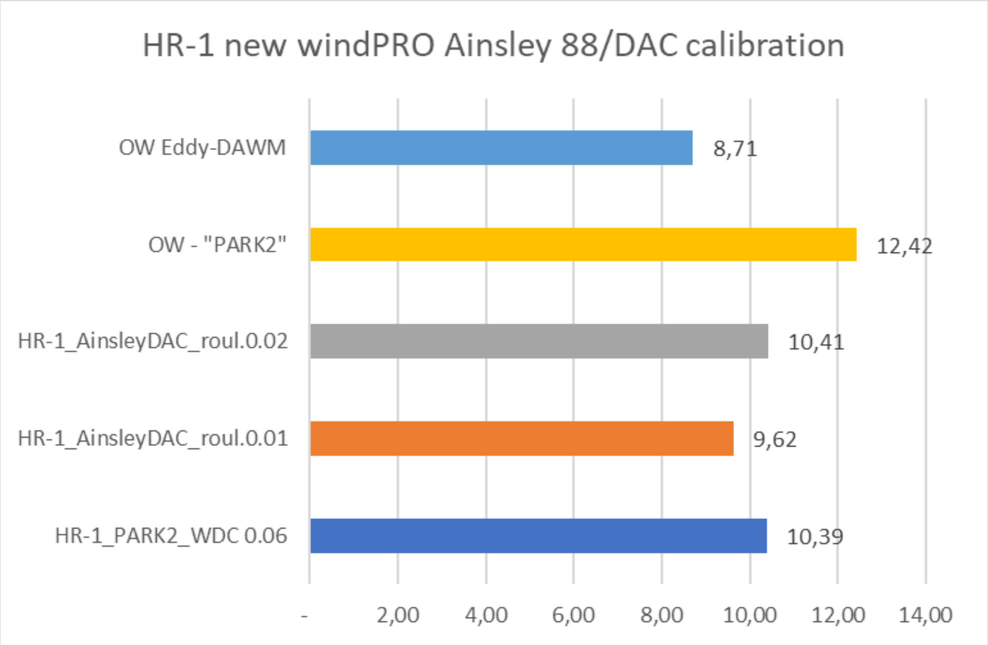
Several validations show that PARK2 handles this site very well with the DTU default Wake Decay Constant, WDC = 0.06. This corresponds to the EMD recommendations to use WDC = 0.8 x TI for offshore sites. (0.8 x 7.5% = 0.06)

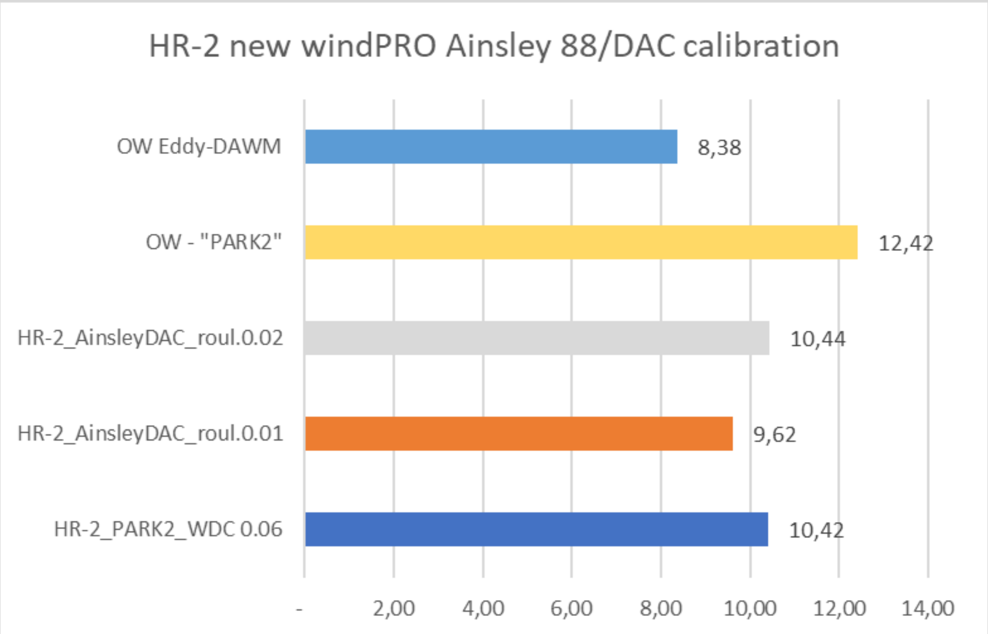
For the Ainslie model, where TI is the main input parameter, this is set to 7.5% in the following calculations. The Deep Array Correction model (DAC) has more parameters as shown in Section 3.6.1.2 The Ainslie/DAC implementation. The added roughness for offshore areas is by default 0.02, used in the tests along with 0.01, to illustrate the sensitivity of the parameter.

The below figures show calculated wake losses with long term (20y) mesoscale model data for the area using the EMD-WRF Europe+ dataset. This is found to reproduce the wind speeds seen very precisely for this area.

For comparison, the Openwind Eddy Viscosity model (Ainslie) and PARK2 model are calculated. While we do not believe the formula revisions for PARK2 compared to PARK1 has been made in Openwind, the N.O. Jensen model can run with linear combination model and excluding mirror wakes, which is close to PARK2. And then the Ainslie with DAC is run with default settings for offshore. For full disclaimer, there are several tuning parameters in Openwind that have not been tested here.

3.8.3.1.1 **Calculating HR1 and HR2 as "stand alone" and combined.**





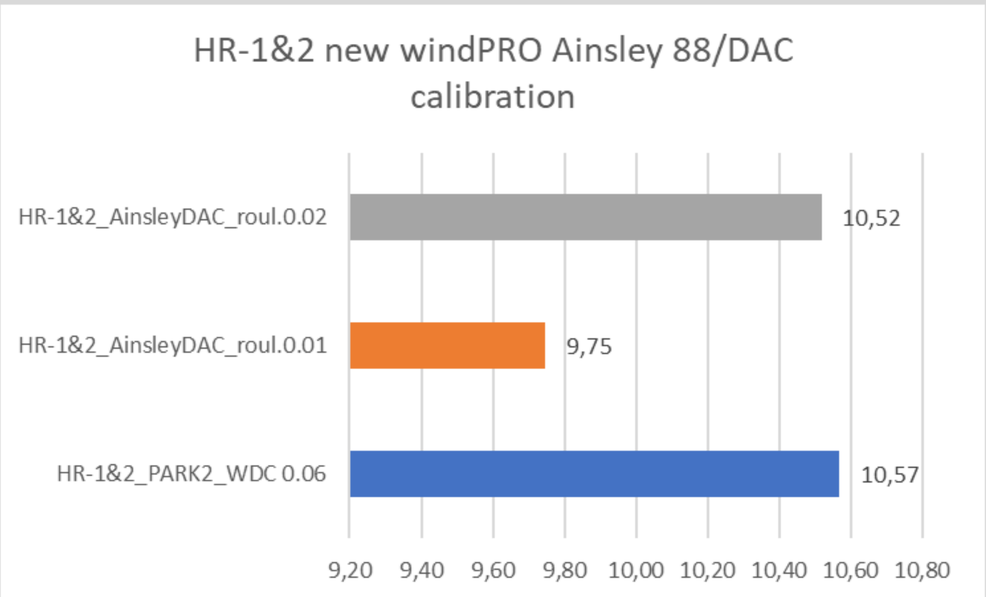


Figure 215 Plots showing calculated long-term wake losses for different combinations.
The new windPRO Ainslie 1988 with DAC default settings, returns almost exactly the same wake loss as windPRO PARK2 (N.O. Jensen) for HR1 alone, HR2 alone and when both windfarms are calculated together. It can be seen how sensitive the DAC model is to the roughness increase by testing 0.01 as alternative to the default 0.02. The result shows a decrease in calculated wake loss of just under 1 percentage point.

The Openwind calculations show some higher calculated wake loss with their PARK2 model and a little lower with Ainslie-DAC.

Which one of the windPRO Ainslie-DAC or PARK2 models performs best is not possible to say based on the real operational data, as the difference is too small to detect. However, based on detailed tests with 10-min operational data, we know that the size order of the calculation results for windPRO PARK2 are very accurate.

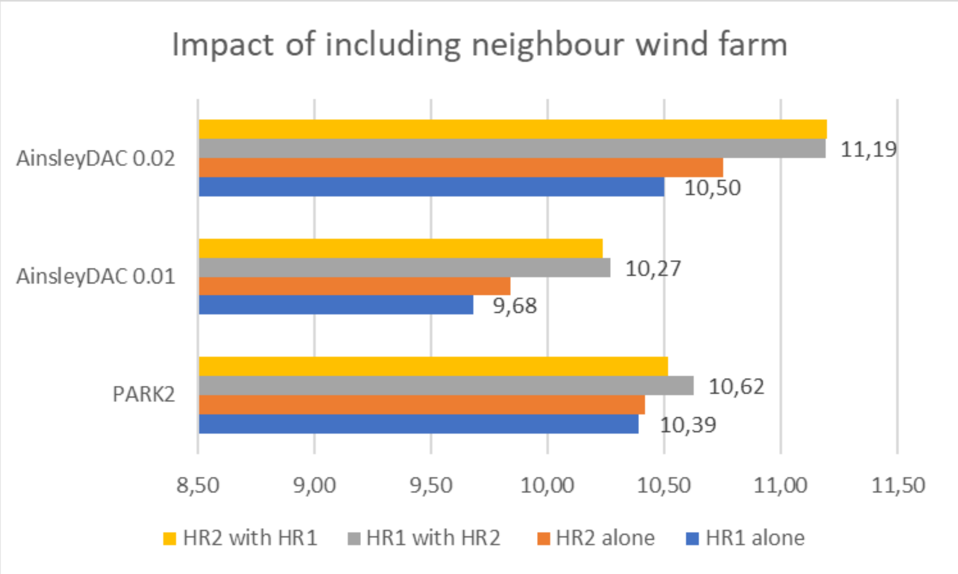


Figure 216 Impact of neighbour wind farm in calculations.

Looking at the impact by inclusion of another wind farm 15 km away, the impact is relatively small. The biggest impact shall be expected on HR1 from HR2 due to the wind direction distribution. This is also demonstrated with PARK2, but only by 0.2 percentage points. This is as expected, because when looking at the data for HR1 before and after commissioning of HR2 there is practically no difference to see. Ainslie DAC has a higher increased wake loss, although also small.

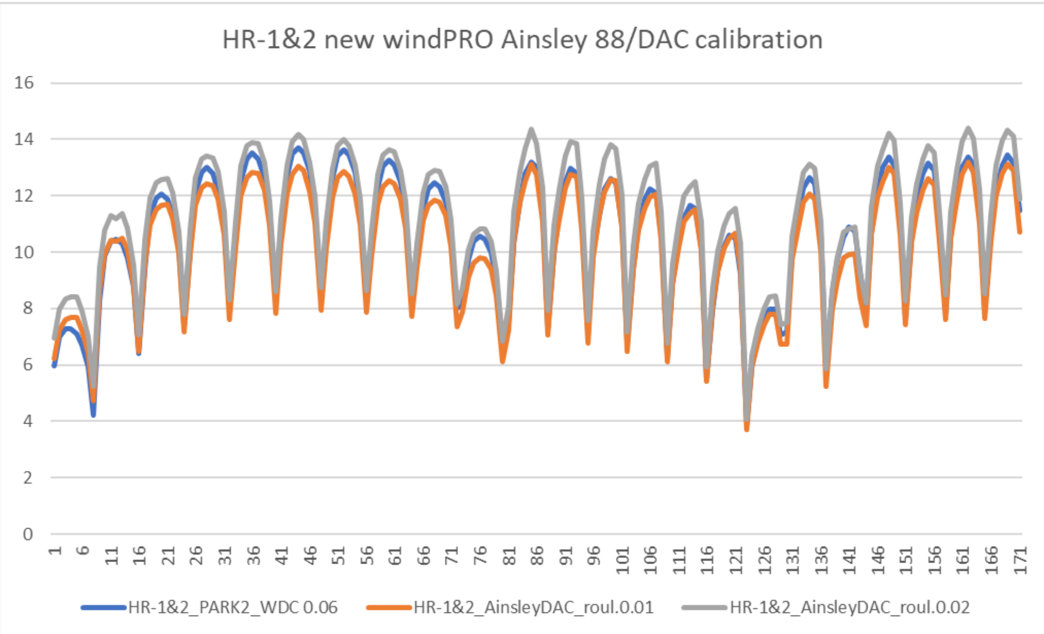


Figure 217 Turbine by turbine calculated wake loss.

In Figure 217 there are three calculation variants with calculated wake losses WTG by WTG. The first 80 WTGs are HR1, the next 91 are HR2. There are small differences, but quite small and very similar patterns with PARK2 and Ainslie DAC with defaults.

Conclusion for HR1&2: **The windPRO Ainslie-DAC (1988) performs almost as PARK2 with default settings – and PARK2 has been validated in several studies to perform very accurately for these wind farms.**

3.8.3.1.2 Calculating HR2 and HR3 as "stand alone" and combined.

In this example, there is an added challenge compared to HR 1&2, with HR3 having significantly larger turbines, RD 164 against HR2's 93 m. And the two wind farms are located much closer together.

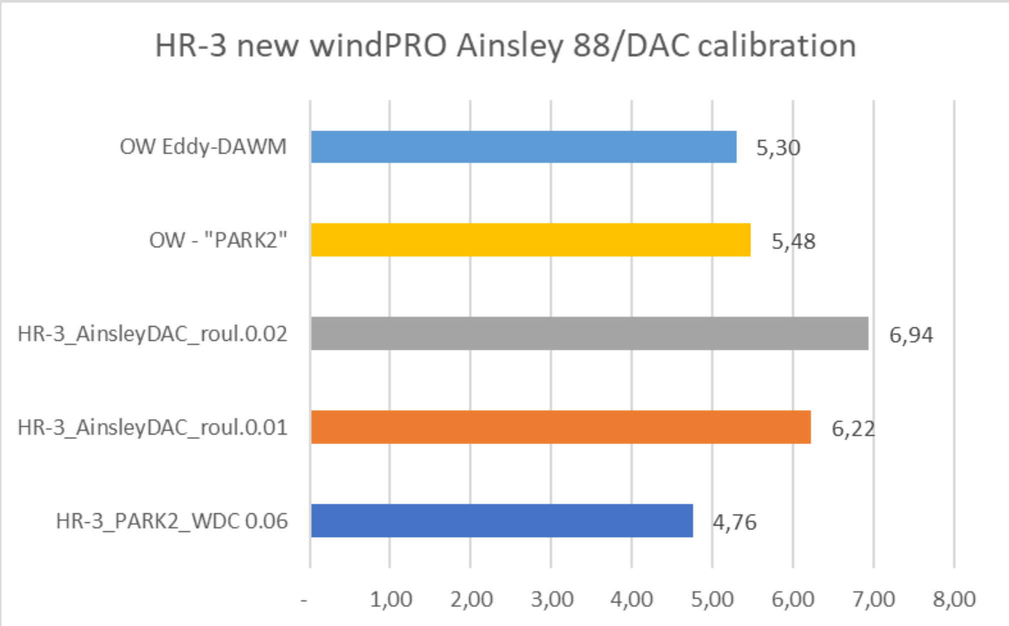


Figure 218 Calculated wake losses for HR3 with 8 MW WTGs.

Above, when calculating HR3 with much larger WTGs, there are much larger deviations. Ainslie-DAC with default settings calculates ~2 percentage points more wake loss than PARK2. Even with a lower increase of roughness, it calculates 1.5 percentage points more wake loss than PARK2. In this case, Openwind PARK2 and windPRO PARK2 are in better agreement and the two different models get more similar results than with the smaller wind turbines.

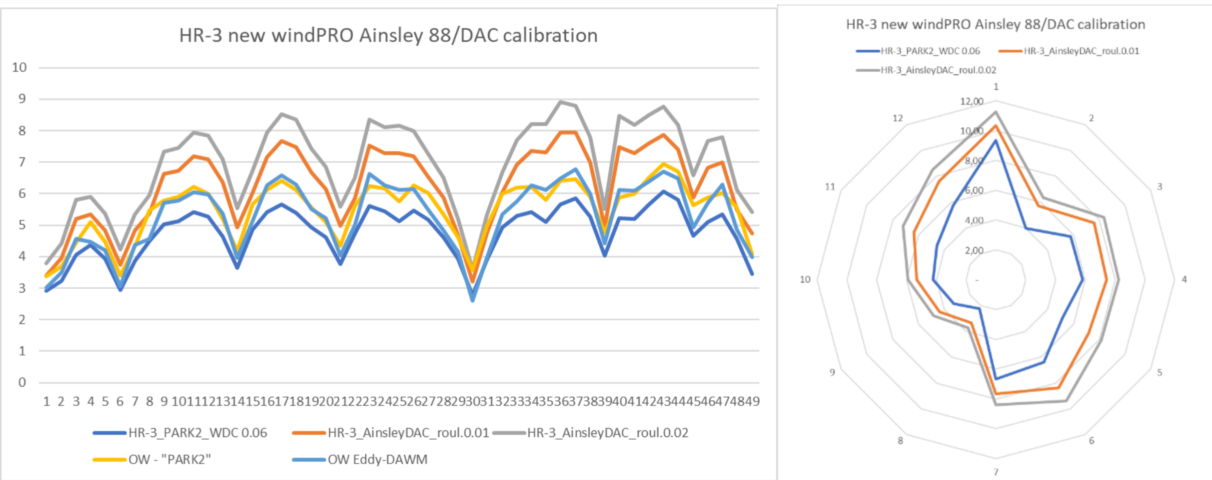


Figure 219 details on wake loss calculation for HR3.

Figure 219 shows how deviations are seen for all turbines and directions. Here, it is hard to tell what is correct as HR3 has not been operating without HR2 impact. Combining with HR2 we might get an idea.

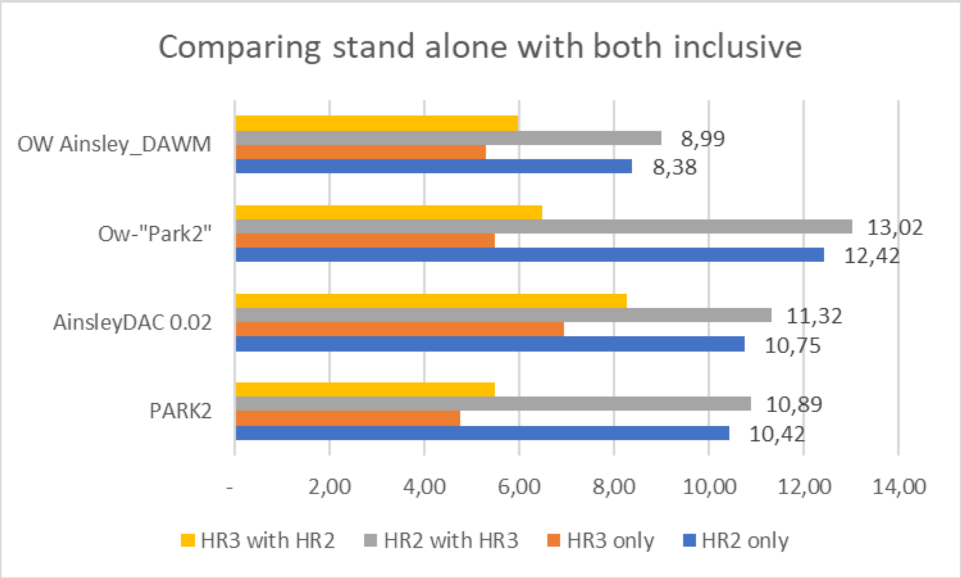


Figure 220 HR2 & 3 wake loss calculation with different combinations.

Here is seen how much impact the different models calculate by including the neighbor wind farm.
Especially interesting is the increase in calculated wake loss for HR2 by the presence of HR3 as this might be detected in the operation data. Albeit, difficult due to market regulation and operational issues.
All model variants agree well on the impact of including the neighbor wind farm.

Conclusion for HR2&3: There are differences in PARK2 and Ainslie/DAC in calculated wake loss when the turbine size gets larger, here 8 MW, where Ainslie/DAC calculates higher wake losses. This might lead to revised default recommendations for either one or both models when the turbines are larger, but it is too difficult to say based on a single example. All models agree on the size order of increased wakes from the neighbor wind farm.

3.8.3.2 Tests for Horns Rev area, time step based.

First, a detailed validation of both the mesoscale data and the wake loss calculation setup is made based on HR1. This detailed validation is possible due to access to 10-min data. Next all models are tested on all three wind farms in the HR area based on monthly measured production data.

For the monthly data it is worth keeping in mind where these are measured. In Denmark, and assumed similar in the UK, the monthly data is measured at the low voltage side at the substation. This means that the measurements are reduced with 1.5 – 2% electrical losses (step up transformer and internal grid each account for typical 0.7-1%). In addition, internal consumption during stops can add 0.1-0.2% by reasonable normal operation. For sites with heavy market regulation shut down, this can be significantly higher.
Using the 10-min SCADAdata, this is typically measured after the step-up transformer, which includes approx. 1% loss. Thus, applying a ratio of 0.99 measured/calculated for all normal 10-min SCADAdata samples yields the perfect result from the wake model
For monthly data the ratio shall be 0.98 if there are no other losses than electrical. In other words, if less than 2% loss in a month, the calculation model is biased, which could be the wake calculation or a wind data bias.

3.8.3.2.1 Horns Rev 1 detail validation of wake model

In a pre-analysis the ratio between back and front row power is found by TI bin, which then is paired with similar ratios for calculations with different WDC values. This gives the following relation between WDC and TI for PARK2:

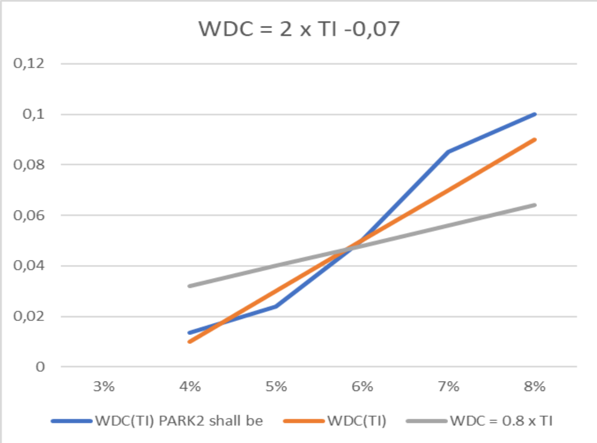


Figure 221 Advanced modelling of WDC by TI based on detailed Power by TI analyses.

The good thing is that a similar analysis on another UK offshore wind farm with access to detailed 10-min data gives a similar result. Therefore, the advanced option for WDC(TI) is added as an alternative to the general recommendation WDC = 0.8 x TI for offshore.

Here, it is seen how the calculation based on mesoscale data and a WDC = 2 x TI – 0.07, handles the wake loss calculation to almost perfection, where a filter criterion is that minimum 79 of the 80 turbines must be running. This leaves 27.000 10-minute approved samples, which is 26% of available samples for the two years 2008 and 2012 with data available.

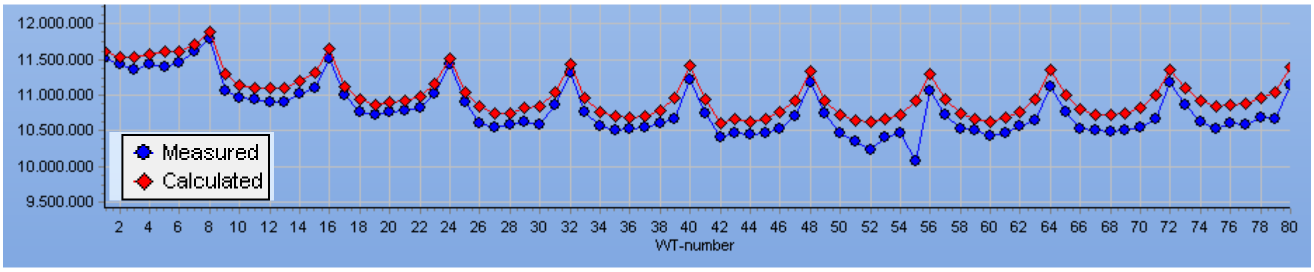


Figure 222 HR1 calculation for 2008 & 2012 compared to measurements.

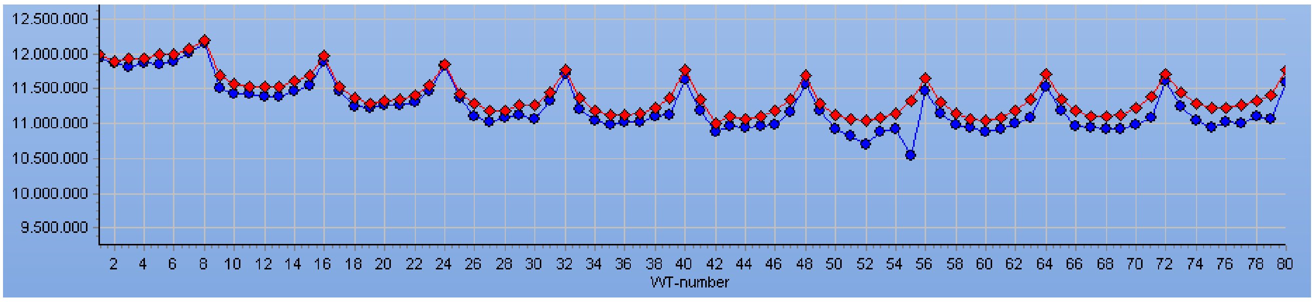


Figure 223 HR1 measured and calculated at TI>6%.

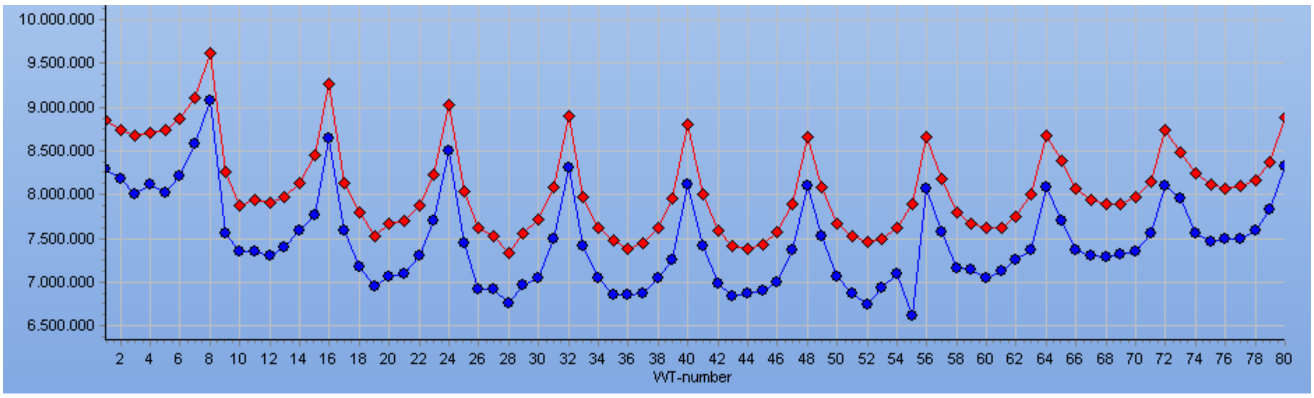


Figure 224 HR1 measured and calculated at TI<6%.

It is worth saying, that the ratio measured/calculated turbine by turbine is good for both higher and lower TI:

Figure 225 Measured/calculated for lower and higher TI for HR1.

There are no signs of "curtains" or east-west bias meaning the wake model handles the site to near perfection. The bias for low TI for all WTGs is caused by mesoscale data having too high wind speeds at low TI. This could be a blockage issue.

But it is good to see how the much larger variation in production between the middle and end row wtg's at low TI is captured well by the wake model with the advanced settings.

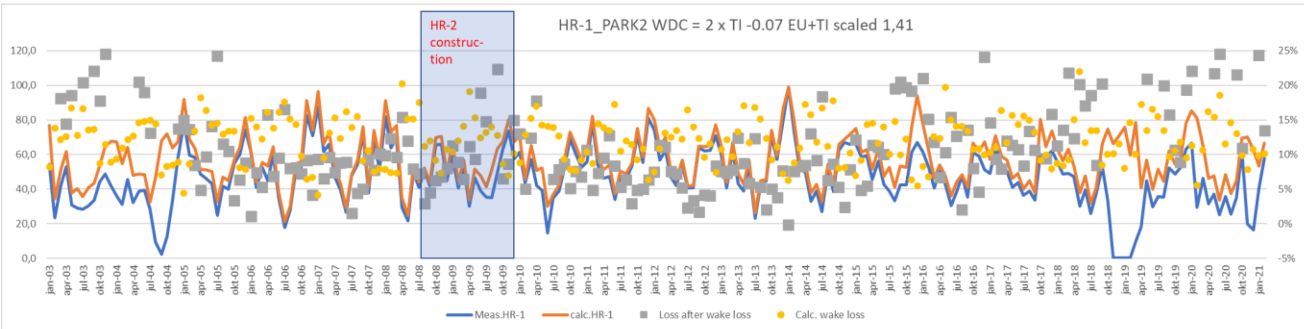


Figure 226 Long term calculation of HR1 compared to measured.

With the advanced wake model settings, close to 20-year operation can be calculated and compared to monthly measurements. A very fine agreement is seen, but also that there are some months with quite high losses. From 2018 we know that one turbine has been taken out of operation permanently due to lightning damage.

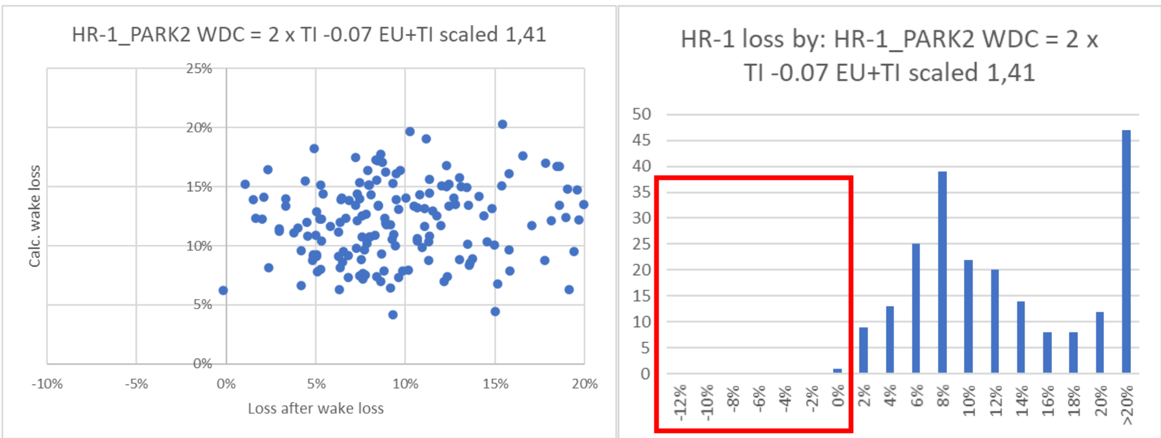


Figure 227 The calculated wake loss vs loss on top of wake loss and binned loss.

The left-side graph above shows no correlation between loss after wake loss and calculated wake loss, which is good. The red square in the right-side graph shows where there should not be any data, apart from mesoscale bias related. The loss/mesoscale bias is nicely normally distributed as should be expected with this very long dataset.

Apart from "extraordinary" losses mean values are:				
Average if < 10%		if < 15%	All	Extraordinary
HR1	6,6%	8,3%	17,2%	8,9%

The table above shows “normal” operational losses in the size order of 7-8%, of which ~1% is grid loss and the remaining is availability, sub-optimal performance AND market regulation. The extraordinary loss by major downtime and possible market regulation is ~9% seen over 20 years.

3.8.3.2.2 Horns Rev 2&3 detail validation of wake model

The wind data used is the EMD-WRF Europe+ dataset. While there can be a bias, which can violate the wake model validation, it has the great advantage that it can be compared to actual production from the Danish Stamdataregister. This is done month by month, which results in a much better validation basis than for statistical calculations in spite of missing 10-minute data as we had for HR1.

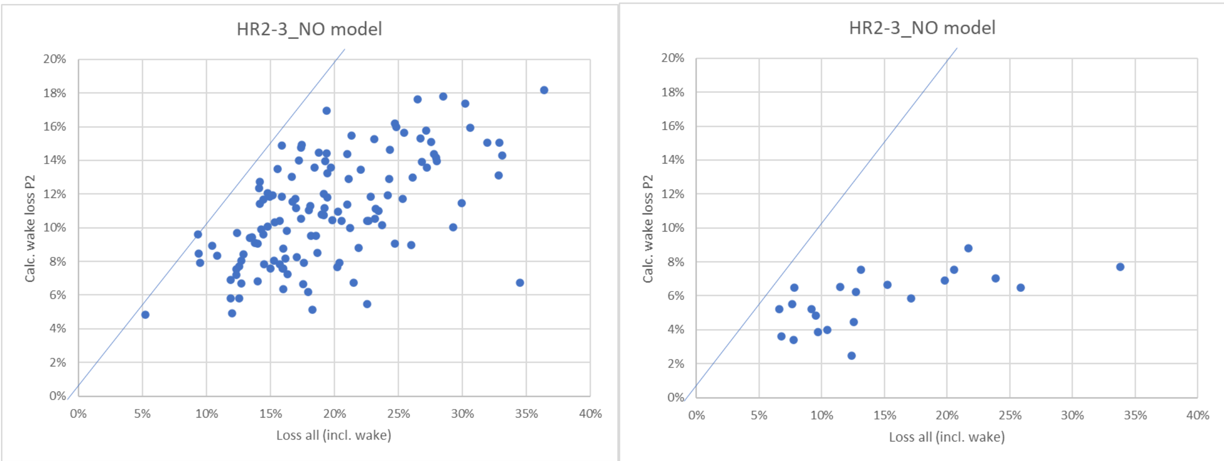


Figure 228 Comparing calculated wake losses with all losses including wake loss, HR2 left, HR3 right.

First, a look at the production data compared to the calculation without a wake model. Here the calculated wake losses by PARK2 (DTU default WDC 0.06) is plotted against the losses by the wind model calculation, without wake loss calculation. Left is HR2, right is HR3. It is seen on the trend how a significant part of the loss is related to wake loss. This is very clear for HR2, less for HR3 due to short operation period, including start up period.

It is to expected that there are no data above the blue line, as the calculated wake losses then would be too high (or the wind data biased). A few points above the line are ok due to the lack of precision of the mesoscale data and the fact that there are no stability or TI correction month by month.

It is seen that the calculated wake losses by PARK2 vary by month from 5-18% for HR2 while they vary from 2-9% for HR3. But the total losses based on the wind model varies much more, and this is a problem for the validation, that we cannot separate wake and other losses precisely.

Below the calculation with wake loss is compared to the measurements:

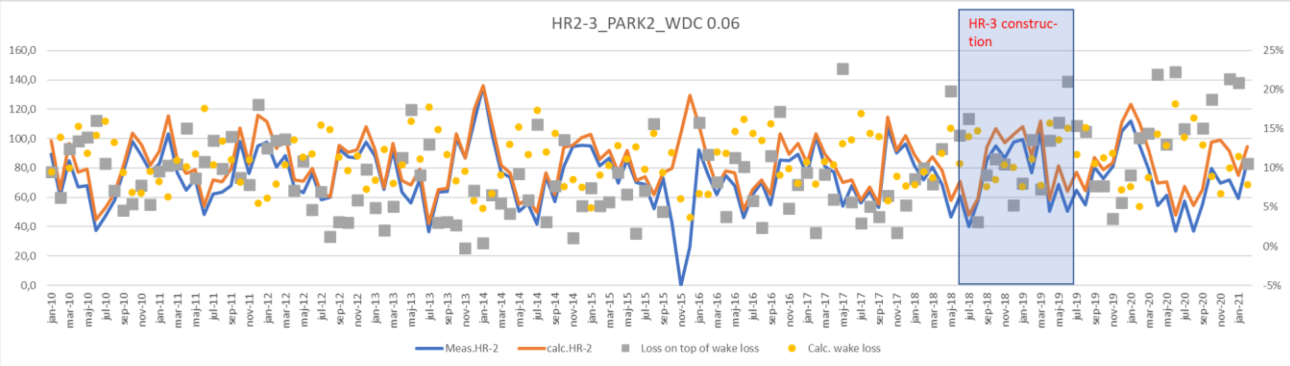


Figure 229 Monthly calculated and measured production for HR2.

Viewing the monthly figures gives a good idea if the wind model seems reasonable. And it does. The grey dots show the loss after wake loss and the yellow the calculated wake loss.

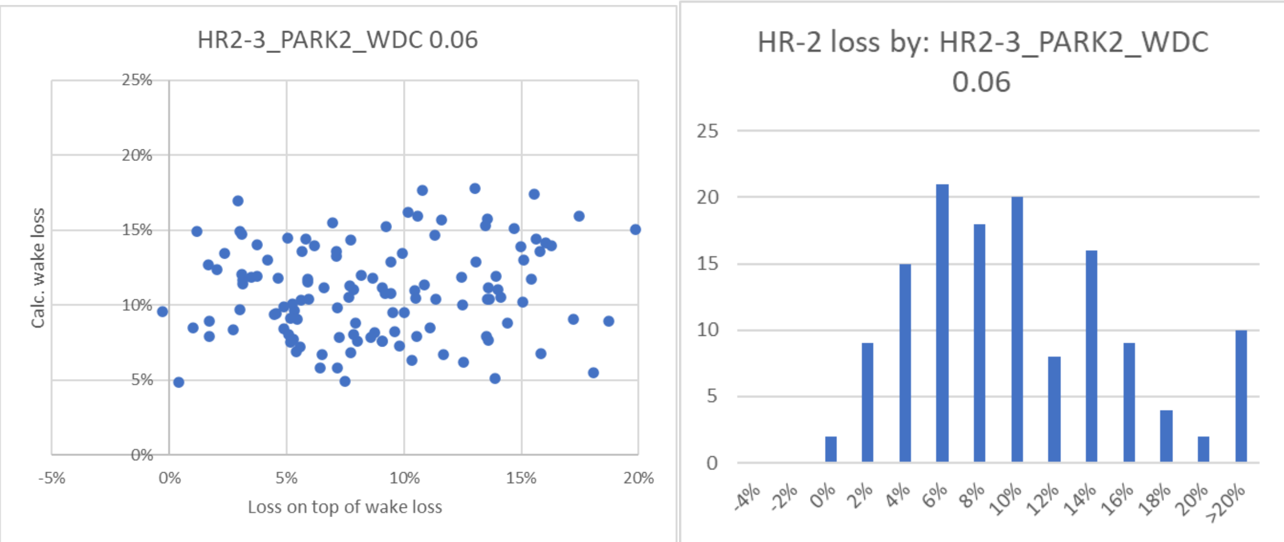


Figure 230 Calculated wake losses and seen "other loss" for HR2.

Above to the left is seen for HR2 that there is no systematic trend that losses are higher/lower where the calculated wake losses are high/low. This is a good indication that the wake loss calculation does not seem biased.

To the right the loss distribution after wake loss reduction in calculations. This looks ok, although we do not know the monthly operational losses. Looking at averages, where extremes are taken out:

Apart from "extraordinary" losses mean values are:			
Average if < 10%		if < 15%	All
HR2	6,4%	8,1%	11,4%
HR3	5,4%	7,2%	18,9%

Probably acceptable loss figures for the “normal operation”, where some grid losses must be assumed for the internal cabling (substation and sea-land cable losses are not subtracted in production figures. Measurements are at the substation on the WTG side). But the availability and sub-optimal WTG operation losses are dominant together with possible market regulation.

It thereby seems that PARK2 (WDC 0.06) and the wind data basis handles the calculation well.

Then we have a reference for the Ainslie/DAC test.

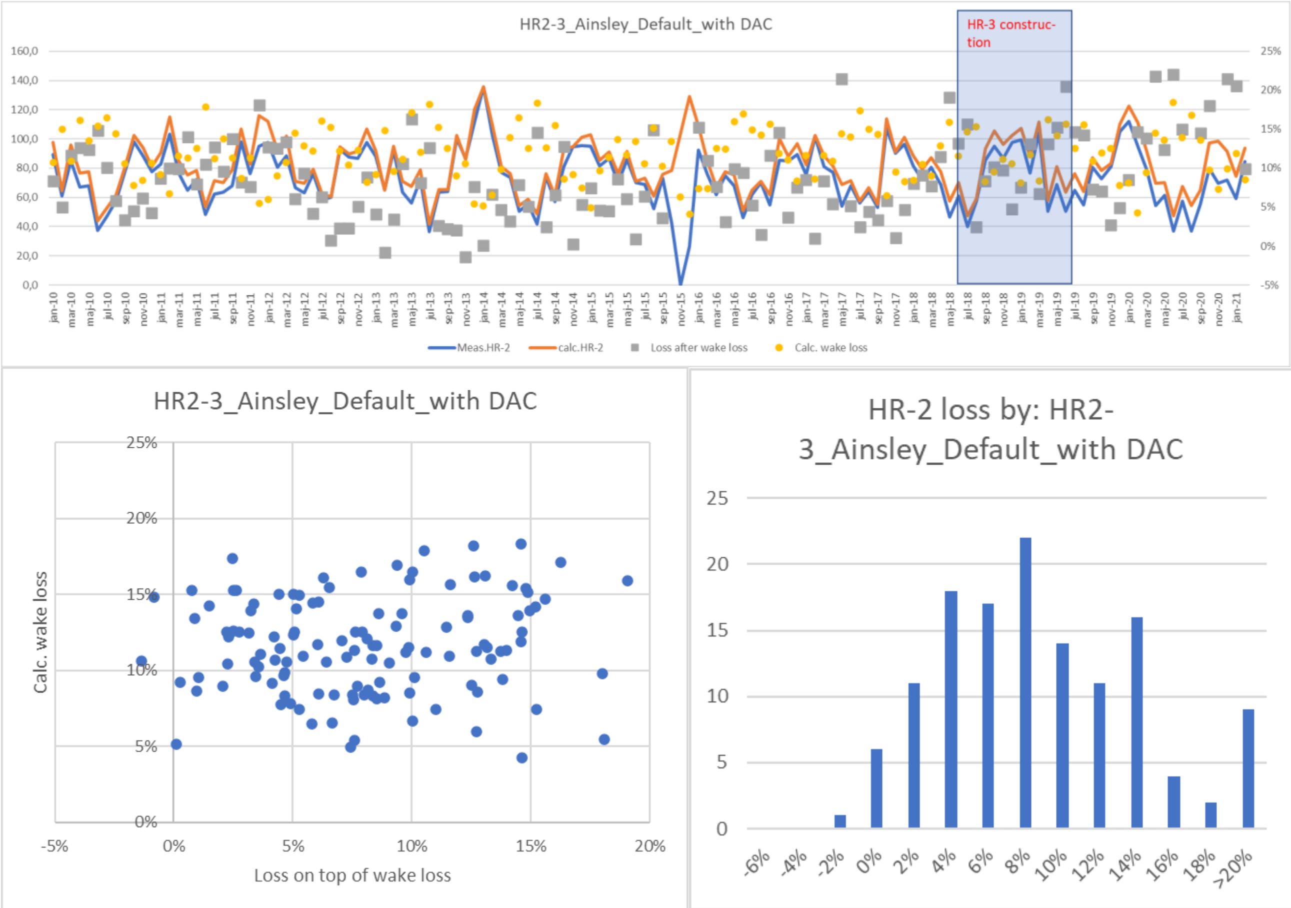


Figure 231 Calculated and measured + losses by Ainslie DAC calculation.

The Ainslie DAC-based calculation performs like PARK2 for HR2.

A similar loss table as for PARK2 justifies that the calculation works well, although the HR3 losses seem too low (too high calculated wake loss for this farm).

Apart from "extraordinary" losses mean values are:		
Average if < 10%		if < 15%
HR2	5,4%	7,5%
HR3	3,2%	4,6%

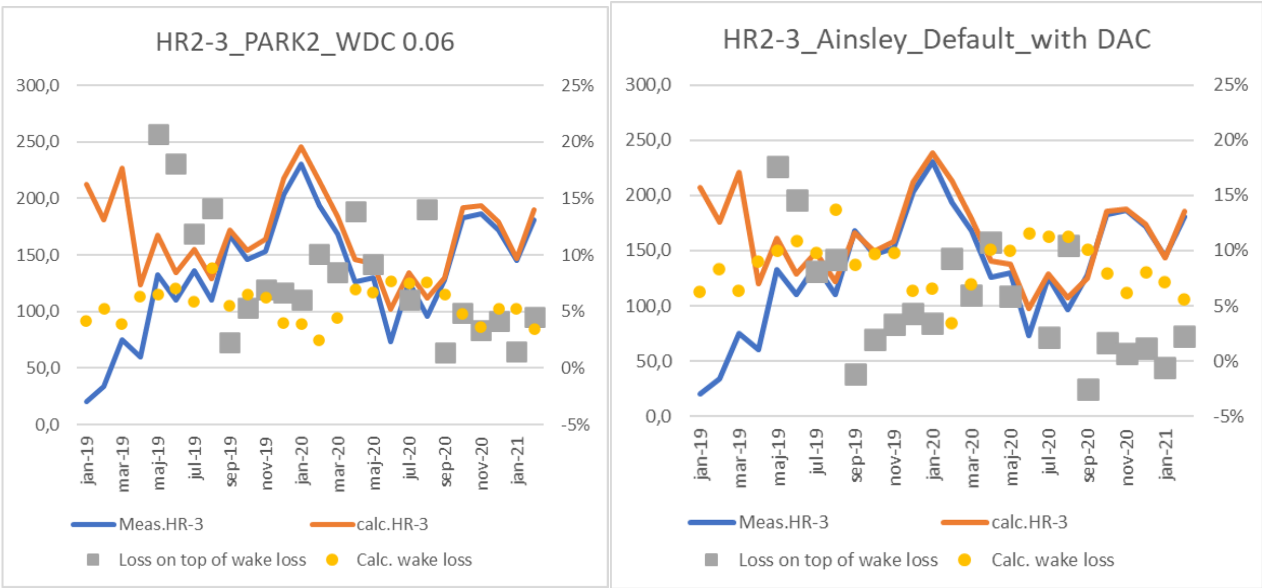


Figure 232 Timeseries calculated and measured by month for HR3.

Comparing Ainslie/DAC with PARK2 – both with default settings. That the losses get negative with Ainslie DAC but not with PARK2 indicates that Ainslie/DAC calculates too high a wake loss for this wind farm.

HR2 results	Calculated wake loss
HR2-3_PARK2_WDC 0.06	10,4%
HR2-3_Ainslie_	11,1%
HR2-3_PARK2_WDC = 2 x TI - 0.07	10,2%

The main results of three calculation variants for HR2 as time step calculations for the full HR2 operation period are shown above. Note the PARK2 with WDC(TI) is based on the EMD-WRF Europe+ TI, which is scaled with factor 1,41. The advantage of making the wake loss TI depending per time step is that the wake losses are calculated more precisely. This way sites with higher or lower TI will be handled more precisely.

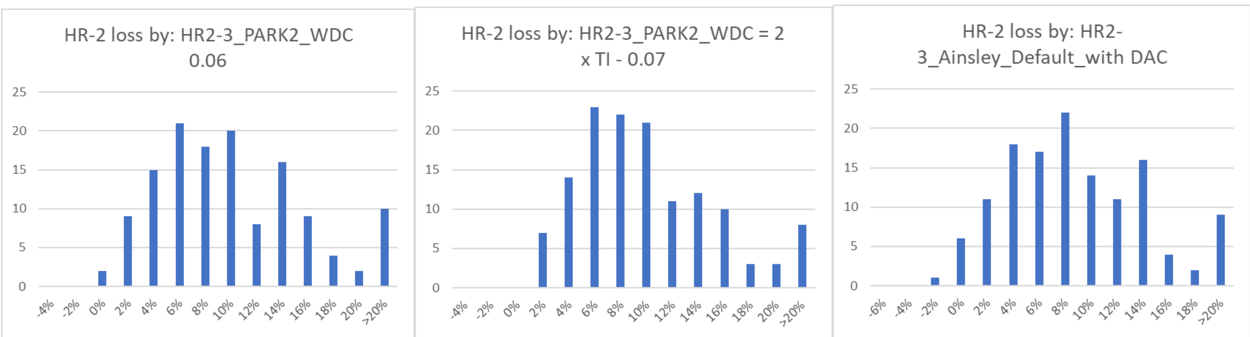


Figure 233 Monthly loss distribution by loss bin for HR2 and different calculation variants.

Showing months by loss bin for eleven operational years. We cannot know for sure how much is related to mesoscale wind bias, but we know from HR1 validations with 10-min operational data for two years that the losses on top of wake losses are in a realistic size order and the wake model calculation is in the right size order.

3.8.4 Lillgrund, Sweden offshore project

This project is special due to the dense spacing - around 3.2x the rotor diameter (RD). The main wind direction is from WSW, along the row orientation.

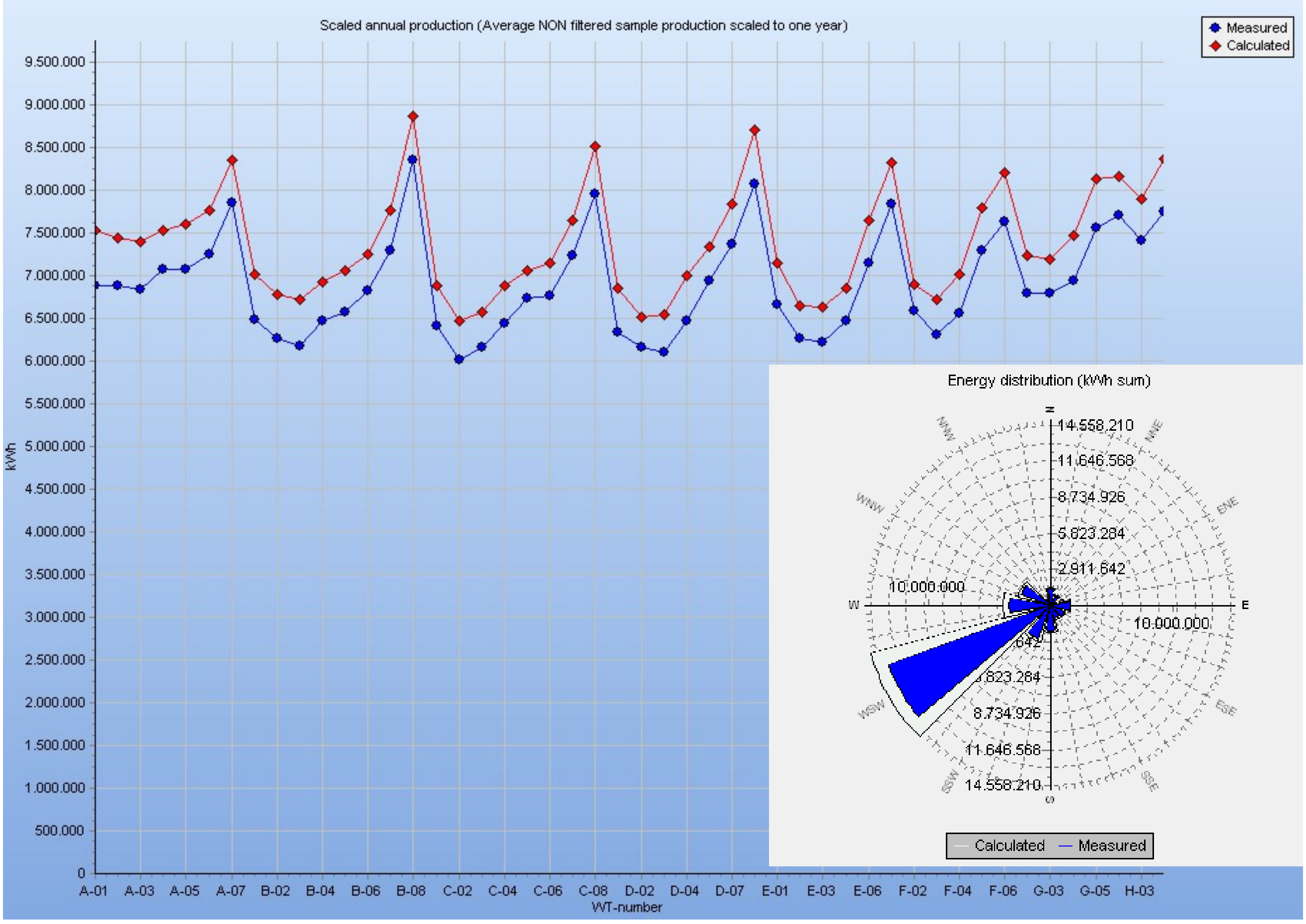


Figure 234 Measured and calculated from Performance Check, month data (includes "other" losses).

Shown above is the output from the PERFORMANCE CHECK module, where both measured and calculated turbine by turbine can be seen. Data is filtered by taking out larger down times in both measured and calculated values. Monthly production data for each turbine for five years (from December 2008) is used. The calculation is based on mesoscale data. In general, a very good match, using PARK2 WDC = 2 x TI -0.05. Thereby subtraction of 0.07 is replaced with 0.05, which is a fine-tuning handle, that in this case change the calculated wake loss from 28% to 26%. The tuned version calculates all WTGs within +/- 2% of measured with respect to differences in wake loss. Other loss is assumed the same for all WTGs after outlier filtering.

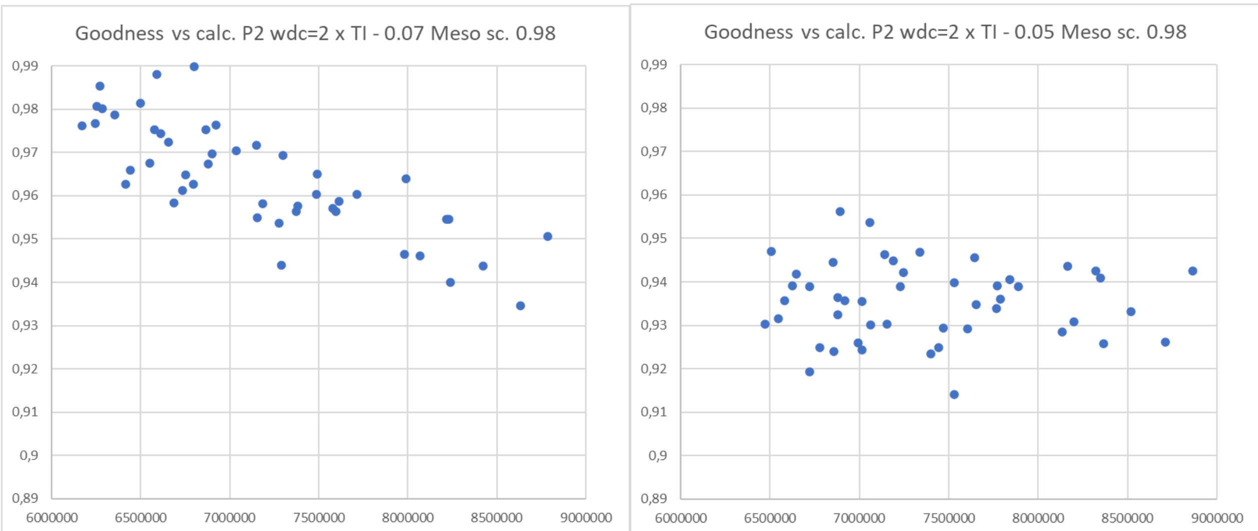


Figure 235 The calibration tool: goodness vs calculated, PARK2 adv. default (left) and tuned (right).

Showing the goodness (measured/calculated for concurrent outlier filtered data) is a good way of finetuning the wake loss model. If there is a down or up trend, the wake model is incorrectly calibrated as seen to the left, where the highest calculated (free in main wind direction) has the lowest goodness. Thereby too high wake losses are calculated. Here mesoscale data are scaled 0.98 which probably are a reasonable size order giving round 6% avg. loss on top of wake loss for the outlier filtered data.

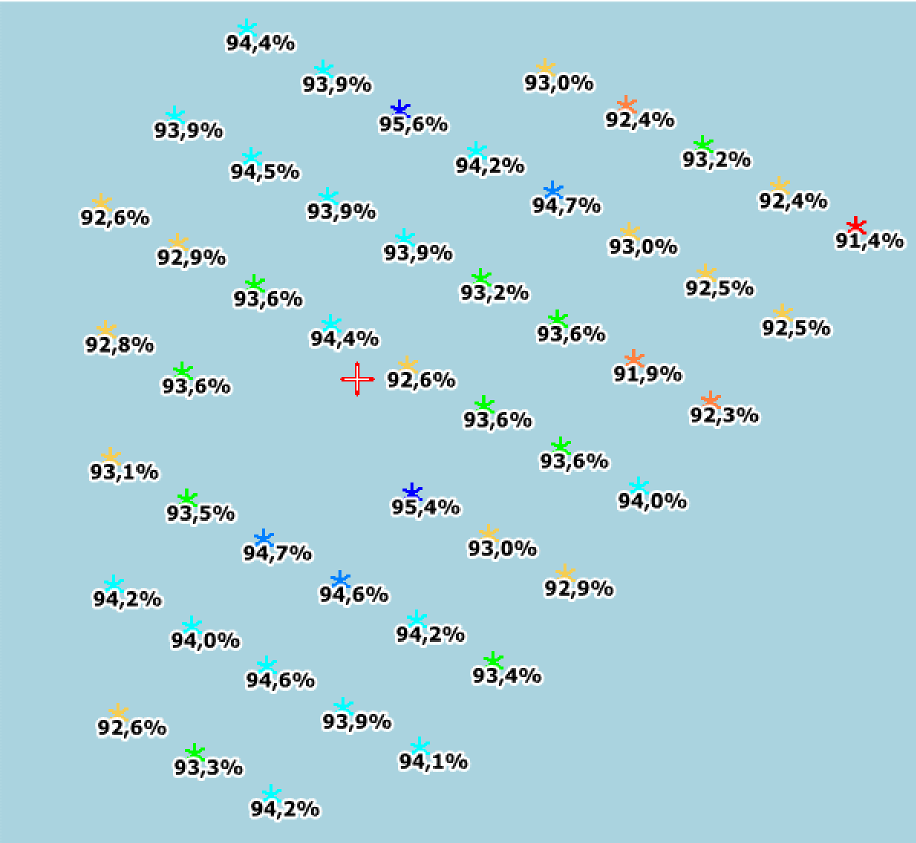


Figure 236 Wind farm layout and ratios measured/calculated P2 tuned, Lillgrund offshore.

The calculated wake losses are for three variants:
PARK2, WDC = 2 x TI – 0.07 (advanced default): 28%
PARK2, WDC = 2 x TI – 0.05 (best WTG by WTG reproduction): 26%
Ainslie default settings: 27%

Thereby both PARK2 and Ainslie by default settings are close to the fine-tuned most trustworthy result for this very high wake loss site.

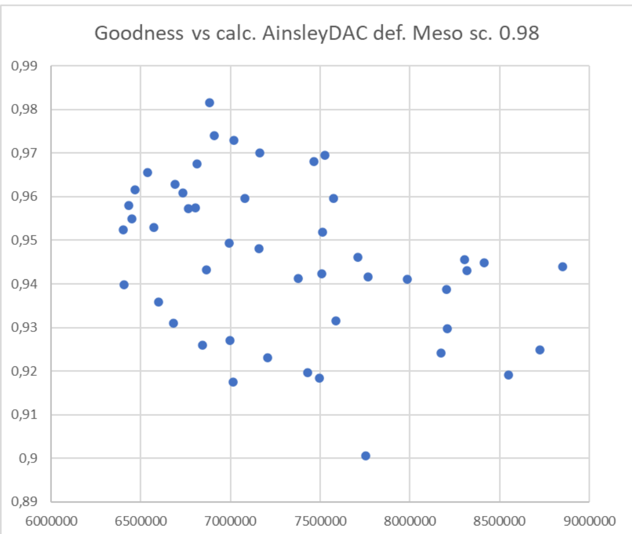


Figure 237 Ainslie with WTG by WTG goodness slightly poorer than PARK2.

3.8.5 Wake calculation validation for large Egypt wind farm

This project is checked each half year for five years, where wake modeling is tested. So here we know very precisely what the wake losses are. Below a comparison for a specific period, 1½ year, with good mast measurements in front of park including Turbulence measurements.
The in-row distance is ~3 RD, between rows ~14 RD. The turbine model is the Gamesa G80 with 60m hub height.

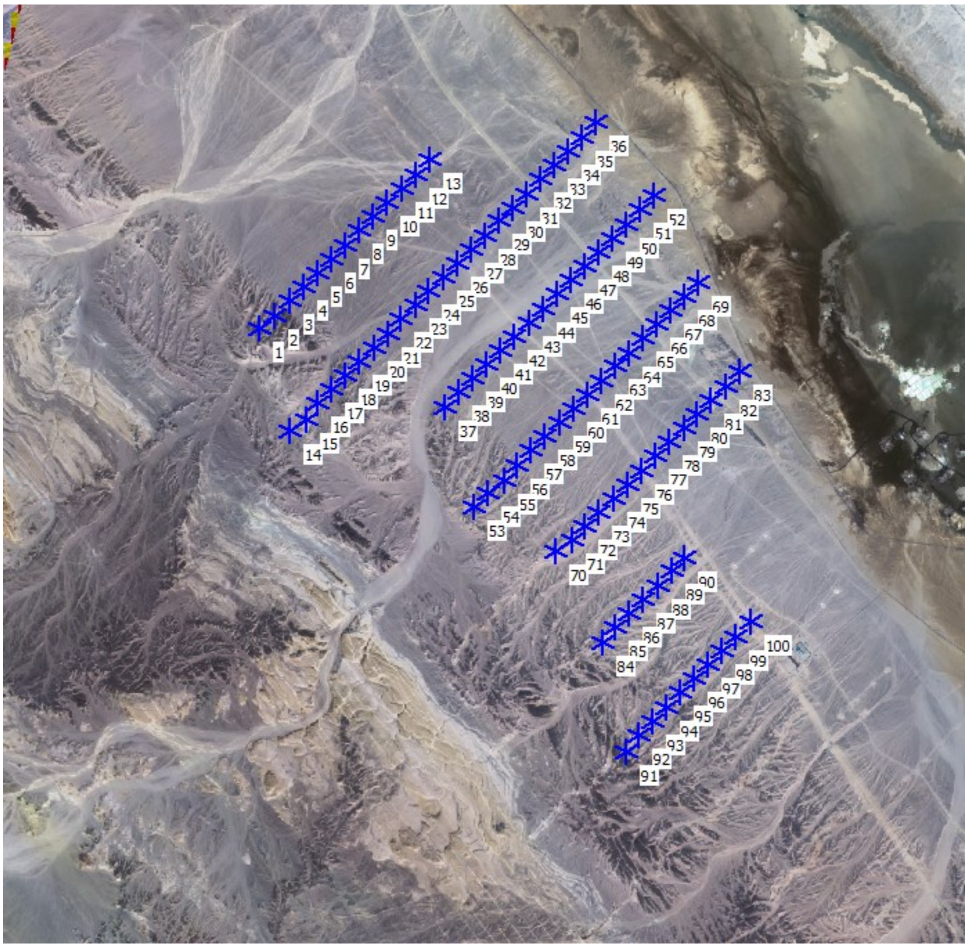


Figure 238 Layout of the Egypt wind farm.

The special thing for this site is the uniform wind direction, NW, but with the specialty that in WNW the TI is very low, around 5%, while in NNW it is more “normal” for onshore, close to 9%:

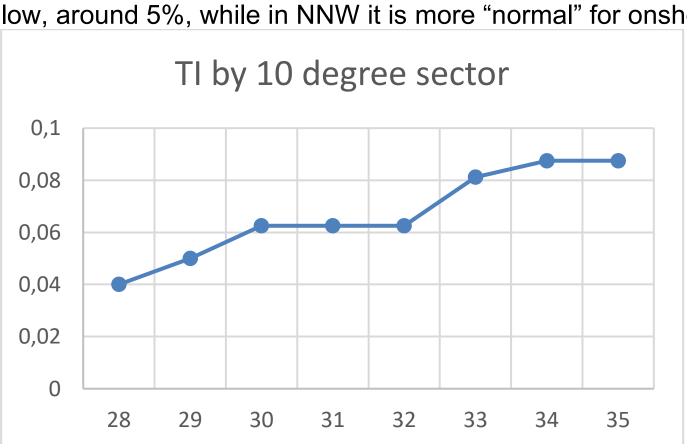


Figure 239 TI by direction sector.

Therefore, the Ainslie model is tested particularly for sectors 29 and 34, to compare to PARK2 wake modeling at low-high TI conditions. The results:

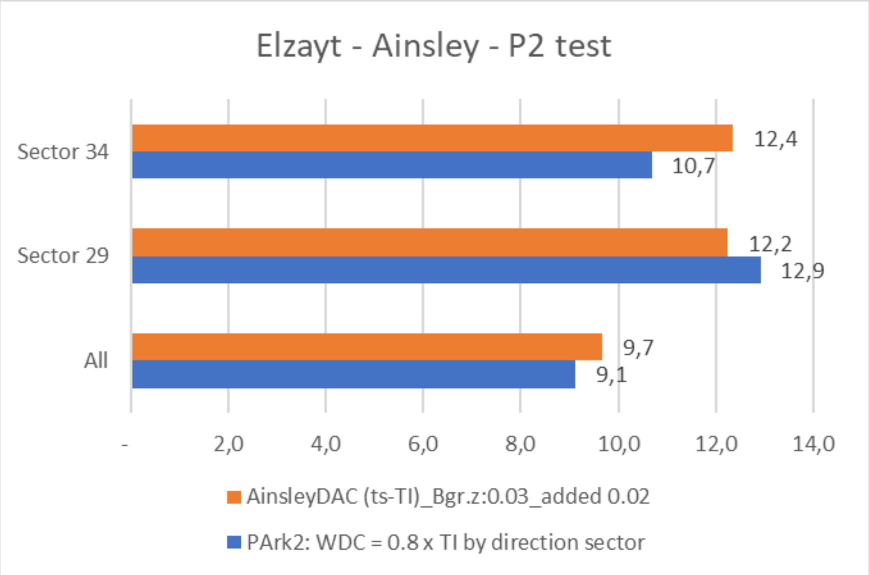
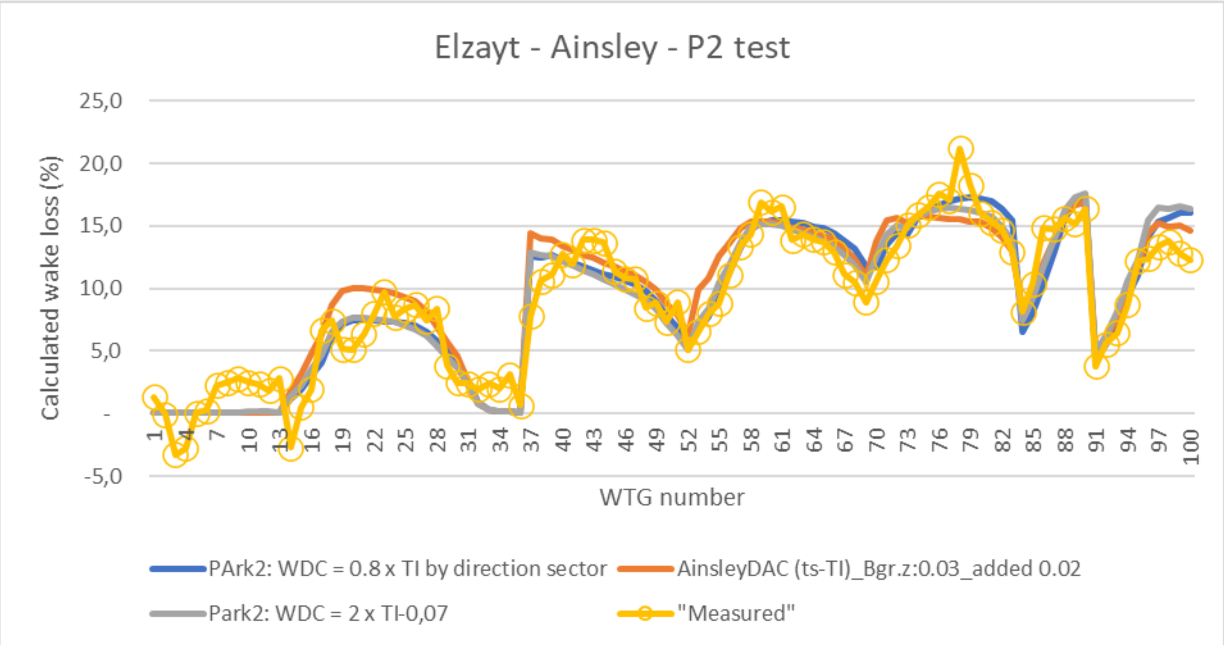


Figure 240 Egypt large wind farm wake loss calculations.

Ainslie is used with onshore background roughness 0.03, but added roughness as for offshore, 0.02. With these settings Ainslie compares well to PARK2. Both calculate 9-10% wake loss, which is the correct value based on 5+ years of measurements. Ainslie does calculate a lower wake loss in the low TI sector 29 compared to PARK2 and the reverse in high TI sector 34. This is as expected from the offshore tests, where it was seen that Ainslie model does react less to changes in TI compared to PARK2.



There is no complete agreement WTG by WTG, but all in all good agreement. In addition, the test of new offshore recommendations for PARK2 is included: WDC = 2 x TI – 0.07. This is seen to work very similarly to the PARK2 calculation with WDC by direction based on WDC = 0.8 x TI.

Setting the added roughness for Ainslie to 0.1 (onshore recommendations) calculates some higher wake losses, although just a few percentage points. This illustrates how sensitive the Ainslie/DAC is to added roughness for a wind farm covering a large area. The site although must be considered “offshore -like” where also the PARK2 model needs offshore settings to behave well. The combination of low TI, low roughness and high wind speeds makes it offshore similar, and this probably explains the need of handling this site with offshore settings.

3.8.6 Large UK offshore wind farm complex

How does the wake modeling work for very large wind farm complex, not just a single or two wind farms?

This we will try to answer by the Irish sea wind farm complex with Walney etc. see below.

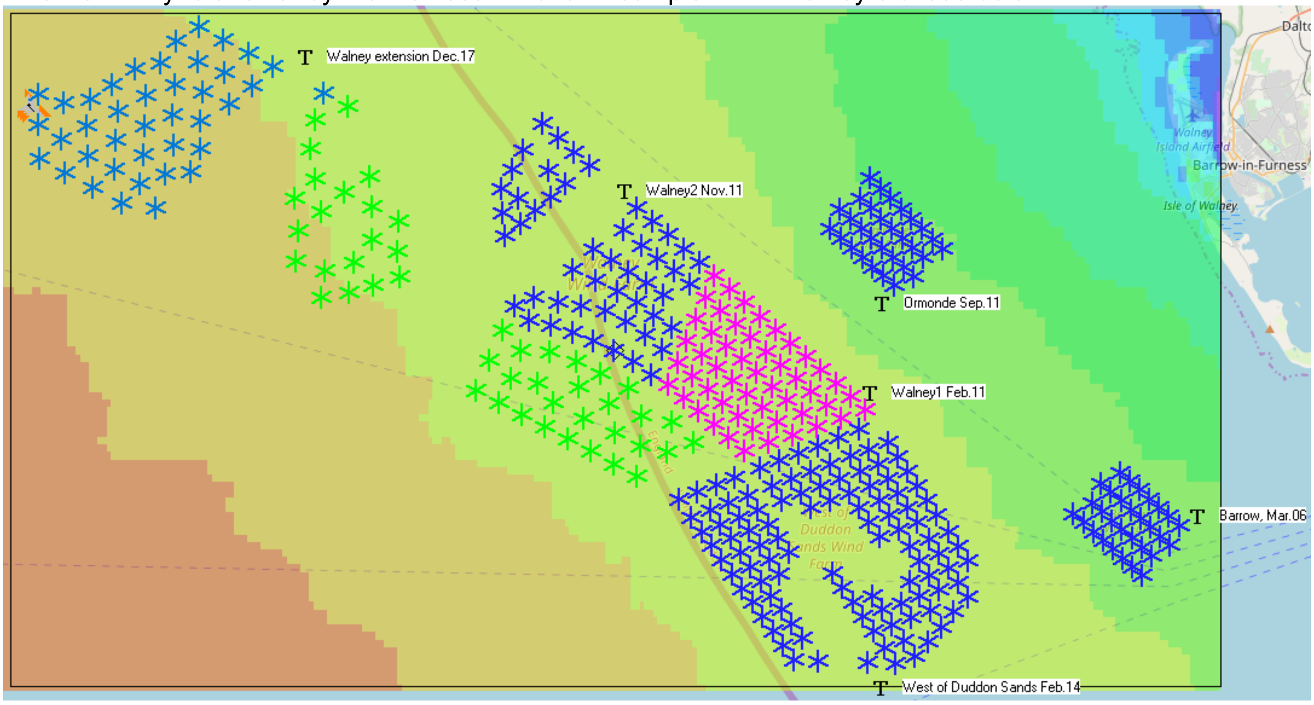


Figure 241 Large wind farm complex covering 45 km east-west.

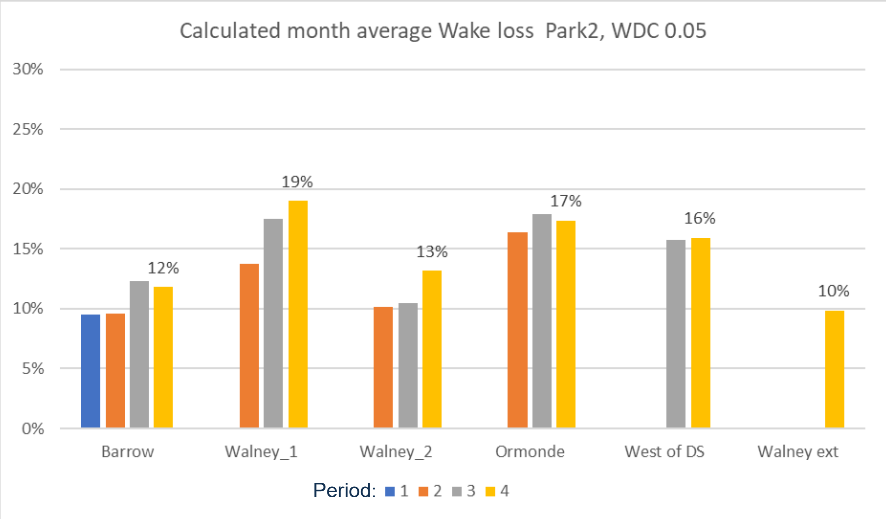
Monthly data from each wind farm are available. The Walney extension consists of two types of turbines, Siemens Gamesa 7 MW (green) and Vestas 8MW (light blue).

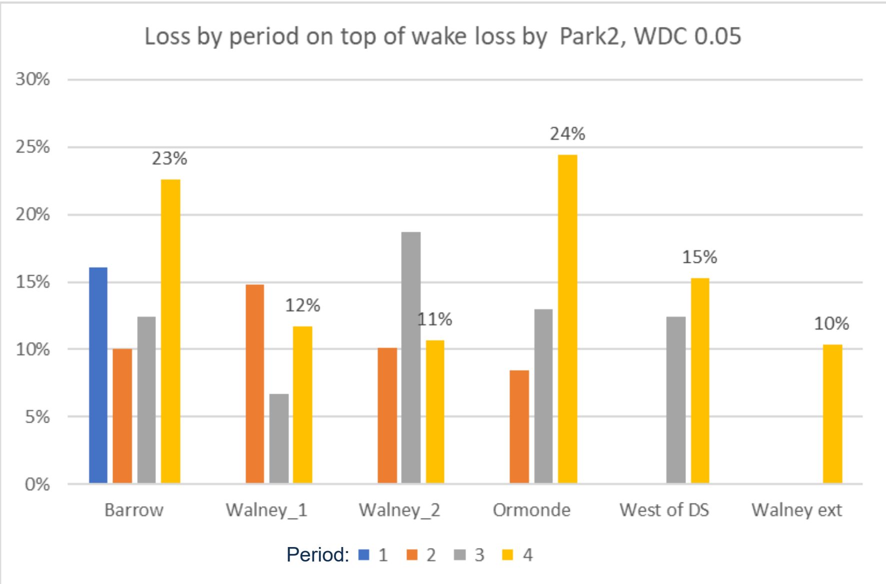
Period:	From	To	Wind farms	Months	Years	WTGs acc.	WTG type
1	Jan-08	Jan-11	Barrow	37	3.1	30	V90 3MW
2	Jun-12	Jan-14	+W1, W2, Ormonde	20	1.7	162	SWT 3.6 (107+120) Repower 5M
3	Oct-14	Nov-17	+West of Duddon Sands	38	3.2	270	SWT 3.6 120
4	Aug-18	Dec-20	+Walney extension	29	2.4	357	V164 8.25 + SWT 154 7MW

An interesting feature of this wind farm area (and in windPRO) is that data can be grouped in 4 periods with different wind farms in operation. Thereby it can be checked if the wake models capture the increase in losses due to new neighbours.

A calculation model is setup based on multiple EMD-WRF Europe+ mesoscale data points to include the horizontal variation of the wind climate in the region. Calculation is by hour, only including operating turbines in relevant months. The months with partly operating wind farms are not used.

While we do not have information on losses apart from the difference between calculated and measured, we evaluate the performance of the wake modelling based on the loss difference from period to period.





The "trade off" between wake losses and operational losses / mesoscale bias is the difficult part. What is what? This is of importance to separate to be able to make better pre-construction calculations.

Availability information do not give the full answer. Many analyses have shown there are more operational losses than the availability information shows.

Four periods, where different number of wind farms are operating, are analyzed. Note that there are months with extremely high losses, where some wind farms have been out of operation most of a month, which influences the data too much. Therefore, we take out months with more than 15% losses to make conclusions based on "normal operation":

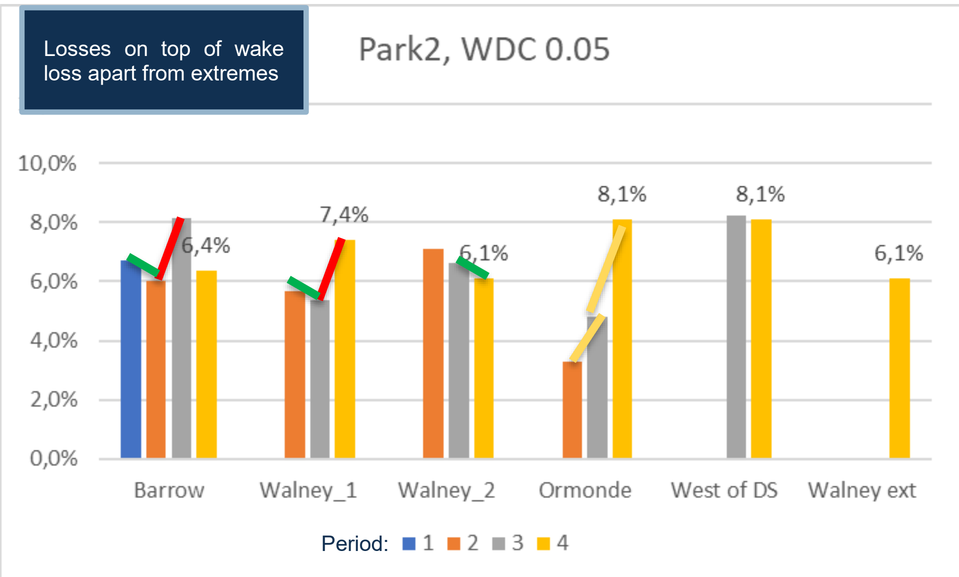


Figure 242 Losses on top of wake losses for months with < 15% loss (74% of month data).

Losses on top of wake losses for months with < 15% loss (74%) for the four periods with a different number of wind farms in operation.

The markers show:

Red – the losses increase with new wind farm that must be expected to have an impact.
Green – the losses decrease with new wind farm that must be expected to have an impact.
Yellow – change in loss is not expected related to new wind farms but change in operation.

There are examples where the wake model does not seem to capture the effects of new wind farms well enough. Conversely, there are also examples where the wake model calculates too much loss increase. This leaves no clear conclusion.
As an alternative approach, advanced wake tuning is applied:

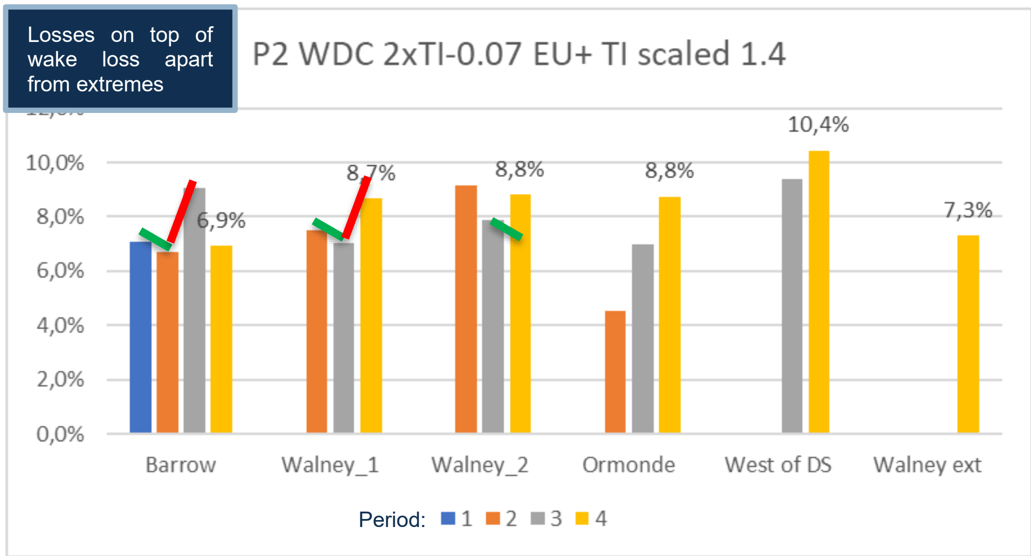
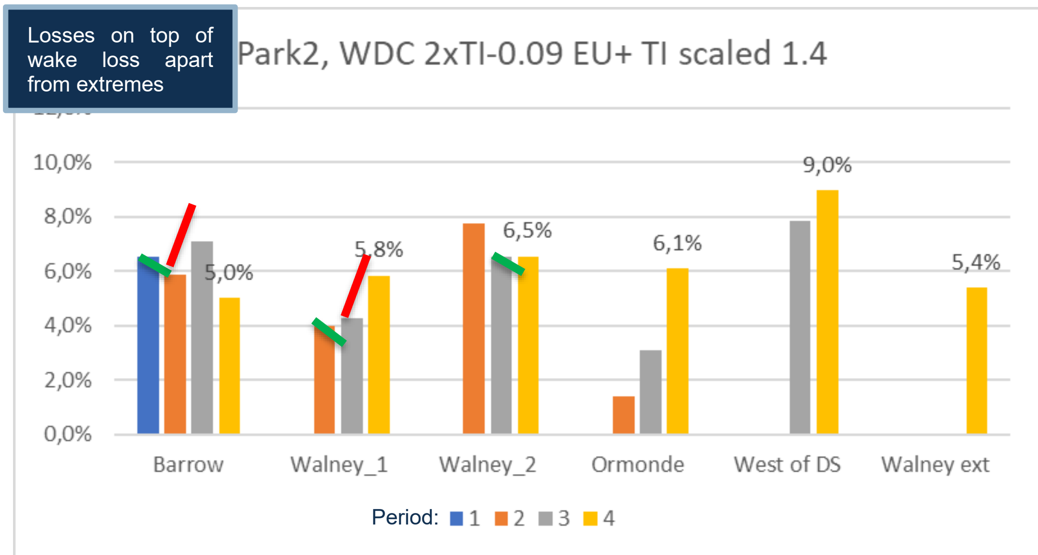


Figure 243 Calculation with advanced WDC(TI) for offshore.

Almost same picture, 71% of 535 months data used. But some higher losses than previous calculation with fixed WDC = 0.05.
The red-green differences from the previous chart are overlayed. This shows how Walney 2 previously had decreasing losses, but now has increased losses. The other examples also show slightly smaller loss increases as neighbor farms are built, compared to the losses using WDC=0.05.

By further adjusting the offset from -0.07 to -0.09 returns more months fulfilling the 15% threshold, 77%.



Compared to using 2xTI-0.07, the losses are now around 2 percentage points smaller, due to higher calculated wake losses. And this also reduces the change of losses as neighbor farms are built. Some of the change partly disappears, some partly get reduced.

Very importantly, the losses are now comparable to the losses observed at the detailed 10-min calibrated sites, which is around 4-7% for most wind farms and periods. The reason why West of DS (Duddon Sands) has higher losses can be related to power curve or Ct curve issues. Similarly, the bias in the other direction for Ormonde can have multiple causes (mesoscale wind, Ct curve, power curve), but the increase in losses does not seem wake related, but related to operational problems:

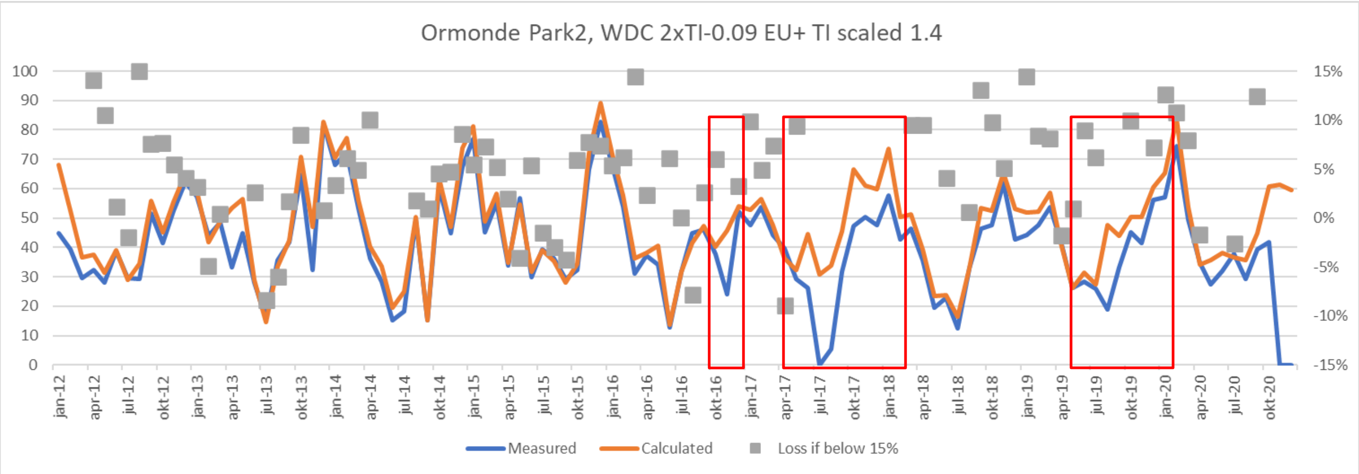


Figure 244 Ormonde measured and calculated by month.

Above, observe the "heavy" drops, first in Oct. 2016 then several months in 2017-18 and again in 2019 and 20. This does not seem wake loss related but caused by operational issues. This explains the loss increase by period, which could be even higher if the model setup for this windfarm was tuned further.

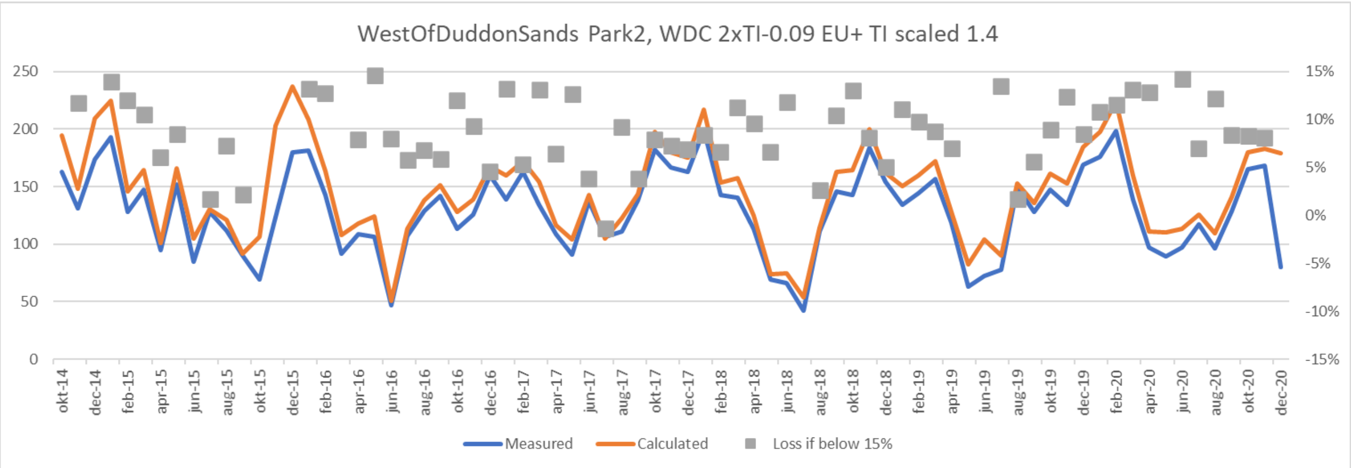


Figure 245 West of Duddon Sands measured and calculated by month.

West of Duddons Sands is performing in a quite stable manner month by month, but with quite high losses every month. This is unlikely a wake modeling issue, but more likely a turbine data issue. The calculated production is a little too high every month probably due to mesoscale bias or power curve bias.

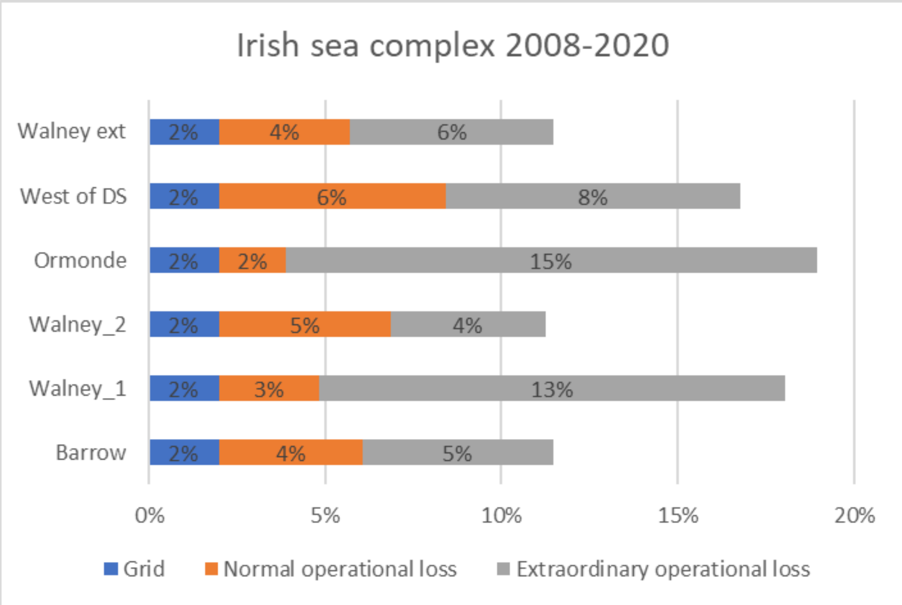


Figure 246 Assumed all time losses in addition to wake losses for the 6 wind farms.

As mentioned, Ormonde and West of Duddon Sands probably skew 1-2% in each direction, maybe simply due to using too few mesoscale wind data points – only 3 points were used in the calculations. While 3-5% normal operation loss seems reasonable, the serious problem is the months with > 15% loss, which might perhaps include market regulation?

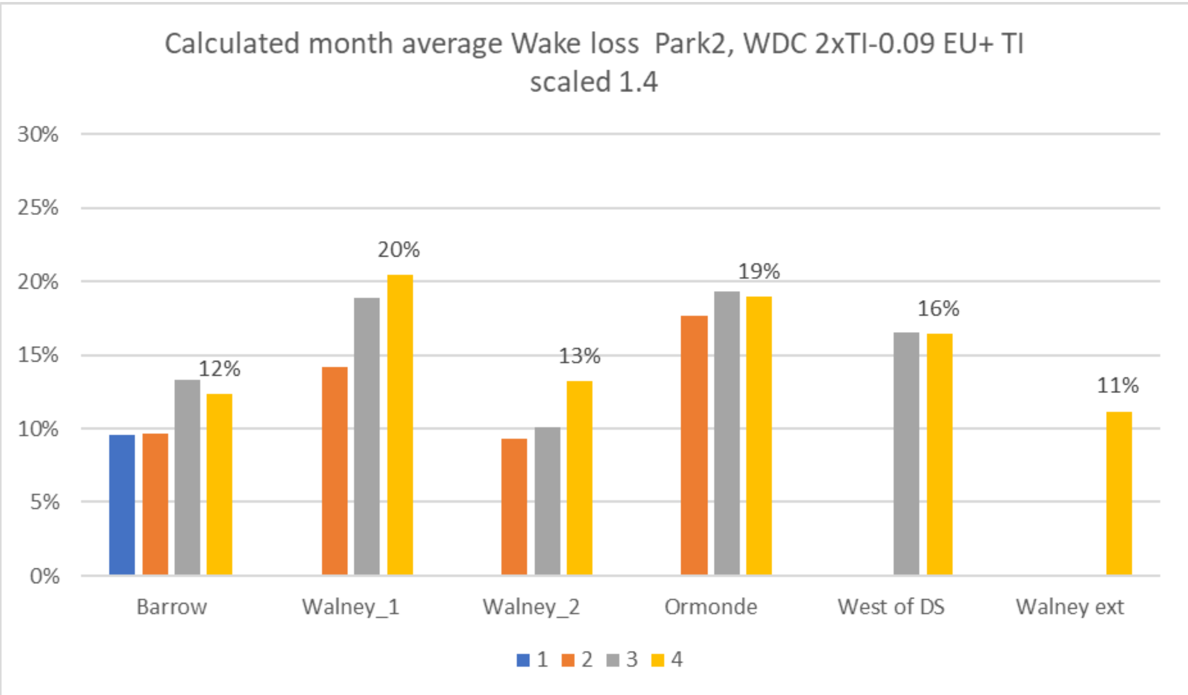


Figure 247 Final calculated wake losses per period per wind farm.

With the “most plausible” calculation setup based on losses on top of wake losses, these are the calculated wake losses for the four periods for the six wind farms. The reason why Barrow and Ormonde have lower calculated wake losses in period 4 than 3 is due to the wind speed and direction distribution. Walney 1&2 have higher calculated wake losses in period 4 due to the impact from the Walney extension.

Finally, a comparison to Ainslie DAC handling of this large area:

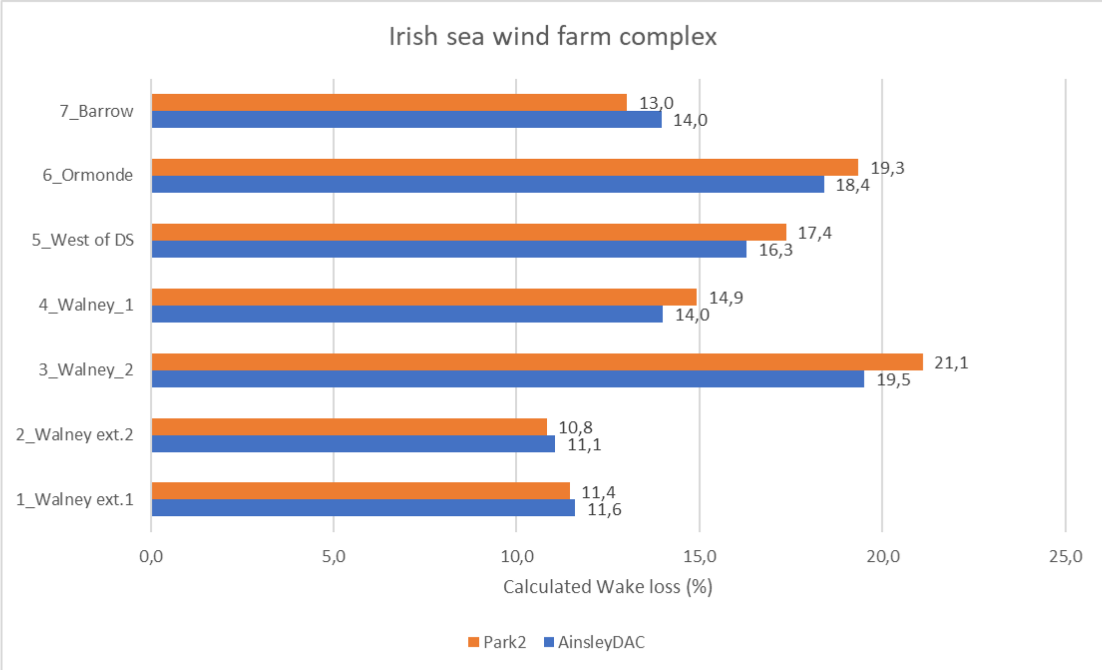


Figure 248 Calculation for 20y all wind farms running full time, compare PARK2 and Ainslie.

As seen, there are differences between PARK2 and Ainslie DAC. In general, these are small, typically below 1 percentage point. But most importantly: the two wake models seem to handle even these large wind farm complexes very well. There is no indication of serious problems.

3.8.7 Very large Egypt wind farm complex

With 700 WTGs, Zafarana is probably the largest onshore wind farm complex measured in number of turbines.

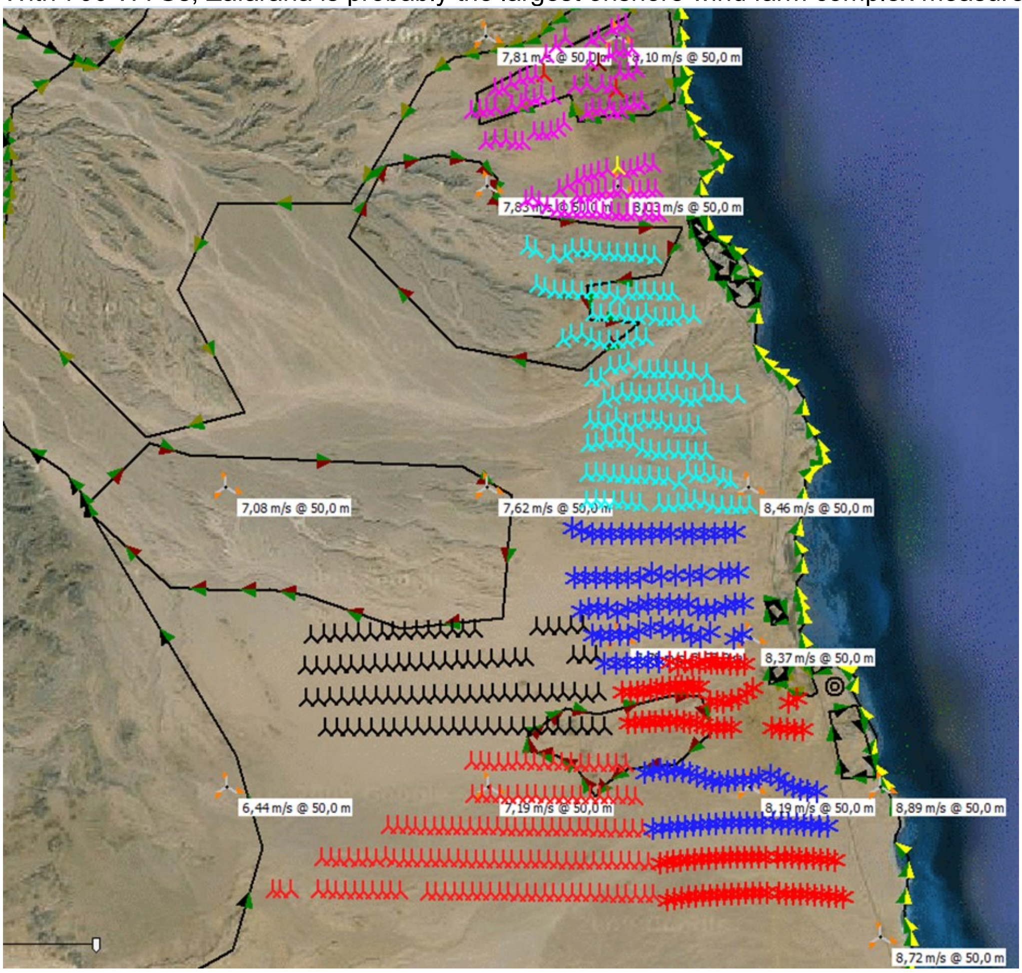


Figure 249 Zafarana wind farm.

Wind is always from northern directions. TI is round 9%. Using PARK 2 with 0.8 x TI gives a good match calculated vs measured:

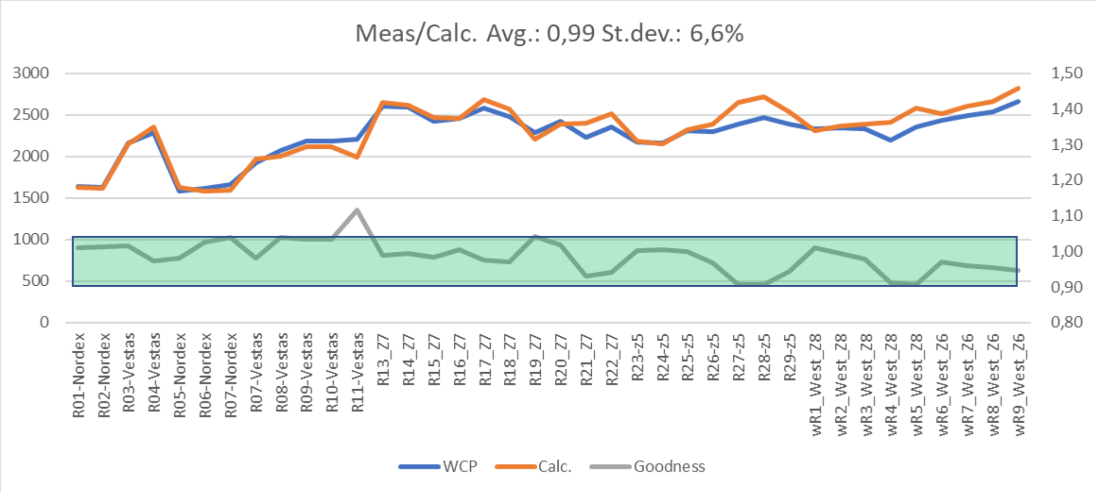


Figure 250 Row by row calculated and measured production with ratio meas/calc.

In 2011 EMD calibrated the wake model for this site. The result was a need of increased roughness to compensate partly for:

1) The original N.O.Jensen model (PARK1) did not reduce calculation result "enough" for the down wind part of the site.
2) There were meso scale effects which the traditional WAsP setup did not include.

In 2022 using PARK2 and mesoscale model data, this site is calculated quite accurately without any needs for added roughness to compensate for model and data inaccuracies. This shows how continuous model and data improvements within windPRO have brought the calculation model accuracy very far within the past 10 years.

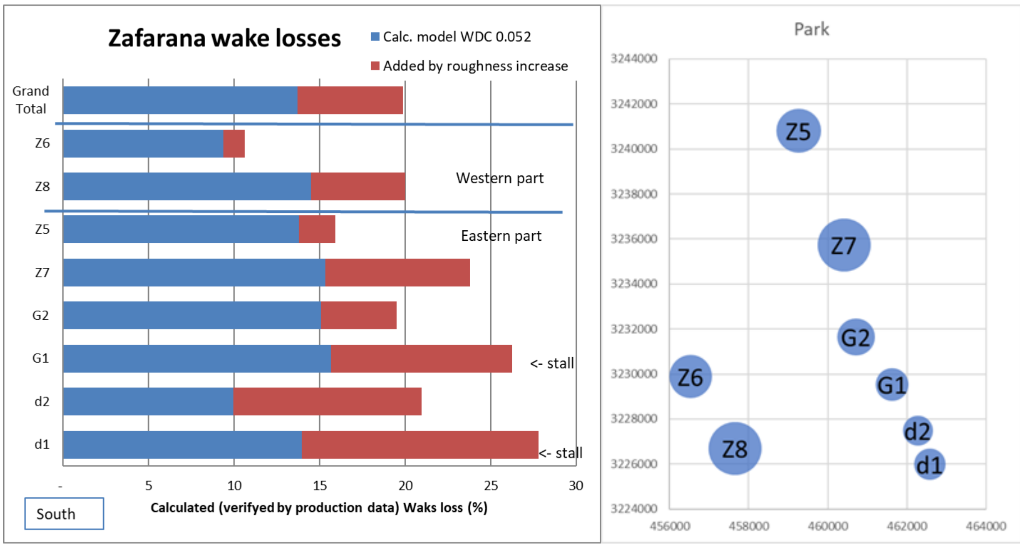


Figure 251 2011 calculations, increased roughness as model compensation very deciding.

With a decent model calculation setup in 2011, the predicted wake loss would be calculated to 13,5%, where real operation data showed 20%. The 2011 "solution" for calibration of the model setup was to increase the roughness. In 2022 the combined mesoscale model data and PARK2 are capable of handling this site just as well without roughness calibration.

3.8.8 Conclusions on wake modeling

WindPRO offers three alternative wake model concepts:

1. N.O. Jensen (PARK1, PARK2, NO2005). EMD recommends PARK2
2. Ainslie with DAC (Deep array correction)

3. WakeBlaster (external model from ProPlanEn)

For the two first wake models, blockage can be calculated as part of the wake calculation. Although typically this will only reduce production around 0.5% for 100 WTGs and is not TI dependent. Therefore, there is no significant change in calculated losses by present blockage implementations based on state-of-the-art scientific methods.

All three model variants calculate wake losses with reasonable accuracy and similar magnitudes. This has been validated based on several wind farms with access to detailed 10-minute operation data per turbine and verified by comparisons of the different wake models on real wind farms and on simulated wind farms with tests of calculated wake losses vs. the size of wind farm.

The key input for concepts of Ainslie with DAC and WakeBlaster is the Turbulence Intensity (TI), which determines the level of calculated wake loss. For N.O. Jensen it is the Wake Decay Constant (WDC), which EMD recommends being adjusted based on TI.

Detailed data analyses show a trend towards wake losses being even more TI-dependent than the models calculate. This can be handled by N.O. Jensen by making the WDC(TI) more "aggressive" than so far recommended, illustrated below:

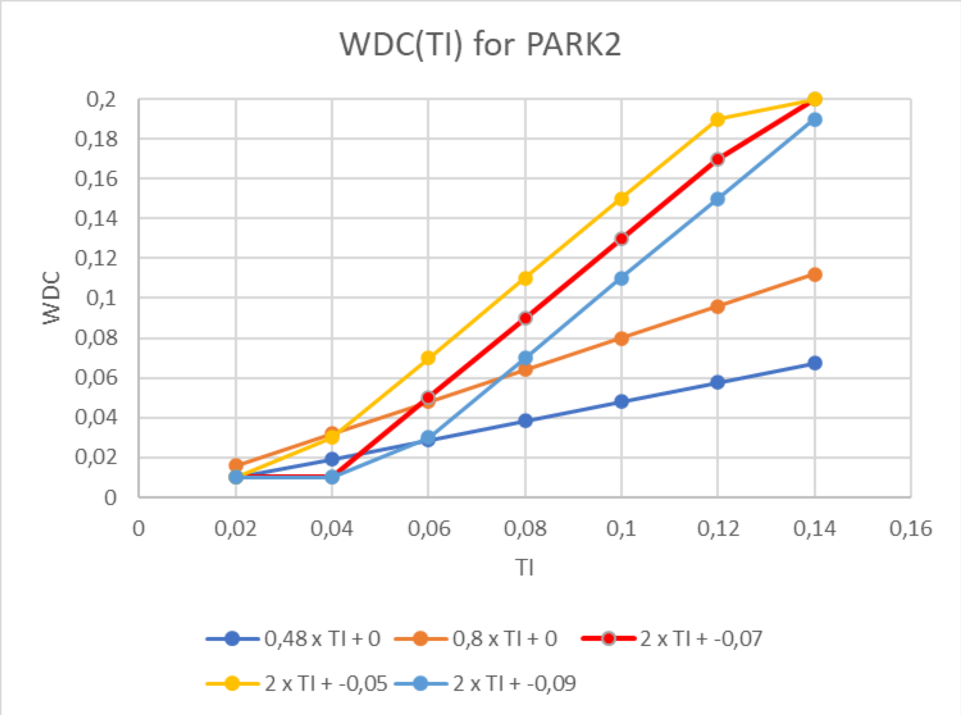


Figure 252 WDC(TI) for different configurations with PARK2.

The updated recommendation for PARK2 onshore is to use WDC = 0.6 x TI. For offshore and low TI onshore sites EMD recommends using a WDC = 0.8 x TI. However, we do see in data/validation examples that the more aggressive relation WDC=2x TI -0.07 for offshore/low TI site works better when subdividing data in TI bins.

The subtracted 0.07 can be used as tuning parameter, where for some sites like Lillgrund offshore with dense spacing 0.05 works best and for very large wind farm complexes like the Irish Sea Complex 0.09 works best. Most likely it is a question of wind farm size. For windfarms with around 100 WTGs the 0.07 seems to work best. The reason for more or less reduction can be that bigger wind farms has a greater impact on the wind regime of the site, which then can be compensated by a lower WDC. A lower limit on WDC of 0.01 and higher limit of 0.2 is recommended.

An important piece of information is that for offshore, the EMD-WRF Europe+ and similar pre-run mesoscale datasets have too low a value of TI offshore. EMD recommends scaling this TI with √2 (=1.41). This experience-based adjuster is built-in for the discontinued EMD ConWx mesoscale dataset and the EMD-WRF On Demand data. But while onshore validations show better agreement on TI onshore without this adjuster, it is not included in EMD-WRF Europe+ and similar datasets.

Calculating for the new generation of offshore turbines from 7 MW and up, there seem to be a slight overestimation of the wake loss with Ainslie DAC model. This is based on a few tests so far.

3.9 Validation examples and model problem issues

3.9.1 MCP validation

The validation is based on Høvsøre 40m data. Here there are 14 years of measurements, so the long-term wind speed is well-known. Data for one year at a time are taken as local data and EMD ConWx mesoscale data are used as reference. Here the years 2015 (high wind), 2016 (low wind) and 2017 (normal wind) are used to see if the long-term expectations are as the long term measured based on these different local years.

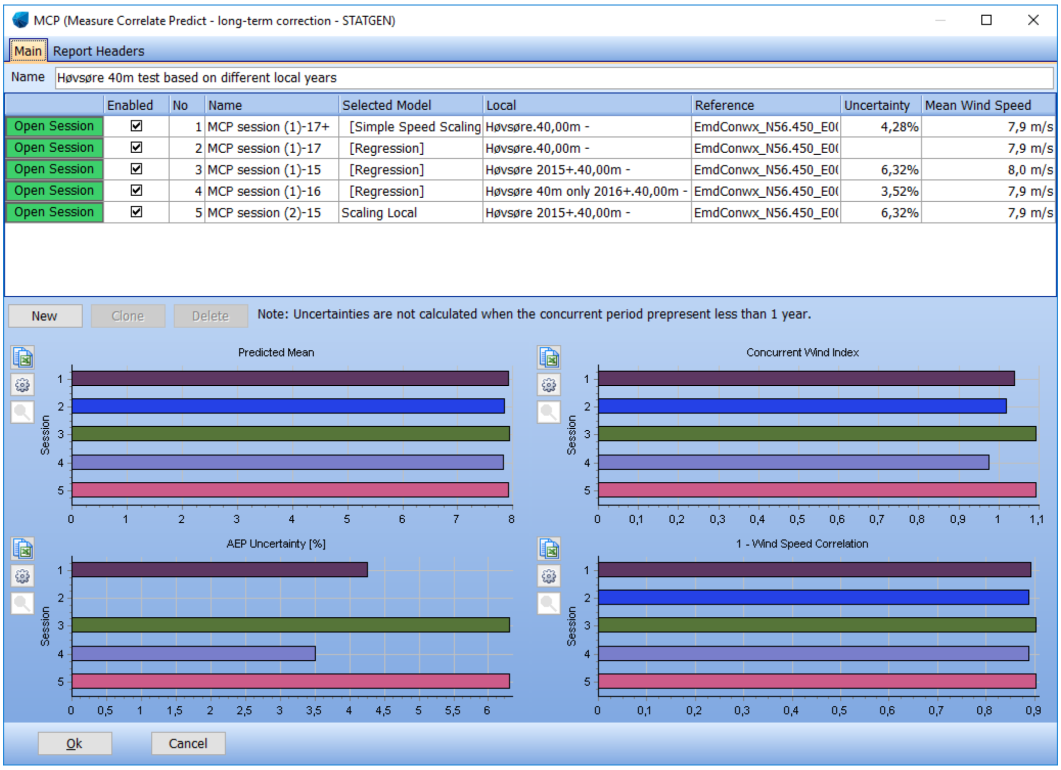


Figure 253 More MCP sessions can show more combinations for comparisons

The session overview page with the examples is shown above.

Below is a table with the different LT predicted mean wind speeds.
Two variants of the 2015 and 2017 based predictions are shown (by cloning the one and changing the selected model).

Below results of the experiments shown in table:

Table 14 Testing MCP with Høvsøre data

LT truth		7,93			
Input	**Method**	**Predicted LT m/s**	**Deviation**	**Deviation%**	**Uncertainty**
2015	Regression	7,96	0,03	0,4%	6,3%
2016	Regression	7,85	-0,08	-1,0%	3,5%
2017	Regression	7,87	-0,06	-0,8%	N/A
2017	Simple scaling	7,93	0	0,0%	4,30%
2015	Scale local	7,93	0	0,0%	6,30%

As seen the largest deviation to the true long-term wind speed (7.93m/s over 14 y) is 0.08 m/s (1,0%). The AEP uncertainty will depend on the turbine technology and wind speed level. For this wind regime, the AEP uncertainty will be around a factor of 2 on any wind speed uncertainty The largest error is therefore well inside the estimated uncertainty. It can thereby be concluded that the tool seems to do a good job and that the EMD ConWx data as reference work almost perfect at this site.

For the first entry labelled “2017 Regression”, one year of data is used, therefore the uncertainty is not presented (as windPRO only calculates uncertainty when there is more than twelve months of overlapping data). Expanding 2017 slightly with some data from 2016, gives the uncertainty shown by “Simple scaling” method.

3.9.2 Mesoscale data long term consistency

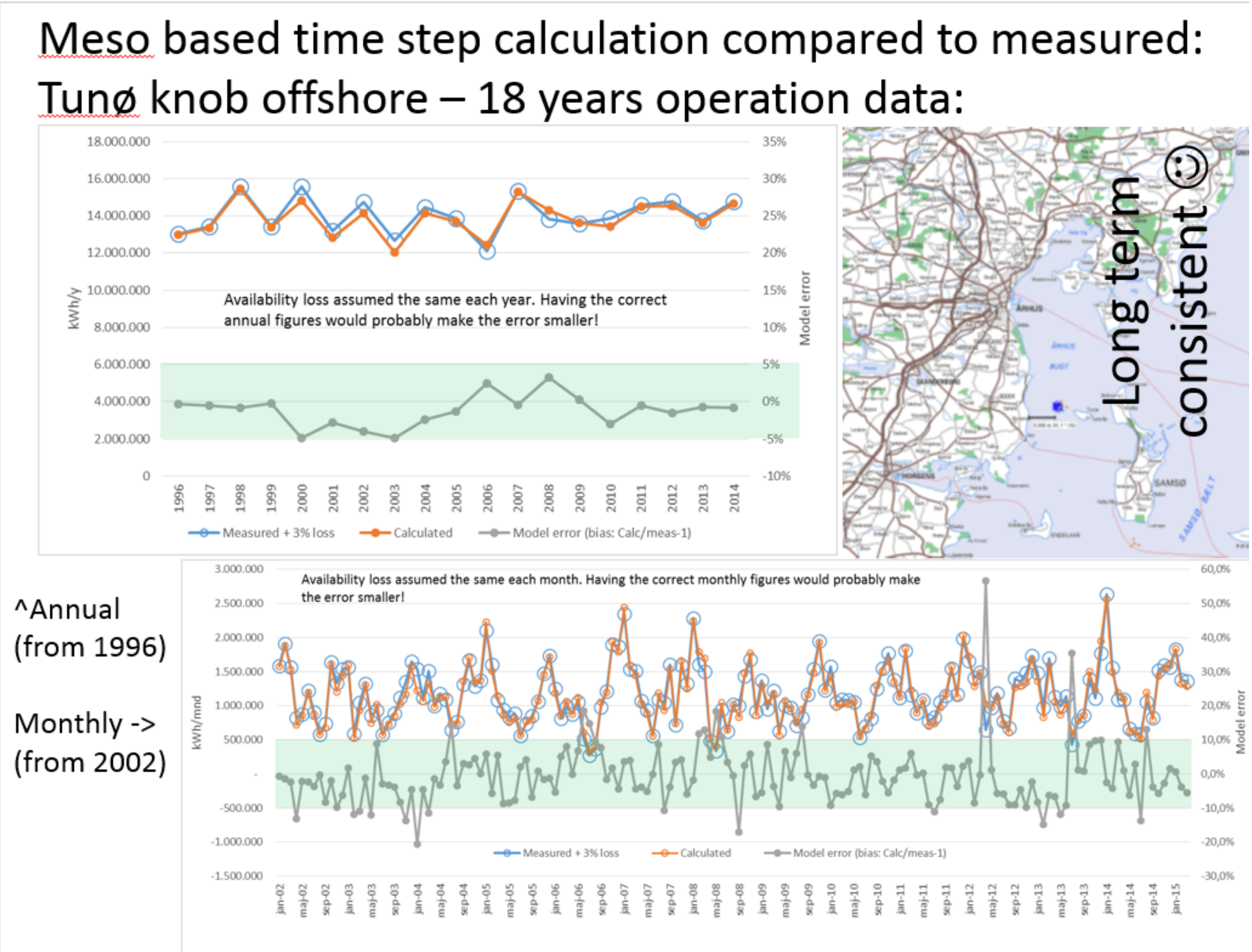


Figure 254 Long-term consistency using mesoscale data

This screen shot shows how well the mesoscale data based calculation matches measured production on a time scale of 18 years. The Tunø Knob offshore wind farm has been operating very well with few problems and a high availability during all 18 years. Therefore, it is a good validation case. It is seen that year-by-year model errors are within +/-5% and month by month within +/- 10%, apart from few months where the problems probably were related to availability issues.

This example alone cannot validate the long-term consistency.

Another test case is Høvsøre wind measurement mast versus MERRA-2 and EMD ConWx:

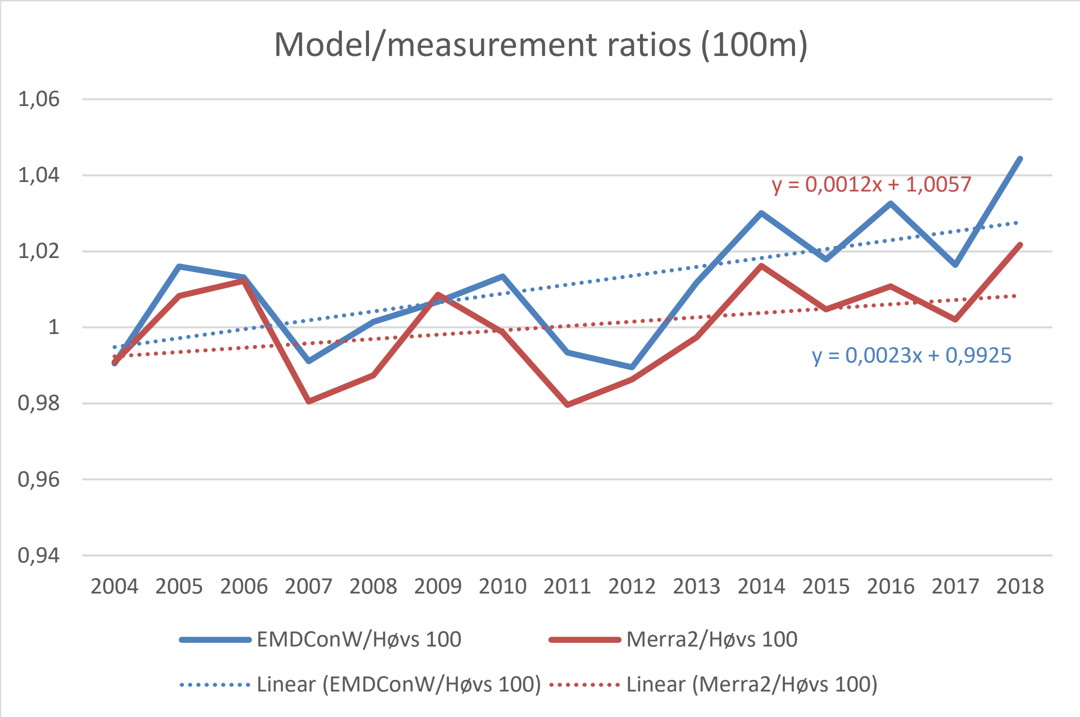


Figure 255 Wind speed ratios Model data/measurements 2004-18

It can be seen as well that the EMD ConWx mesoscale dataset and the MERRA-2 data has a trend relative to measurements.

It is in size order 1-2% per 10 years as an average for this site. What could be the explanations?

- Roughness increase, more trees, buildings and turbines affect the measurements, but not the model data.
- Measurement equipment changes in time, although it is assumed this is recalibrated regularly (?)
- Measurements are never “perfect”.

What is certaintly seen is different behaviour in low and high wind years. See graph below:

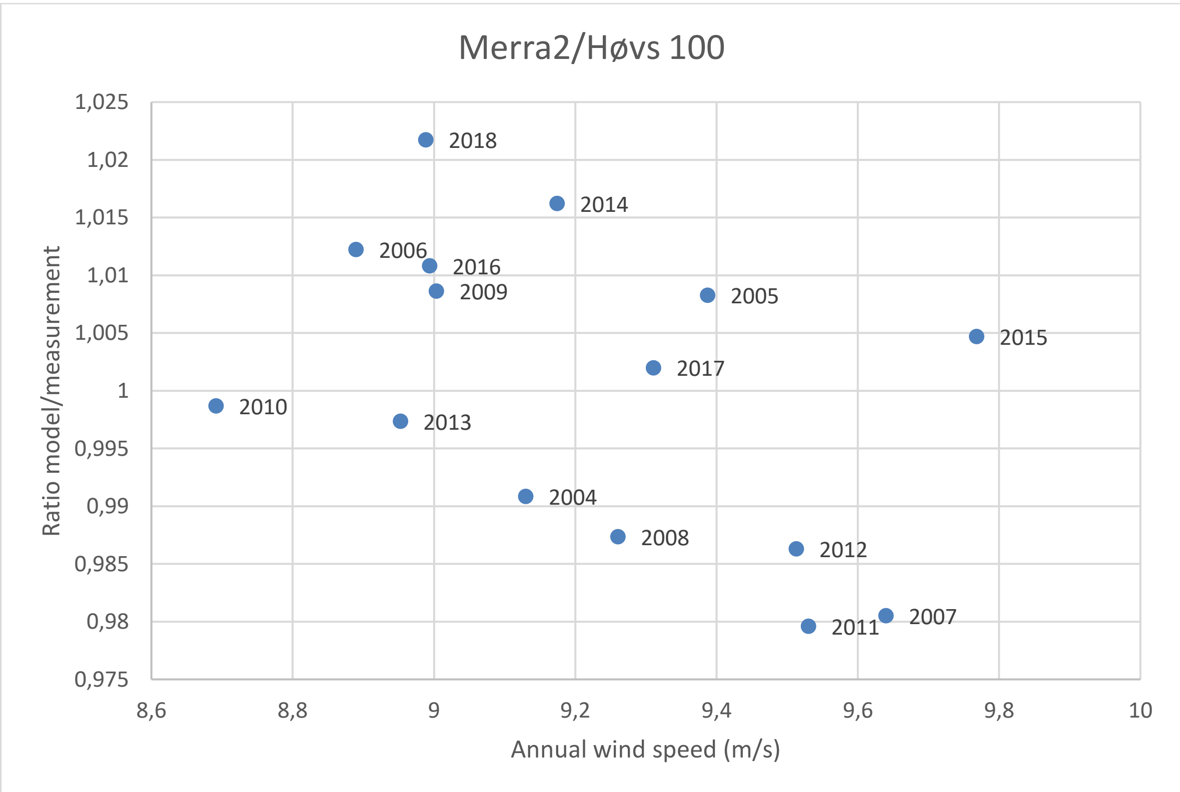


Figure 256 MERRA-2/measurements for Høvsøre 100m (MERRA-2 scaled to Høvsøre average)

There is a clear trend, that in low wind years, the model data are too high and in high wind years they are too low. In other words, model data varies less by high/low wind years than do the measurements. This problem can be handled by post processing the model data, something EMD is working on finding good methods to solve.

Later tests have revealed that the seen trend is higher when looking ONLY at eastern directions, where roughness increases in time, and there is basically no trend with wind from west, where the roughness remains constant due to the met mast is close to the sea in west direction. Therefore the observed bias is identified mainly to be increased roughness in time, and is not reflected in the model data.

3.9.3 WAsP versions modifications

The WAsP model itself will not be explained in detail here (see Risø/DTU WAsP manual), only the changes of high importance for the user in the more recent versions. From the very first versions, until and including ver. 9, the model itself has only changed marginally, and the calculation results, thereby, also. The major improvement during the earlier WAsP model changes is the capability to handle more map file points. However, from version 10.0, model modifications have been made. These mainly relate to stability correction handling, especially for offshore and near shore, but, also, the roughness map interpretation has been improved. The corrections were partly included in ver. 10.0, but first fully implemented in ver. 10.1 and 10.2. We, therefore, do **not** recommend using ver. 10.0 in offshore or coastal regions. The corrections relate to the default heat flux parameters - the way roughness in a coastal zone is interpreted and to formula modifications. The result of the corrections is a smoother change between on shore and offshore stability correction. The wind statistics for offshore is different if it is generated from WAsP 9 or WAsP 10.2+.

This means that an offshore or near shore wind statistics made from WAsP 9 SHOULD NOT be used in any version from WAsP 10.2 or vice versa.

This can best be illustrated by an example: 4 wind statistics are generated from the same time series data:

Mean wind speed [m/s] (top left)

Height [m]	0 (0,00 m)	1 (0,03 m)	2 (0,10 m)	3 (0,40 m)
10,0	7,4	5,2	4,5	3,6
25,0	8,1	6,2	5,6	4,7
50,0	8,7	7,1	6,5	5,6
100,0	9,4	8,4	7,7	6,7
200,0	10,3	10,3	9,4	8,2

Mean wind speed [m/s] (top right)

Height [m]	0 (0,00 m)	1 (0,03 m)	2 (0,10 m)	3 (0,40 m)
10,0	9,0	6,4	5,6	4,4
25,0	9,8	7,5	6,8	5,7
50,0	10,5	8,6	7,8	6,8
100,0	11,3	9,8	9,1	8,1
200,0	12,2	11,7	10,8	9,5

Mean wind speed [m/s] (bottom left)

Height [m]	0 (0,00 m)	1 (0,03 m)	2 (0,10 m)	3 (0,40 m)	4 (1,50 m)
10,0	7,4	5,4	4,7	3,7	2,5
25,0	8,1	6,4	5,8	4,8	3,7
50,0	8,7	7,4	6,7	5,8	4,7
100,0	9,4	8,6	7,9	7,0	5,9
200,0	10,2	10,3	9,5	8,5	7,3

Mean wind speed [m/s] (bottom right)

Height [m]	0 (0,00 m)	1 (0,03 m)	2 (0,10 m)	3 (0,40 m)	4 (1,50 m)
10,0	8,7	6,4	5,6	4,4	2,9
25,0	9,5	7,5	6,8	5,7	4,4
50,0	10,2	8,6	7,8	6,8	5,6
100,0	10,9	9,8	9,1	8,1	6,8
200,0	11,8	11,5	10,7	9,6	8,3

Figure 257 Four windstatistic results for Lillgrund offshore, different WAsP's.

Top row is using WAsP 9 and bottom row is using WAsP 10.2. Left column is assuming a class 0 site and the right column is assuming a class 1 site

In the left column, the class 0 data is almost the same using the two WAsP versions. The highest level is at 200m, although the result is slightly lower with WAsP 10.2 – a part of the formula modification. BUT, for the onshore classes, the wind speeds are essentially higher with WAsP 10.2 - around 0.2 m/s.

This means that a WAsP 10.2 calculation could calculate up to around 10% higher AEP than WAsP 9 at an onshore site, if the data basis were offshore.

In the right column, the onshore site, the onshore class data 1, 2 and 3 are almost identical from the two versions. Again 200m has slightly lower results with WAsP 10.2 – a part of the formula modification. BUT the class 0 data is around 0.3 m/s lower when calculated with WAsP 10.2.

This means that a WAsP 10.2 calculation would calculate up to around 10% lower AEP at an offshore site, if the data basis were onshore.

The changes are, of course, not serious as long as a consistent approach is used in the sourcing of the raw data (e.g., use offshore data for an offshore site). But, it should be mentioned that, in the coastal region, where there is part water and part land, quite unpredictable changes can be seen. Here, it will be especially important to use the same WAsP version for generation of wind statistics.

From the tables, it is also seen that, with large hub heights (>100m), WAsP 10.2 calculates slightly lower wind speeds than WAsP 9 – this is so both on and offshore have a general modification of the stability correction model. Based on quality test data in an offshore environment and from tall masts, this correction appears to give a better reproduction of the measurements.

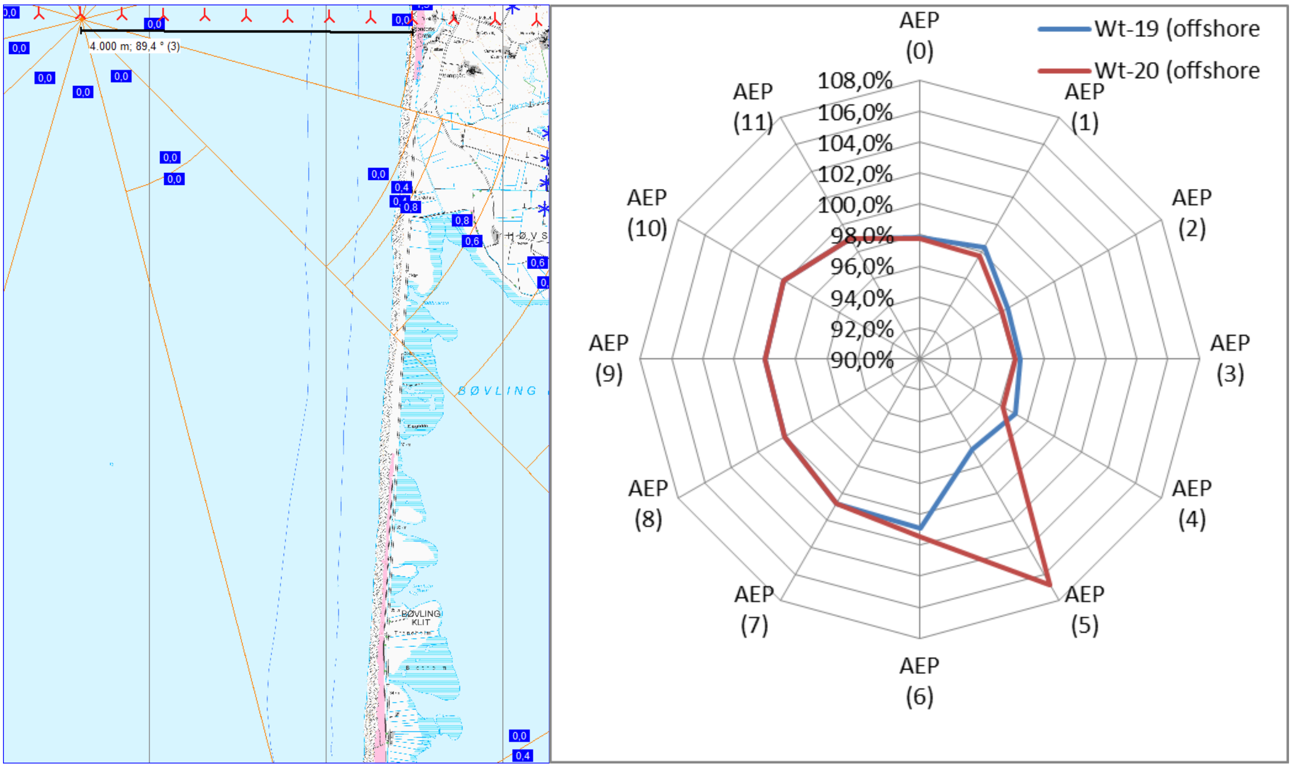


Figure 258 Test case calculations showing the WAsP stability model shift.

The example above illustrates the improvement regarding smoothing the stability model shift. Two turbines just 200m apart, both around 4 km offshore, are calculated. In Sector 5, there is a roughness change from class 0 to class 0.4 at a 10 km distance. The graphs show the ratio of the calculated AEP between WAsP 9/WAsP 10.2. Looking at the rose, it is seen that, in Sector 5, what happens for the two turbines is very different. This is where the distance to the roughness change in Sector 5 is just around 10 km. A change from 0 to a higher class decides that WASP 9 shall change between on- and offshore stability in that direction. The parameter: "Width of coastal zone" decides this and can be changed, but the default is 10 km. It's an obvious inconsistence, which is in WAsP 9, but not in WAsP 10.2. But, the graph also shows how the calculation results are smaller in general with WAsP 9 when the wind comes from land, while the WAsP 9 and WAsP 10.2 results are the same when wind comes from the open sea.

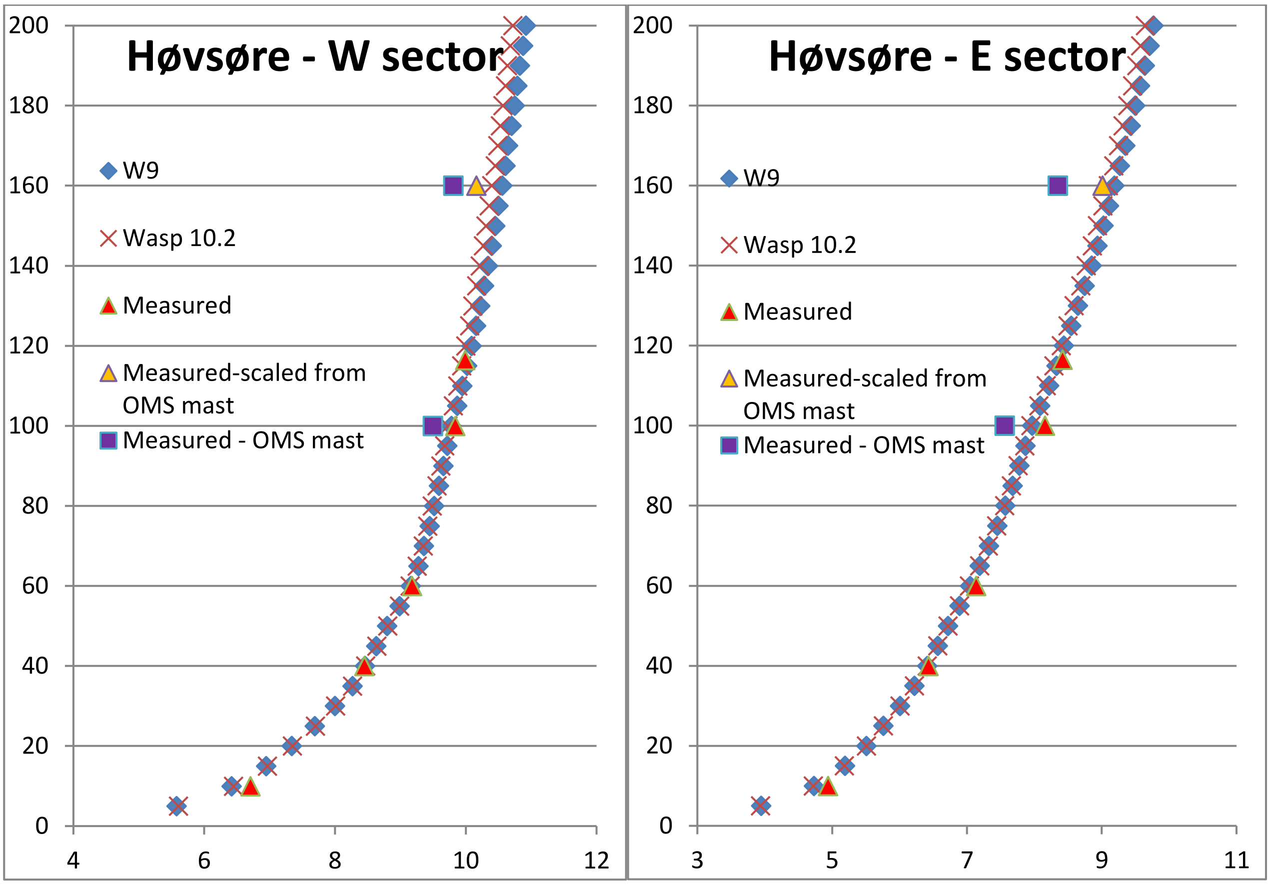


Figure 259 Wind profiles, measured and calculated

A test on reproducing measured profiles in large heights is shown above. It is seen that WAsP 10.2 predicts the vertical profile slightly better than WAsP 9. The 160m points (purple squares) are from another mast nearby and, therefore, not fully comparable to the measured (red triangles). Based on both masts measured at 100m, the 160m point is scaled (yellow triangle), and it is observed that the WAsP calculated profile matches measurements well up to 160m, with a small advantage for WAsP 10.2 relative to WAsP 9.

3.9.3.1 Tests of calculation in a coastal region with different hub heights.

The calculation setup can be seen in the figure on the next page:

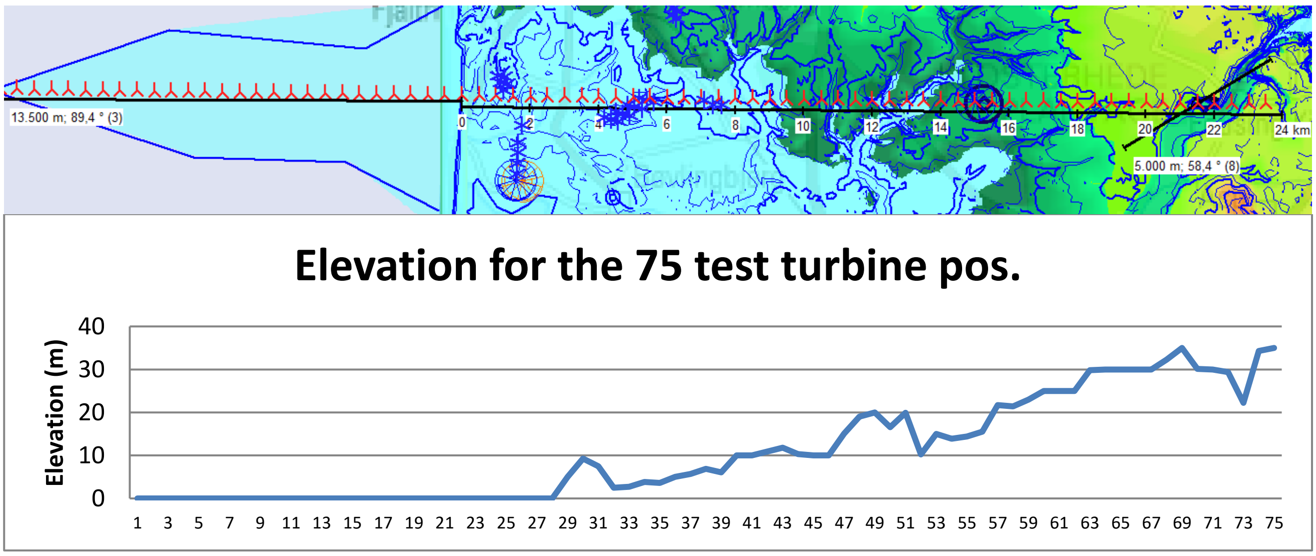


Figure 260 Model setup for test of WAsP model

Based on a met mast 1800m from the west coast, a row of turbines are calculated based on the two different WAsP versions, where the wind statistics are generated with same version as is used in the calculation. The turbine row starts 13.5 km offshore and ends 23.5 km onshore.

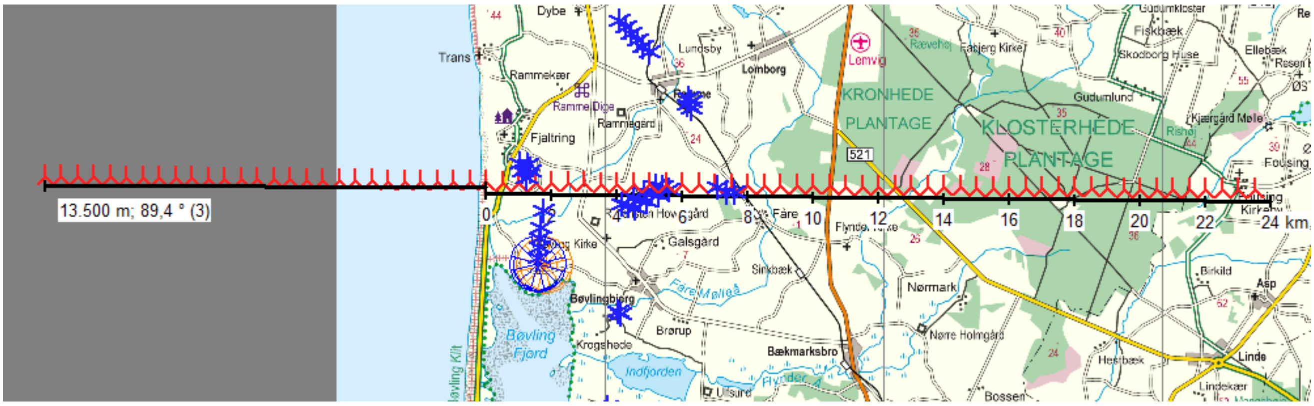


Figure 261 Map details for test setup

The map gives an idea of the surface roughness around the test row. The row crosses a large forest area along the onshore part.

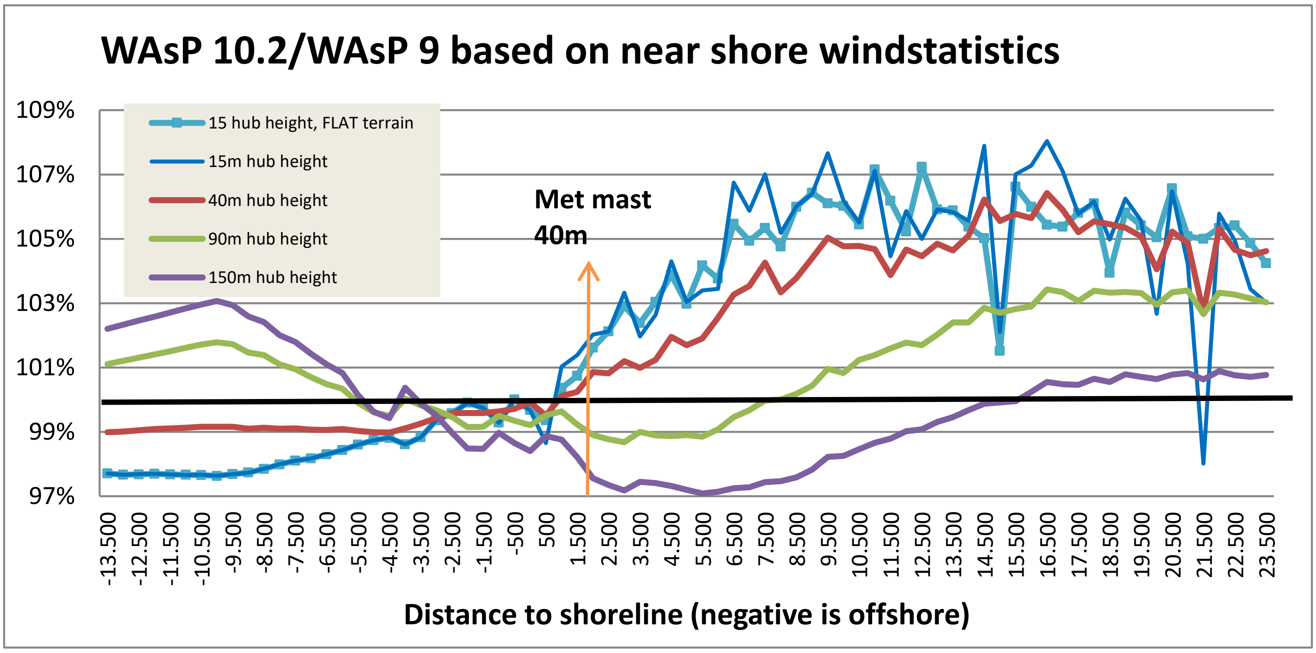


Figure 262 Results of WAsP 10.2 vs WAsP 9 calculations

For a 15 m hub height there are two variants: one calculated without orography and one with. For all other heights, orography is included, and for all calculations, digital roughness maps are included.

It is seen that there are quite some differences between the WAsP 10.2 and WAsP 9 results, but it is not that easy to come to a clear conclusion as to why. Starting with the 150m hub height, WAsP 10.2 results are around 1% lower the first 3 km offshore, but then rise up to 3% higher around 10 km offshore. Onshore, the results are lower the first 15 km, up to 3%, but get then slightly higher. A “reversed” pattern is seen for very low hub heights, but with up to 8% higher results onshore. There are two dramatic peaks in the graph. The leftmost peak is due to differences in roughness interpretation in the two models. The rightmost is due to different orography interpretation. This just illustrates that besides the major model changes, some minor bug fixes also contribute to the differences and leads to a recommendation to always use the latest version.

In conclusion, there are obvious improvements, and especially offshore and in coastal regions, we recommend using WAsP 10.2 due to better reproduction of the measured shear. For fully onshore sites (when measurements also are fully on shore) there seems only to be differences when hub heights are > 100m. However, if measurements are in coastal regions, the changes in calculation results can be quite large. We cannot yet say, based on actual turbines, if one or the other models performs better. But the most important conclusion is: **Do not use different WAsP versions in coastal regions to generate and use wind statistics!**

3.9.4 Displacement height calculation

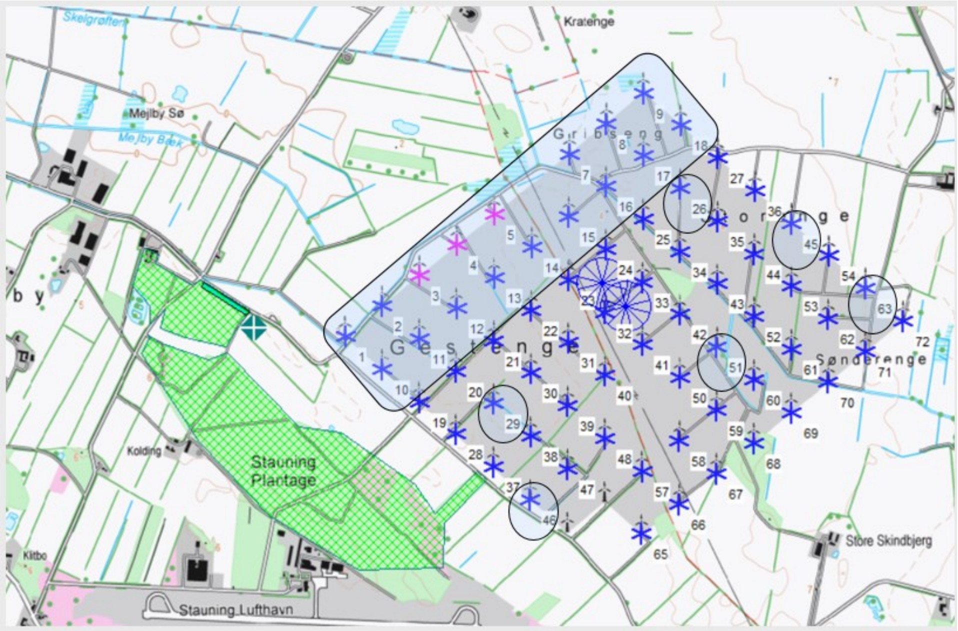


Figure 263 Test wind farm for displacement height

Above is an example of a large wind farm: 67 x 225 kW turbines (31m hub, 29m RD), with a 15 m forest just to the west (main wind direction). This is an ideal test case, except for the production data logging not being very good.

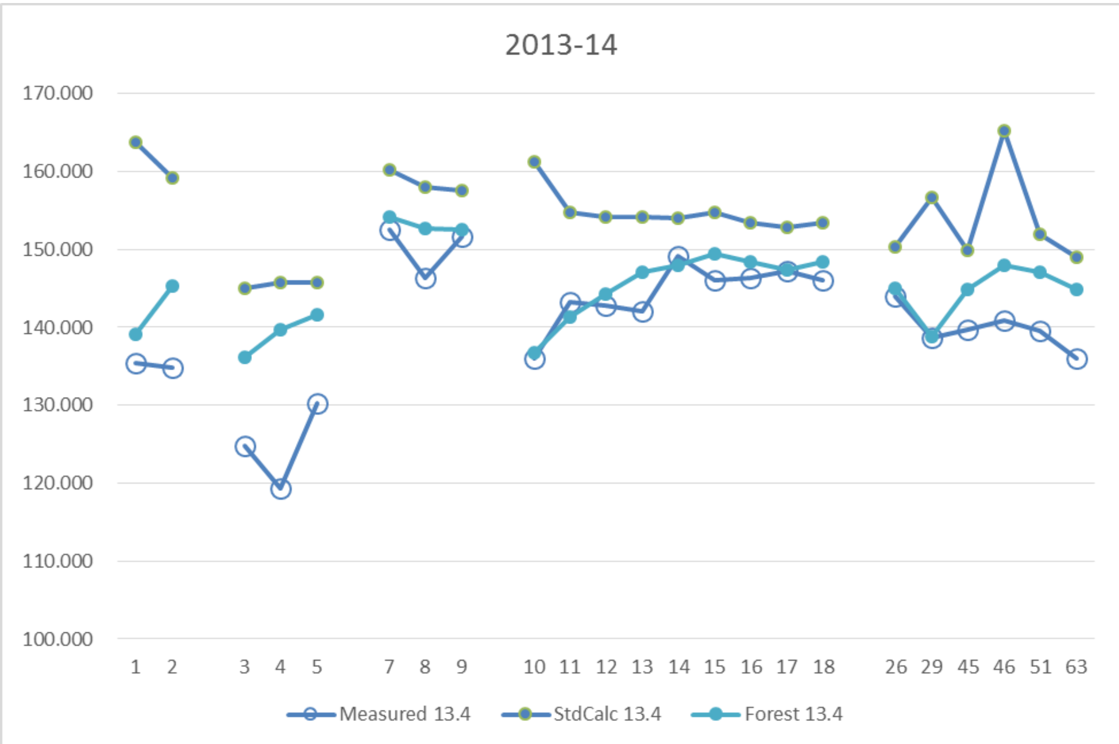


Figure 264 Results of calculation with and without displacement height

For a shorter period (one quarter), reasonably good production data are collected for the turbines marked on the map in Figure 167 and shown in this graphic. The standard calculation is a calculation based on mesoscale wind data for the same period as the production data. Note especially the turbine row T10-T18. Here, the west most (T10) is calculated as having the highest values due to low wake losses. But the actual production from these turbines is lowest and the production increases towards east. The obvious reason is the influence from the forest. Calculation with the forest model (displacement height calculator) captures the decrease in production very well for the turbines nearer to the forest.

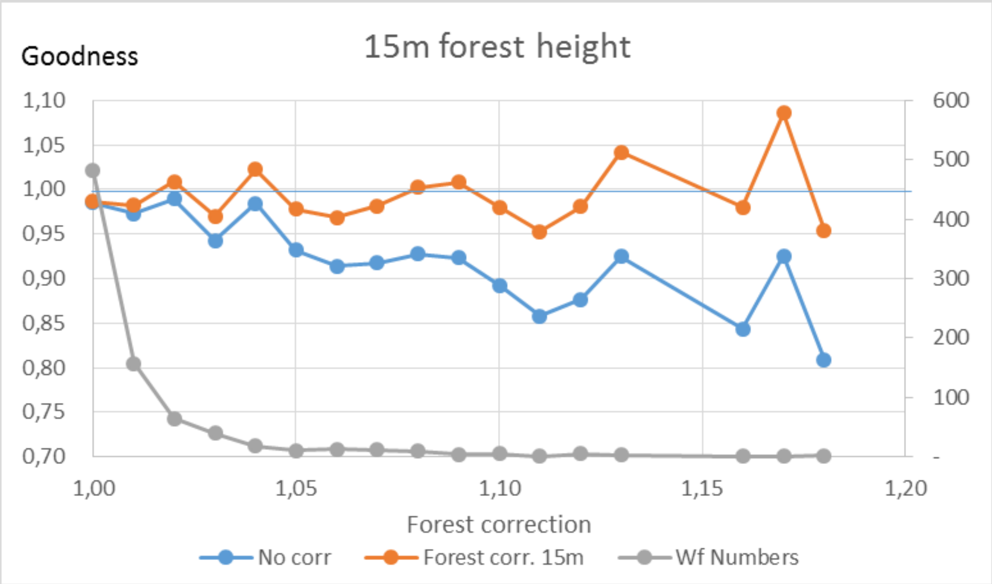


Figure 265 Test of displacement height used for 4000 DK turbines

In another example, an analysis was performed for 4000 operating DK wind turbines where calculated results were compared with measured production. The forest concept was tested simply by giving a roughness class of 3 and higher a "forest status". On the x-axis is how much this corrects the individual wind farms, on average: up to 18% reduction. And, also shown is how the goodness (measured/calculated) is lifted from 80% to almost 100% for most of the influenced turbines. It is obvious that the forest model performs well in improving the goodness of the more forest- influenced turbines, and that it brings the trend closer in line with that of the least influenced turbines.

3.9.5 Elevation model pitfalls

Based on many post construction evaluations, some trends are seen when performing a calculation in elevated terrain. The two major issues are:

- In less steep terrain, higher elevated turbines are under predicted by the WAsP model relative to lower elevated turbines. With WAsP-CFD, similar results are seen, although there is some improvement.
- In steep terrain (>30% slopes) higher elevated turbines are over predicted by the WAsP model relative to lower elevated turbines. The RIX correction can partially repair this problem, however, the WAsP-CFD, or other CFD models, would be a better choice than the WAsP model in this scenario.

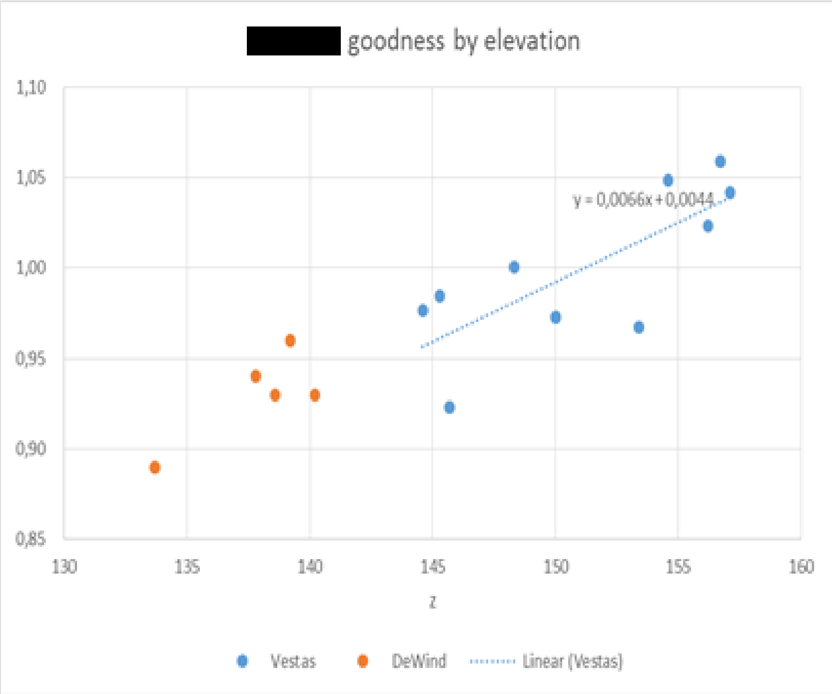


Figure 266 Ratio measured/calculated for a site in Germany with elevation differences.

Above is an example from a German site with turbines in elevation from 133m to 157m. A very clear trend is seen in that the turbines with lower elevation are over predicted relative to the turbines with higher elevation - almost 7% per 10m elevation difference. Based on more internal calculation examples, the value varies from 3-7% per 10m. **This has high importance when having reference turbines with different elevations relative to the new project to be calculated.**

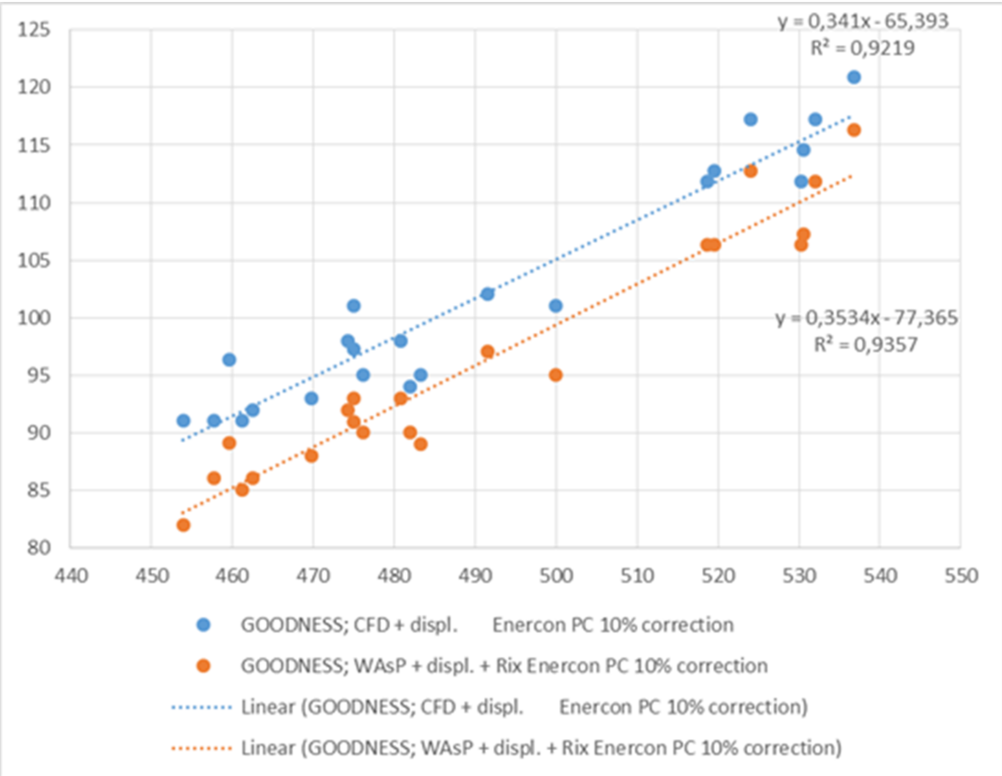


Figure 267 Example as in previous figure but including WAsP CFD calculation.

Above is another example, where WAsP-CFD is tested as an alternative to WAsP. For WAsP with Rix, a ratio of 3.5% per 10m is shown. This ratio is lowered to 3.4% per 10m when based on WAsP-CFD – almost no improvement.

For complex terrain (large steepness), see the WAsP-CFD validation paper.

3.9.6 Checking the Power Curve

3.9.6.1 The C_e value

A key parameter when checking the power curve is the non-dimensional C_e curve, which can be used for direct comparison of different power curves. If the maximum C_e value exceeds 0.5, the power curve must be assumed incorrect. C_e is the electrical efficiency, meaning that losses in energy conversion of rotor and drive train (gearbox and generator) are included. If these losses were zero, the C_e could have a maximum of 0.593, the "Betz-limit", where it, mathematically, can be proven that a turbine rotor cannot take more than 59.3% of energy out of the wind. Theoretically, if the rotor took 100% of the energy out of the wind, the wind speed behind the rotor would be 0 m/s, and the air would stop behind the rotor. While the rotors are not "ideal", there will be losses in the drive train, therefore, a C_e of 0.5 is considered an upper limit.

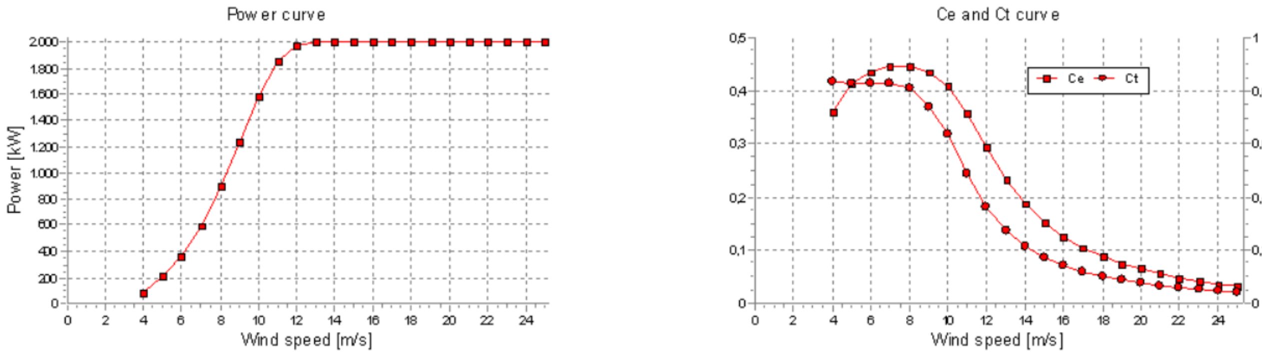


Figure 268 Example of power, C_e and C_t curves from windPRO

Above is an example of power, C_e and C_t curves of a 2 MW turbine with a 90 m rotor diameter. Max. C_e is 0.45 in this example. The example is a turbine developed around 2000. Since then, the standard C_e has increased towards 0.5. This is due to better blade design, more efficient control systems and drive train solutions, and the use of permanent magnets in the generators.

3.9.6.2 HP/PN-check

Another possible method for checking the power curve is the HP/PN method, where HP is the abbreviation for Helge Petersen, first manager of Risø (DTU) test station for wind turbines, and PN is for the founder of EMD, Per Nielsen.

Helge Petersen did a comprehensive study around 2000 where many power curves were compared. The conclusion was that grouping the turbines by design/control strategy (pitch/stall and 1-generator/2-generator), and normalizing by specific power, all turbines had identical power curves. This resulted in a set of tables, giving the output per square meter rotor area for the different designs/control strategies as a function of mean wind speed with specific power as a parameter.

HP curve comparision

Vmean	[m/s]	5	6	7	8	9	10
HP value	[MWh]	206	331	464	578	665	754
WT/TRIPOD 1.225 25.00 -0.80	[MWh]	206	331	457	572	671	749
Check value	[%]	0	0	2	1	-1	1

Figure 269 Example of HP check of power curve

Above is an example of the HP/PN comparison. As seen in this example, the HP value at 5-6 m/s average wind speed matches exactly the supplied power curve value. At 7 m/s, the HP value is 2% higher than the power curve value. At 9 m/s, it is 1% lower. If the deviation is more than +/-3% at a given wind speed, there should be concerns about the reality of the power curve. Note that the comparison is based on Rayleigh distributed wind (Weibull k=2) at standard air density (1.225kg/m³). If turbines are running in noise-reduced mode, the HP check value tells the losses due to noise reduction. If the non-noise reduced mode has a check value of 1 and the noise reduced a value of 7, the noise reduced operation can be considered to cause a loss of around 6% (see example below).

HP curve comparison

Vmean	[m/s]	5	6	7	8	9	10
HP value	[MWh]	3.248	4.971	6.649	8.153	9.427	10.451
Level 1 - - Mode 1 - 07-2009	[MWh]	3.181	4.864	6.515	8.003	9.267	10.280
Check value	**[%]**	**2**	**2**	**2**	**2**	**2**	**2**
Level 0 - - Mode 0 - 07-2009	[MWh]	3.202	4.904	6.568	8.064	9.331	10.343
Check value	**[%]**	**1**	**1**	**1**	**1**	**1**	**1**
Level 2 - - Mode 2 - 07-2009	[MWh]	3.063	4.645	6.210	7.644	8.881	9.888
Check value	**[%]**	**6**	**7**	**7**	**7**	**6**	**6**

Figure 270 Example of HP check of power curves with noise reduction

From windPRO 4.1 the generic power- and Ct-curve generator calibration is updated to better match the characteristics of newer turbines with hub heights above 100 meters.

The generic power- and cT-curve generator assumes the turbine operates at rated power until cut-out. However, larger turbines typically employ a ramp-down at high wind speeds. As such, it is always recommended to obtain the actual power curve from the manufacturer. EMD strives to keep the turbine catalogue up to date with the latest available turbine specifications from the manufacturers. If some information is missing, please ask your manufacturer to provide the data to EMD, so the information can be added to the catalogue.

3.9.7 Test of Turbulence scaling

With the SCALER and time step PARK calculation, it is possible to establish the turbulence for each time step at each WTG position in hub height, see Section 4.8.4. This can partly be used for turbulence correction of the power curve (only for pitch regulated turbines) and partly to control the WDC in wake loss calculations.

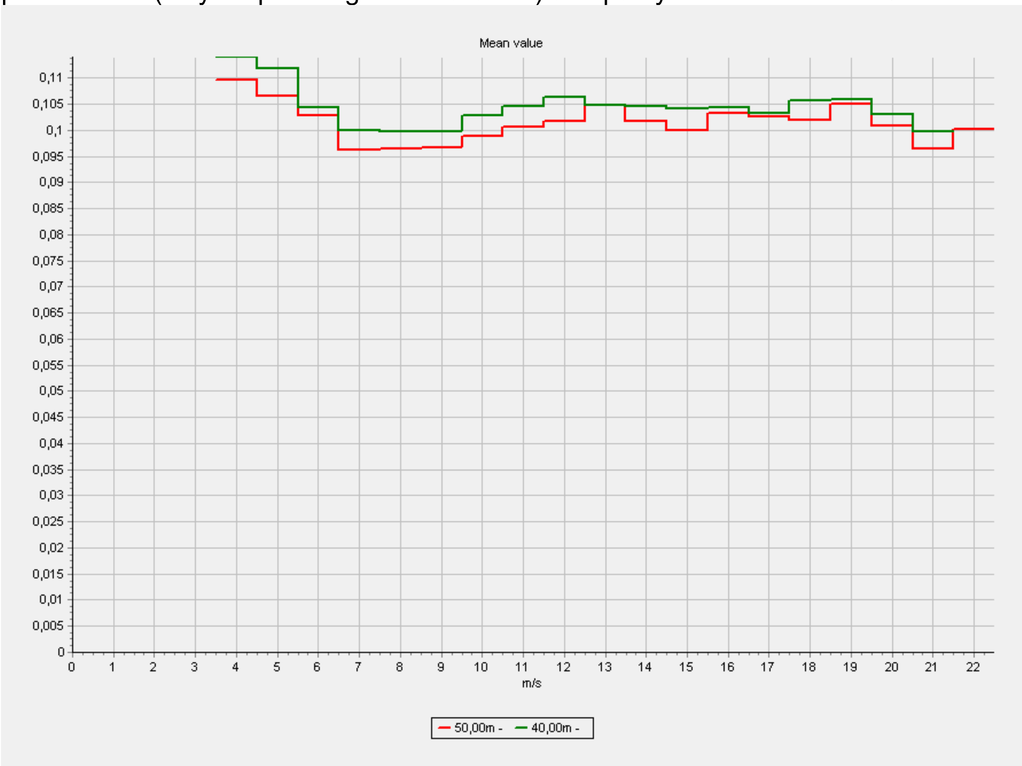


Figure 271 The site mast with measurements, turbulence in 40 m and 50 m.

Below the different variants of establishing the turbulence by SCALER calculations at a specific turbine position is tested.

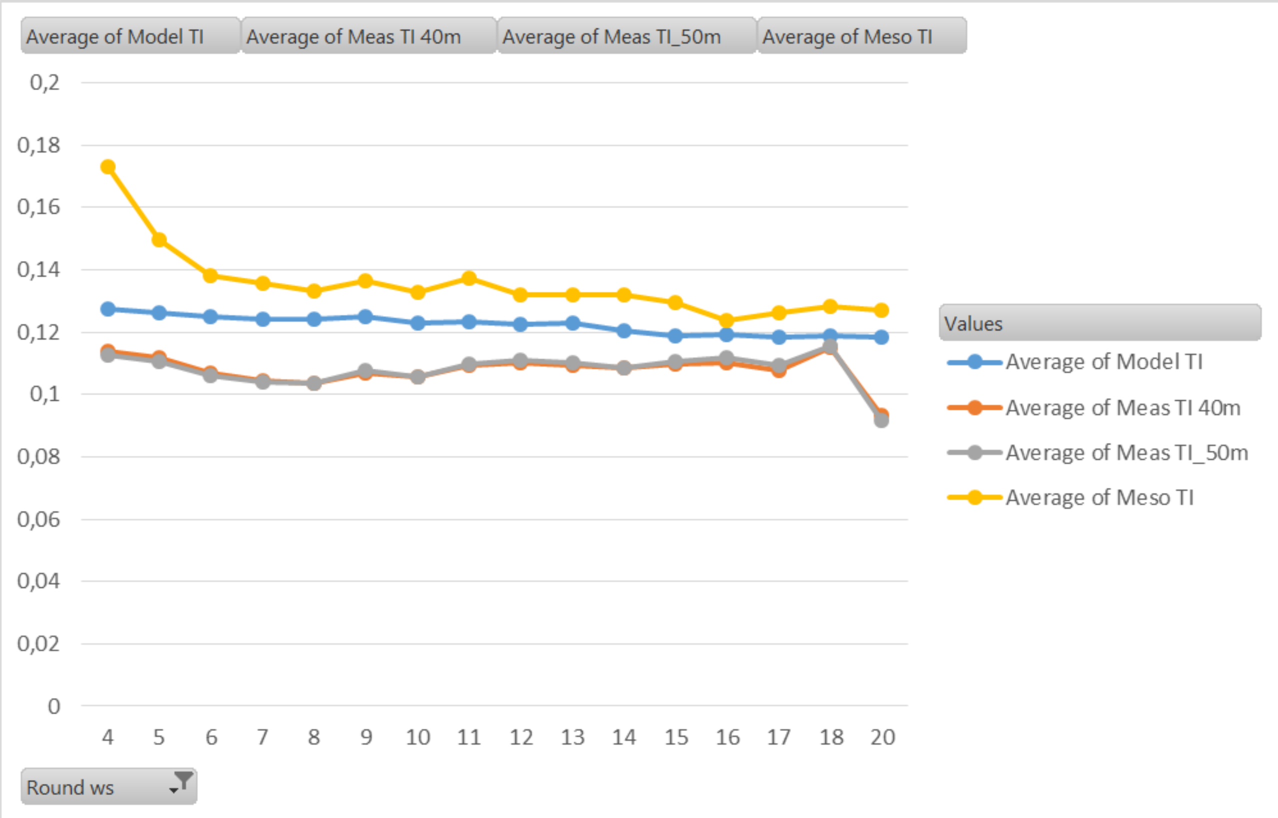


Figure 272 Turbulence calculated at WTG-1 at 47 m hub height from different sources.

As seen the calculated turbulence based on 40 m as well as 50 m measurements is exactly the same. This shows the model performs the transformation correct based on different heights.

The Model calculated TI is based on WAsP CFD model results. This comes out with slightly higher turbulence than measured. Finally, the TI taken from mesoscale data (EMD ConWx) is shown. This is again somewhat higher than the measurements. Overall this means there are not very large deviations.

To test the calculation concept more comprehensive, the calculated TI at two different turbines is tested. At WT-10 the calculated (free) wind speed is 5% higher than at WT-1, therefore round 5% lower calculated TI are expected at WT-10.

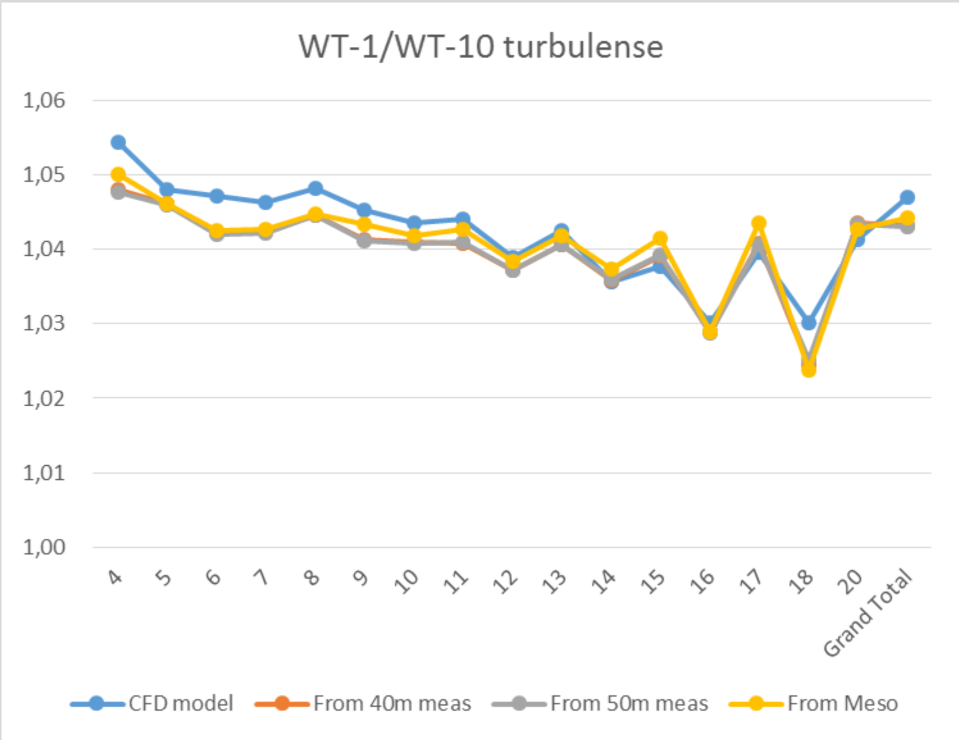


Figure 273 The ratio of TI at WT-1 and WT-10 with different calculation settings.

As seen, the result comes out reasonable as expected. The calculated TI is 3-5% higher at WT-1 than at WT-10. In addition, it works similar based on all four described calculation settings.

It is hereby shown that the SCALER calculates the TI at different positions as expected. The accuracy of the calculated turbulence will although not be more precise than the data and models behind. In some terrain, the real turbulence might differ more than the model calculations show.

3.10 Appendices: From windPRO 2.9 manual, not included in this manual:

3.10.1 MCP2005 – Measure/Correlate/Predict (long term correction)

The previous version of MCP, first release in 2005, will still be available for backward compatibility.

3.11 Table of figures and tables